Influence of Ventilation Operating Modes on Energy Efficiency

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Abstract: The most significant increase in construction volumes in Latvia was registered in the time period from 2005 to the middle of 2008. Many large suburban areas around Riga were landscaped for building single-family-type houses. People have been using these properties for 12–15 years, and now, the challenge for the inhabitants is to find the most efficient way to maintain a high level of living comfort. Deteriorating systems require investments, so it is in the interest of owners to ensure that the benefits of such investments are maximized and that energy consumption is as low as possible. In this study, the authors simulated various scenarios where HVAC system parameters were changed, and the thermal performance of building structures was improved. Annual energy consumption, indoor quality and thermal comfort were analyzed. The importance of this work is justified by the need to realize and define the energy efficiency levels of existing single-family houses and demonstrate the amount of investment required to move closer to established energy efficiency targets.

Keywords: HVAC systems; energy consumption; thermal comfort

1. Introduction

The Paris Agreement on Climate Change supports the attempts of the European Union to decarbonize the building sector and facilitate the transition from fossil fuels to renewable and locally available energy. The latest version of the Energy Performance of Buildings Directive 2018/844/EU requires the simultaneous integration of indoor environmental quality assessment with energy performance and cost-optimal requirements, without compromising comfort, wellbeing and healthy indoor climate conditions. For the promotion of energy performance in the building sector, the directive uses the common term “nearly zero-energy buildings”, which is applicable both for new buildings and buildings undergoing major renovations. In many European countries, the construction of nearly zero-energy buildings is encouraged on the national level, limiting the thermal energy consumption of buildings for heating purposes to 40–60 kWh/m² [1]. However, energy consumption for cooling buildings is not strictly regulated.

The Passive House (PH) standard provides a cost-efficient way of minimizing the energy demands of buildings in accordance with the global principle of sustainability [2,3]. The PH standard is a voluntary quality assurance standard focused upon maximizing the health and wellbeing of occupants while reducing the demand for space heating to a very low level, or 15 kWh/m². Complementary synergistic technology approaches based on the same physics of thermal energy transfer and storage are implemented in the “net zero-energy building” approach, which means over the span of one year, a building does not use more energy than it generates.

The construction and operation of buildings is a complex process that requires an integrated approach at all stages in order to successfully meet the required energy consumption levels. When it comes to sustainable construction in particular, various certification tools are in place to help address different aspects. The best-known international certification systems are overviewed in [4], showing that all certification systems are aiming to award...
buildings that ensure environmental protection, reduce energy consumption, encourage resource efficiency and strive for ambition and innovation.

During the last decade, the HVAC solutions available to the single-family house market have been significantly improved. A lot of smart solutions are available for controlling and operating systems in accordance with different IAQ parameters. Additionally, strategies for monitoring and adjusting ventilation are available, including using IoT monitoring systems and cloud computing [5]. However, not all possible contaminant sources are always realized and properly addressed. In most cases, the focus is on CO$_2$ and VOCs [6–10]. Retrofitting buildings in the area of Eastern Europe and changing from coal furnaces to gas heaters can cause the occurrence of significant CO problems [11].

When choosing suitable options for renovation, it is necessary to compare the advantages and disadvantages of applying different renovation scenarios and evaluate the comfort parameters for each of them. A unique performance and comfort optimization solution, validated by simulations built on real data acquisition, is described in [12,13].

In the case of renovation of existing buildings, careful economical evaluation and optimization methodology should be applied. Building strategies for low-energy buildings include a variety of methods and approaches. Different modeling, optimization and simulation strategies have been described in four studies, where the authors have emphasized the importance of careful calculation procedures before the implementation of energy-saving measures [14–17]. Cost-optimal analysis and indoor environmental quality assessment for nearly zero-energy buildings in temperate climates were presented by Tanasa et al. The cost-optimal analysis results show that among the investigated scenarios, the lowest global cost is achieved by a house that has a passive house envelope, mechanical ventilation with heat recovery, a heat pump and a solar collector [18].

Material selection is another issue when choosing different refurbishment solutions. The environmental impact and benefits of adding materials and technologies in order to reduce the energy consumption of a building by evaluating the embodied and operational energy were assessed by Kovacic et al. [19]. Another study provides an assessment of different materials in terms of CO$_2$-eq savings. A careful selection of materials can reduce net CO$_2$-eq savings by up to 68%, especially when using wood material [20]. Many studies have demonstrated that the thermal transmittance of envelope materials is not a valid parameter for the comparison and harmonization of envelope energy losses because countries set different transmittance values for each climate zone, which are then defined on the basis of different ranges of degree variations per day and calculated using different base temperatures [21–23]. Results from Albayyaa et al. show that the total energy required for heating during winter is reduced by 37% and 36% using passive solar and energy efficiency design strategies for constructing standard fibro and brick veneer houses, respectively. On the other hand, increasing the thermal mass (building materials with higher R values), utilizing different walls and flooring systems, replacing fibro houses with brick veneer houses and applying PSEEDS could reduce the total energy requirement by up to 58%. Thus, incorporating PSEEDS and higher thermal mass in the construction of residential buildings can yield significant savings in energy costs over the considered lifetime period of 50 years [24]. A study by Panão et al. shows the measured and modeled performance of the internal mass of a thermal energy battery for energy-flexible residential buildings [25]. Reda et al. propose to consider possible directions of further research in the low-energy building context, including interaction with utility networks. The general conclusion is that at northern latitudes, the energy generated onsite with conventional solar technologies is not enough to reach the net-zero energy target, and research should focus on innovative solutions, such as seasonal storage and advanced “building to urban energy networks” solutions to go even beyond the net-zero energy horizon and achieve positive energy buildings [26].

Air change rate is one of the key factors that shows the correlation between a building’s energy efficiency level and a healthy indoor environment. The proposed air change rates of 0.3–0.7 h$^{-1}$ represent the most commonly extracted values from the database of energy
performance certificates, which is available for practicing energy auditors. According to Blight et al., an air change (ACH) rate of 0.3 h\(^{-1}\) is recommended; otherwise, the air can become “stale” (excess CO\(_2\), flushing of indoor air pollutants) and excessively dry (less than 40% humidity) [27]. Such low levels of air change imply the careful selection of interior finishes and furnishings, to minimize indoor air pollution from VOCs (e.g., formaldehyde). Such a low air exchange rate is very commonly applied to regular buildings without consideration of the careful selection of interior elements, as well as with the “assumption” that this air change rate will be provided by means of natural ventilation with window openings. This approach leads to the fact that many single-family homes suffer from “sick house” syndrome, and there are real complaints about the existing microclimate. In turn, the increase in air exchange entails a significant increase in energy consumption, which negatively affects the energy efficiency of the building and bills for consumed energy. Considering these factors, it is necessary to conduct a detailed analysis of building systems and propose possible solutions to improve the indoor microclimate and energy performance of buildings while reaching the goals set by the existing energy policy of the European Union.

2. Materials and Methods

Computational analyses were carried out using IDA Indoor Climate and Energy (IDA-ICE) 4.7 software. IDA-ICE is a tool for dynamic simulation of thermal comfort, indoor air quality and energy consumption in buildings. The accuracy of this simulation tool has been studied in several reports, which have conducted an empirical validation study of models in IDA-ICE related to the thermal behavior of buildings and HVAC equipment. A number of studies have been devoted to investigating methods of energy saving and thermal comfort with the help of simulation in IDA Indoor Climate and Energy software (IDA-ICE) [28–31]. These studies have shown the accuracy of the simulation results and their correlation with real measured parameters [32,33].

It was concluded that the agreement between the simulated and measured data was good, and disagreements were similar to the measurement uncertainty. IDA-ICE was validated according to prEN 13,791. The analyzed building model was created with Autodesk Revit software and transferred to the simulation software in IFC format.

The method proposed for the study is the analysis of the building model realized in the energy simulation software. Scenarios with different activities, such as changes in ventilation operation modes, improvement of building insulation or window change, were simulated and analyzed.

3. Results

3.1. Case Study

A two-story residential building situated in Mežares parish, Latvia, was designed as the simulation model. The thermal properties, hourly load for equipment, occupancy and lighting were set. The building is two floors high, with a balcony and a garage. A model is shown in Figure 1. The first floor consists of an entrance hall, living room and kitchen, while the bedrooms are located on the second floor, as seen in the plans in Figures 2 and 3. The locations chosen for evaluation are the living room with a kitchen zone on the first floor marked Nr. 7 on the Figure 2a plan and a bedroom on the second floor marked Nr. 12 on the Figure 2b plan.

The building has a strip foundation; the first floor is constructed as slab-on-ground. Light concrete block construction with mineral wool insulation is chosen as the typical local construction method. The wall envelope of the base project consists of several layers of mineral wool with a total thickness of \(-250\) mm, and the total U-value of the wall is 0.30 W/(m\(^2\)K). The roof envelope of the base project primarily consists of one layer of loose mineral wool with a total thickness of 650 mm that is blown into gaps between the roof wooden I-joists; it has a vapor barrier, and the finish is gypsum board on a wooden frame. Roof bituminous roll materials are installed on the OSB layer that rests on the I-joists.
The floor envelope of the base project primarily consists of a 250 mm base gravel layer, a 250 mm XPS 300 insulation layer, a vapor barrier, a 150 mm concrete slab and a parquet floor covering. The total U-value of the floor envelope is 0.13 W/(m²·K).

The climate data and wind profile are used according to ASHRAE 2013. The building data used in the energy analysis are presented in Table 1. Calculations are taken from the American Society of Heating and Air-Conditioning Engineers (ASHRAE) hourly climate data for the whole year for Riga.
Figure 3. (a) Outdoor and Indoor air temperature; (b) simulated and measured relative humidity.
Table 1. Outdoor average climate data for Riga (source: ASHRAE).

| Variables                  | January | February | March | April | May | June | July | August | September | October | November | December |
|----------------------------|---------|----------|-------|-------|-----|------|------|--------|-----------|---------|----------|----------|
| Dry-Bulb Temperature       | −0.1    | −3.0     | 1.3   | 6.3   | 12.2| 15.3 | 17.2 | 18.1   | 12.3      | 7.9     | 2        | −1.3     |
| Rel. Humidity of Air, %    | 87.6    | 85.7     | 82.5  | 69.8  | 65.7| 70.9 | 78.3 | 76.6   | 77.1      | 83.7    | 81.5     | 84.9     |
| Direct Normal Rad, W/m²    | 41.3    | 64.5     | 105.4 | 141.4 | 183.2| 176.7| 162.6| 143.8  | 104.0     | 93.3    | 59.3     | 36.6     |
| Diffuse Rad. On Hor. Surf, W/m²| 14.2   | 31.9     | 57.9  | 88.3  | 116.3| 135  | 126.6| 103.8  | 71.9      | 39      | 18.6     | 10.7     |
| Wind Speed, x-Component, m/s | 1.9    | 0.7      | 0.6   | 0.3   | 0.8 | 1.1  | 1.7  | 1.4    | −0.8      | −0.2    | 1.3      | 0.9      |
| Wind Speed, y-Component, m/s | 1.3    | 0.4      | −1.2  | −1.2  | 0.1 | 0.1  | 0.1  | 0.2    | 0.8       | 1.9     | 0.1      | 1.0      |

Seven different scenarios were simulated and selected for discussion in this paper. The selected scenarios are presented in Table 2 and summarize the most important parameters that were used for the comprehensive evaluation of the indoor microclimate and energy consumption of the building.

Table 2. Scenarios used during the simulation, their main description, ventilation system identification and heating used in each of the scenarios accordingly.

| Case | Type of Ventilation System | Name of Ventilation System in IDA-ICE |
|------|---------------------------|--------------------------------------|
| “0” | Natural                   | Basic case                           |
| 1A   | Natural                   | Basic case + window opening night ventilation (time schedule, proportional–integral (PI) temperature control) |
| 1B   | Natural                   | Basic case + improved insulation      |
| 1C   | Natural                   | Basic case + improved insulation + window change |
| 1D   | Mechanic                  | Basic case “0” + heat recovery        |
| 1E   | Mechanic                  | Basic case + improved insulation + heat recovery |
| 1F   | Mechanic                  | Basic case + improved insulation + window change + heat recovery |

For the basic scenario, Scenario “0”, natural air exchange was simulated (natural supply through windows or wall vents and mechanical exhaust in bathroom/kitchen). Windows were never opened in winter. Number of inhabitants: 4; heat source: district heating; lighting: 3 bulbs (60 W) in each room; heat gains from equipment: 3 W/m²; window opening only summer 25% from 1 of June to 15 of September, 08:00–20:00; occupant activity: 1MET (0.85 + −0.25 CLO); external wall U-value: 0.17 W/(m²×K) (fibro blocks 0.25 m + light insulation 0.15 m); window U-value: 1.46 W/(m²×K); external door U-value: 1.3 W/(m²×K); floor on ground U-value: 0.15 W/(m²×K); roof U-value: 0.15 W/(m²×K); air change rate: 0.3 h⁻¹.

For Scenario “1A”, in addition to the scheduled conditions of the basic scenario, window opening was added, and every hour, the windows were opened for 10 min from 7:30 to 20:30 all year round (special realistic schedule based on window orientation).

For Scenario “1B”, in addition to the conditions of Scenario “1A”, the façade insulation was additionally simulated. The U-value of the external walls of 0.14 W/(m²×K) was improved by mounting polystyrene (0.2 m thick).

For Scenario “1C”, in addition to the conditions of Scenario “1B”, the installation of triple-glazed windows was simulated. The U-value of the window was 0.74 W/(m²×K).

For Scenario “1D”, in addition to the conditions of Scenario “0”, the installation of mechanical ventilation was simulated. The set indoor air temperature was +20 °C during wintertime and +22 °C during summertime (AHU 75%).
For Scenario “1E”, in addition to the conditions of Scenario “1D”, the façade insulation was additionally simulated. The U-value of the external walls of 0.14 W/(m²×K) was improved by mounting polystyrene (0.2 m thick).

For Scenario “1F”, in addition to the conditions of Scenario “1E”, the installation of triple glazed windows was simulated. The U-value of the window was 0.74 W/(m²×K).

3.2. Validation of the Model

Analyzing the model, the problem of overheating in the summer period was highlighted, so the summer period from 1 May to 30 September was considered in detail. In the period from 10 May to 15 May, the measured temperature at certain moments is 15 degrees Celsius higher than the simulated temperature. Analyzing the data of the measured and simulated outdoor and indoor temperatures, the following observations can be noted: in the period from 4 June to 15 June, the measured temperature is on average 5 °C higher than the simulated temperature; from 5 July to 20 July, the simulated temperature is 10 °C below the measured temperature (Figure 4).

Analyzing the relative humidity graph, the actual readings exceed the simulated readings by 20% in May and September (Figure 3).

Considering the lethal period from 6 November to 20 December, we can make the following observations: the measured air temperature is on average 1.5 °C higher than the simulated temperature. This factor can affect the total annual consumption. However, the measured outdoor temperature during the period from 5 to 15 November is 10 °C higher than the simulated temperature, and during the period from 13 to 17 December, the measured temperature is 15–20 °C higher than the simulated temperature (Figure 4).

The measured and simulated CO₂ readings show a significant difference of 55.82%. The simulated CO₂ average is 773 PPM, and the measured average is 1386 PPM (Figure 5). According to EN 16798-1 “Indoor Environmental Quality Categories”, the indoor comfort quality levels have the following breakdown: QI—high, QII—medium, QIII—moderate and QIV—low. An average level of CO₂ would be most applicable. The highest level can be chosen for areas where people with special needs are (children, the elderly, people with disabilities). Lower levels do not pose any health risk but may increase discomfort. The CO₂ concentration limits are based on the indoor concentration of the substance, taking into account the outdoor concentration. In areas with comfort quality levels: QI—CO₂ delta 550—in the living room and 380 in the bedroom, QII—CO₂ delta 800—in the living room.
room and 550 in the bedroom, QII—CO$_2$ delta 1350—in the living room and 950 in the bedroom and QIV—CO$_2$ delta 1350—in the living room and 950 in the bedroom.

Differences in temperatures for all cases can be explained by the difference in outdoor temperature charts and do not influence the reliability of the results. Additionally, this can be confirmed by low deviations between the simulated and measured heat consumption data. However, the measured CO$_2$ data are significantly higher and can be explained by the location of the sensors in the area where CO$_2$ is exuded, while IDA ICE shows average CO$_2$ levels for the whole volume of the building. This parameter shows discrepancies, and simulated values cannot be used as a reliable source for evaluation of the IAQ.

The measured overall heat consumption in 2021 is 3.25% higher compared to 2020. According to the simulation program, the annual heat consumption does not change since the calculation is carried out according to the same temperature values (Figure 6a,b). The measured heat consumption is higher than the simulated heat consumption by 3.83%. The data in Table 3 show what investments need to be made according to different scenarios and the cost of energy per year, assuming that the price is 0.20 EUR/Kwh (price correlates with the actual situation during measurements in 2020–2021).

![Figure 5. Measured and simulated CO$_2$.](image)

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![Figure 6. (a) Measured and simulated heat consumption for Scenario 1B; (b) measured and simulated outdoor air temperature.](image)
Table 3. Energy consumption and costs for different scenarios.

| Title | Energy Consumption, KWh/m² | Energy Consumption per Year, KWh (F = 120 m²) | Heating Costs, EUR/Year | Investments, EUR |
|-------|----------------------------|-----------------------------------------------|-------------------------|-----------------|
| O     | 52.74                      | 6328.8                                       | 1266                    |                 |
| 1A    | 120                        | 14 400                                       | 2880                    | 4950            |
| 1B    | 118.8                      | 14 256                                       | 2851                    | 11,650          |
| 1C    | 108.6                      | 13 032                                       | 2606                    | 7450            |
| 1D    | 111.6                      | 13 392                                       | 2678                    | 2500            |
| 1E    | 110.1                      | 13 212                                       | 2642                    | 7450            |
| 1F    | 99.54                      | 11 944.8                                     | 2389                    | 14,150          |

4. Discussion

Scenario “0” is the basic case where energy consumption is quite low, but the problem of overheating occurs during the summer period. Analyzing operative temperature data for Room Nrs. 7 and 12, we can highlight the overheating temperature sector between 27 and 36 °C in the time period between 20 April and 1 June and between 15 September and 15 October. For Scenario “1A”, a window opening schedule is recorded daily throughout the period between 1 June 2020, and 15 September 2020, from 7:00 to 20:30. Opening the windows leads to a sharp increase in energy consumption from 52.74 kWh/m² to 120.3 kWh/m², or an increase of 128% when comparing Scenarios “0” and “1A”. This action will improve the quality of indoor air. The PPM reduction is 8.3% from 12:00 to 11:00 for 6.5 months a year (period from 15 September to 15 March). It also creates additional expenses for energy, at 1614 EUR/year. Analyzing the operative temperature data for Room Nrs. 7 and 12, we can highlight the overheating temperature sector between 27 and 36 °C in the time period between 20 April and 1 June and between 15 September and 15 October. For Scenario “1B”, the U-value of the external walls is improved to 0.14 W/(m²·K), and the façade is installed by mounting polystyrene (0.2 m thick). Additional insulation of the façade ensures only 1.24% energy saving when comparing Scenarios “1A” and “1B”. The investment of EUR 4950 provides a negligible financial saving. It is not recommended to improve the insulation in this type of building for energy-saving reasons. It should only be performed in the case of insulation damage in particular areas. For Scenario “1C”, in addition to external wall insulation, installing windows with a U-value of 0.74 W/(m²·K) is planned. This ensures only 8.59% energy saving when comparing Scenarios “1B” and “1C”. However, the investment of EUR 11,650 does not pay off during the lifespan of the house. For Scenario “1D”, a mechanical ventilation system is added, resulting in a decline in energy consumption by 7% in comparison with Scenarios “1A” and “1D”. The main advantage of AHU installation is the PPM reduction is 51.7% from 12:00 to 5:50 for 6.5 months a year (period from 15 September to 15 March) and 50% from 11:00 to 5:50 for 6.5 months a year (period from 15 March to 15 September). The investment of EUR 2500 provides EUR 60 savings per year, and its payback period is about 55 years, though the indoor air quality has a positive impact and long-term nonmaterial effect on the quality of sleep, life and health of residents of the house. Analyzing the operative temperature data for Room Nrs. 7 and 12, we can highlight an overheating temperature sector between 27 and 36 °C in the time period between 20 April and 1 June and between 15 September and 15 October. This scenario is a recommended and guaranteed solution for overheating during summer periods and maintaining a healthy environment throughout the year. For Scenario “1E”, in addition to the mechanical ventilation system, the U-value of the external walls is improved to 0.14 W/(m²·K), and the façade is installed by mounting polystyrene (0.2 m thick). The additional insulation of the façade ensures only 0.9% negligible energy and financial saving in comparison to Scenarios “1D” and “1E”. The investment of EUR 4950 provides negligible financial savings. For Scenario “1F”, in addition to the AHU installation and external wall insulation, installing windows with a U-value of 0.74 W/(m²·K) is planned. This ensures 10.8% energy saving when comparing Scenarios “1F” and “1D”. However, the investment of EUR 14,150 does not pay off during the lifespan of the house.
5. Conclusions

Regularly opening windows (Scenario “1A”) daily throughout the period between 1 June and 15 September, 2020, leads to a PPM reduction of 8.3%, improves the quality of indoor air, but increases energy consumption sharply. The improvement of the insulation of external walls, described in Scenario “1B”, is not recommended for this type of building (a private house built 10–15 years ago) for energy-saving reasons and can be applicable in the case of insulation damage, in particular façade zones. The installation of a mechanical ventilation system, as described in Scenario “1D”, reduces energy consumption by 7% in comparison to Scenario “1A”. The main advantage of AHU installation is the PPM reduction of 50–51.7%. This scenario is a recommended and guaranteed solution for overheating during summer periods and maintaining a healthy environment throughout the year. The investment payback period is too long, though the indoor air quality has a positive impact and long-term nonmaterial effect on the quality of sleep, life and health of residents of the house.

Validation of the model demonstrates positive results, and differences in temperatures for all scenarios can be explained by the difference in outdoor temperature data.

The results of this work provide information to homeowners on how various combinations of building utility system improvements affect overall energy consumption.

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