MATEC Web of Conferences **396**, 20011 (2024) https://doi.org/10.1051/matecconf/202439620011
WMCAUS 2023

Buildings made of massive timber logs with a derogation from the application of technical conditions for traditional masonry technologies

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Abstract. Timber log walls are a unique form of construction - erected from solid material, they are both a building structure and a thermal barrier. Walls of wooden logs have numerous advantages, especially favourable physical and mechanical properties, including insulation and thermal capacity. The technical conditions, which are the Polish interpretation of the Nearly Zero Energy Building (nZEB) building, which a newly designed building must meet, must meet 2 conditions simultaneously: the value of the EP index, which determines the annual calculated demand for non-renewable primary energy for heating, ventilation, cooling and preparation of domestic hot water for the entire building, and adequate thermal insulation of the external walls. Calculating the thermal insulation of a wood partition, relying only on thermal conductivity coefficients without considering other properties of the material, does not reflect the true insulating properties of wood. The lack of research on the insulating properties of wood, and thus the lack of national technical and installation requirements for log houses seriously limits the development of this type of construction and forces to undertake reliable research and development work in this area. The proposed introduction in this type of building of the methodology of the so-called Integrated Energy Design (IED) allows to carry out multi-criteria analysis of design variants at the stage of the virtual model in the BIM standard, in terms of the final energy efficiency of the building. Conducting various types of variant analyses and simulations allows to achieve optimal energy efficiency and to verify and correct the adopted solutions. The high energy efficiency of the building demonstrated by such simulations can be the basis for a deviation from the current regulations, which will allow the implementation of newly designed buildings in massive log technology, without the need for additional thermal insulation. As a result, it will be possible to preserve the unique architectural expression of buildings erected with this technology, with visible massive timber logs both on the exterior facades and on the interior.

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1 Introduction

It is estimated that about 40% of total energy consumption in European countries is for heating buildings, and what's more, the construction sector is growing rapidly, leading to a further increase in energy consumption. In order to reduce the negative environmental, economic and social impacts caused by the energy intensity of the construction sector, it is necessary for the sector to drastically reduce the level of energy consumption, generated from non-renewable fossil fuels, and increase the share of renewable energy use.

The Nearly Zero Energy Building (nZEB) standard is a building standard that requires buildings to consume minimal energy. It is a building standard that is used in the European Union and relies on buildings to meet the minimum energy consumption requirement and use the rest of their energy from renewable sources. The nZEB standard requires that new buildings use very little energy and produce as few greenhouse gas emissions as possible. It also requires that buildings be designed to take advantage of solar energy, wind and ground heat. The standard is gradually being implemented in EU countries and in Poland.

Timber log walls are a unique form of construction - erected from solid material, they are both a building structure and a thermal barrier. Walls made of wooden logs have numerous advantages, especially favourable physical and mechanical properties, including insulation and thermal capacity. In countries that have regulations for log houses, the outer wall should be built of round logs with a diameter of not less than 25 cm or rectangular logs with a thickness of not less than 15.2 cm. In Poland, there are no technical and installation requirements for log houses, hence the problem in meeting the requirements for thermal insulation of walls. Calculating the thermal insulation of a wood partition, relying only on thermal conductivity coefficients without taking into account other properties of this material, does not reflect the true insulating properties of wood. The lack of Polish research on the insulating properties of wood, and thus the lack of national technical and installation requirements for log houses seriously limits the development of this type of construction and forces to undertake reliable research and development work in this area.

The article presents a multi-criteria approach to the design of buildings in the technology of massive logs and the methodology of the so-called Integrated Energy Design, which allows a much more accurate analysis of the energy efficiency of such buildings.

2 Architectural and construction solutions

2.1 Functions of building solutions

The culmination of the architect's work is the implementation of the designed building erected with specific selected building materials and technology. The future function of any building is to protect users from the weather and other external factors. The aesthetic form of the building must meet the tastes and aesthetic needs of the investor, but all the component parts of the building, in addition to aesthetic impact, perform a number of very important functions. Architectural and construction design, which takes into account the whole problem of general construction, resembles putting together a puzzle, in which you need to fit together many elements and reconcile the many functions performed by these elements. The function of protecting the building from the outside elements takes precedence over appearance and aesthetics.

2.2 The most important protective functions performed by building components

- Building basement. The construction solutions protect the building from ground moisture, rainwater (penetrating in the foundation backfill and splashing off onto the plinth walls), pressure of backfill soil and mechanical damage to the insulation coatings.

- Exterior walls. Construction solutions must reconcile different, often conflicting functions: thermal protection, water tightness against rainwater infiltration, acoustic insulation and functions related to the physics of the structure, in particular protection against diffusion of water vapour penetrating from the interior.
- Roofs. Building solutions protect interiors from rainwater and, at the same time, must meet requirements related to thermal insulation, sound insulation and building physics (slope ventilation, vapour barrier).

The form of individual building elements and, as a result, the architecture of the whole is affected by the impact of external factors such as temperature fluctuations, rain, snow, wind, sound, vibration, air pollution, etc. Building solutions protect the building from external factors, and this is their function above plastic shape and aesthetics.

Correct, properly designed building, structural and material solutions - imposing a number of architectural constraints - help prevent building damage and offset the risk of defects and faults in individual building elements.

Reliable and well-considered elaboration of construction details makes it possible to create high-quality architecture, durable and effectively protecting interiors from external factors and authentic - through the forms resulting from the structure, materials and construction technology adopted.

It is unacceptable to omit detailed construction details in the design, which specify material and technological solutions. Such unreliability results in the realization of a building that is unpredictable in its shape and architectural expression, while a side effect of under-design and poor selection of construction solutions is the risk of numerous construction damages during operation, also indirectly affecting the quality of the building's architecture.

3 Methodology

The Integrated Energy Design (IED) methodology allows multi-criteria analysis of design alternatives to be carried out at the virtual model stage in the BIM (Building Information Modelling) standard. This makes it possible to take into account all elements and aspects of the design that affect the energy efficiency of the building. Designing a building as a virtual spatial model, in which all the parameters of the real building are entered, such as layers of partitions with specific materials and their physical properties, technical parameters, prices, etc., allows various types of analysis and simulations to be carried out at an early design stage. This is impossible in traditional designs, developed in CAD-2D (Computer Aided Design) programs in the form of a set of flat projections, sections and elevations. A distinctive feature of BIM-IED design is that the main workload is shifted to the early phases of the design process (the concept stage), so the opportunities to influence efficiency are greatest, with the lowest simultaneous costs and the least difficulties involved. The ability to develop solutions design solutions on the scale of assembly details makes it possible to optimize the prefabrication of components structural components in digitally controlled CNC woodworking machines.

The energy efficiency of a designed building can be tested through simulations known as "energy modelling." Conducting such simulations requires the creation - using appropriate BIM design support software - of a virtual building model in which all building partitions have a layered structure and specific physical properties assigned (mass, specific heat, heat transfer coefficients, etc.). The functional layout and number of users and technological processes are defined, along with time schedules for use. The virtual building is equipped with systems for central heating, DHW, ventilation, lighting, etc. Control systems for these installations are also configured. By entering data on the parameters of the indoor air filling each room - that is, the designed operating temperatures, temperature zoning of individual rooms, usage schedules, etc. - we transform the BIM model into the so-called Building Energy Model (BEM). In the Building Energy Model BEM, we can study the impact on energy efficiency of different design variants (e.g., different thicknesses of thermal insulation of the building envelope), test various installation and automation variants, etc. The BEM building model is located in a specific geographic location, for which a set of meteorological data is used. As a standard, calculations for the simulation are made at a frequency for every hour of the year (8760 hours), which gives tremendous accuracy to the results, incomparable, for example, to those obtained from a building's energy performance certificate. In addition to the amount of energy broken down into different components (heating, cooling, pumps and fans) and different energy carriers, it is possible to analyze thermal comfort (PPD, PMV indicators according to Fanger methodology), study the operation of energy recovery systems, etc. Conducting various types of variant analyses and simulations makes it possible to achieve optimal energy efficiency and verify and correct the adopted solutions.

Multi-criteria analyses, carried out in terms of energy efficiency, allow for a holistic, integrated treatment of the final product, which will be an all-season residential building. The innovative way of organizing the study has 3 distinctive features:

- The process of organizing design work with a shift of focus to the early stages of design, in order to achieve greater efficiency and minimize costs.
- Prioritizing energy-efficient, integrated architectural, construction and installation solutions.
- Instead of traditional - linear - design, implementing integrated design, in which four modules are crucial:
    a) external environment (climate),
    b) user requirements (human factors),
    c) building envelope (building envelope),
    d) technical equipment of the building (building services).

Integrated Energy Design of energy-efficient buildings also means an appropriate strategy for the selection of architectural and construction solutions and Technical Building Equipment (TWB). The guideline for this strategy - the so-called "Pyramid of Energy Efficiency" (Trias Energetica) - is the appropriate sequence and hierarchy of activities in the process of architectural-building design and installation solutions, linked to the energy and economic analyses.

1. The first step is to reduce energy demand through appropriate measures (optimal building shape and orientation, appropriate functional layout and temperature zoning, very high thermal insulation and air tightness, supply and exhaust ventilation with heat recovery and ground exchangers).
2. The second step is the use of renewable energy - it involves the use of technologies based on local renewable energy sources, such as solar collector systems, photovoltaic cells, ground source heat pumps, wind energy technologies, etc.
3. If project analyses show that there is still a need for utility energy, the third step leads to the use of the least polluting fossil fuels in the most efficient way possible.

3.1 Achieving the nearly zero energy demand building (nZEB) standard

The European Union is steering the construction industry toward lower emissions through nZEB regulations, which aim to achieve more energy-efficient buildings at the national level as of 01/01/2021. An indirect result of the project will be a reduction in heat loss in the construction sector, allowing the ambitious goal of climate neutrality in the building sector to be achieved. The near-zero energy building (nZEB) standard is regulated by the technical and building regulations in force in each country of the European Union. All requirements for the nZEB standard are the same for newly designed buildings.

The technical conditions to be met by a newly designed building must meet 2 conditions simultaneously: the value of the EP index, which determines the annual calculated demand for non-renewable primary energy for heating, ventilation, cooling and domestic hot water preparation for the entire building, which must be less than 70 kWh/(m^2/year), the thermal insulation of external walls, which is to be at $t_i \geq 16°$ C at least U = 0.20 W/m 2 K. In countries that have regulations for log houses, the exterior wall should be built of round logs with a diameter of not less than 25 cm or rectangular logs with a thickness of not less than 15.2 cm. In Poland there are no technical and installation requirements for log houses, hence the problem in meeting the requirements for thermal insulation of walls. Meeting the thermal insulation coefficient required today for the exterior partition of a residential building, without an additional layer of thermal insulation, is impossible to achieve, since such requirements would be met by logs as thick as 71 cm! Calculating the thermal insulation of a wood partition, relying only on thermal conductivity coefficients without taking into account other properties of this material, does not reflect the true insulating properties of wood. The lack of Polish research on the insulating properties of wood, and thus the lack of national technical and installation requirements for log houses seriously restricts the development of this type of construction and forces to undertake reliable research and development work in this area.

3.2 Accessibility for people with special requirements

Accessibility for people with special requirements, also known as universal accessibility or accessibility for all, is an approach to the design and construction of buildings, infrastructure and environments that ensures that they can be used by people with different needs and abilities.

Accessibility for people with special needs refers to people with various disabilities, including those with mobility, hearing, visual, intellectual or sensory limitations. Everyone should have equal access to public spaces, buildings and services to enjoy full civil rights, as well as to participate in social, professional and cultural life.

To ensure accessibility for people with special requirements, their needs should be taken into account from the design and planning stages of buildings. The design should include appropriate solutions, such as wheelchair ramps, proper signage, good lighting, and assistive systems. It is also important to properly design interior spaces so that they are accessible to people in wheelchairs, with walking sticks, or with guide dogs.

Accessibility for people with special requirements is crucial for equality and social inclusion, and improves the quality of life not only for people with disabilities, but for society as a whole. Many countries have introduced laws and regulations that impose accessibility requirements for people with special requirements on newly designed or upgraded buildings and infrastructure to ensure equality of opportunity and full inclusion of all citizens.

Accessibility of buildings for people with disabilities includes many aspects, such as:

1. The entrance to the building should be barrier-free, complying with accessibility standards and regulations, so that people with disabilities can enter the building without obstacles.
2. Ramp - the building should be equipped with a ramp and a barrier-free door, which allows people with disabilities to move freely through the building.
3. Bathrooms - buildings should have bathrooms that are accessible to people with disabilities, such as grab bars, special facilities for wheelchair users, etc.
4. Wide doors - doors should be wide enough for wheelchair users to move freely through the building.

5. Height of handles and grips - handles and grips should be placed at a height that allows easy access for people with disabilities.
6. Lighting - buildings should have adequate lighting that makes it easier for people with disabilities to move around.
7. Public address system - buildings should be equipped with a public address system that allows communication for people with hearing difficulties.

4 Single-family residential building in the technology of massive timber logs on the example of a typical project

4.1 Description of the building

Massive timber walls with large-section amphibious tie-beam construction are most strongly associated with building traditions in the Podhale region. Combined with a tram roof and an upper half gable, the architecture of the house resembles the forms of old Chocholow cottages with light-coloured tie beam walls. Nowadays one can see more and more realizations of buildings with traditional tie-beam construction, which seem to express nostalgia for the roots of regional building solutions and the renaissance of forms that grew out of Polish traditions.

4.2 Building basement

Buildings with massive wooden tiered construction are most often designed in mountainous areas, where they are a reference to ancient building traditions. Often these are buildings on a slope, hence the decision to make a basement is functionally and economically justified. The depicted ground floor of a wooden tie beam building is a combination of traditional wooden construction with a basement with concrete walls covered by a reinforced concrete slab. The tie beam walls rest on the cantilevered edge of the reinforced concrete floor slab. Such a solution makes it possible to flush the plane of the wall logs with the plinth wall, which is finished with a stone curtain wall of the basement wall thermal insulation. The support of the tiered walls is protected from moisture by strips of bituminous felt. Between the walls is made a floor of planks on joists supported on bricks, between which mineral wool was laid. The basement building is founded on monolithic footings and a reinforced concrete footing. The reinforced concrete floor slab lying on the footings is introduced under the external load-bearing walls. The exit to the garage is formed by a U-shaped reinforced concrete structure acting as retaining walls. The concrete basement walls are protected by vertical waterproofing made of hot-water membrane. The thermal insulation of the basement walls made of extruded polystyrene has a concrete pressure- screen wall on the outside, which supports the stone cladding of the pedestal. The basement reinforced concrete floor has a cantilevered overhang at the perimeter, supporting the log wall structure. Between the walls is made a floor of planks on joists supported by bricks, between which mineral wool was laid [1], [2], [3].

4.3 Exterior walls and ceilings

The wooden structure of the building's walls is made up of beams joined to a log (in the old nomenclature, the so- called "coal") Podhale, sealed with braids of wood wool. Openings in the log walls are bounded by massive frames made of posts and lintels, connected to the tongue-and-groove joists, so they stiffen the box of the log structure. The exterior walls of the first floor have no additional insulation while they have a high airtightness, thanks to the sealing of the joints through the so-called tongue-and-groove joints made of flexible plastic. The gable walls of the attic have a wooden post-and-beam structure filled with mineral wool and an elevation of vertical board siding. A wooden beam ceiling with a visible structure is supported by longitudinal walls and joists. Externally hung ceiling beams support the eaves. The airtightness of the building envelope in this technology is very important [4], [5].

4.4 Building's roofing

The building, which has a massive wooden tie beam structure, has a t-timber roof with tram trusses located in the axes of the ceiling joists. Overhung above the eaves, the ceiling beams are restrained in the wall by the pressure of the last wall plate, which also acts as a masonry wall. The extensions of the floor beams and the outermost beams support the foot beams, on which the dampers are fixed, and on the gable walls they support the rafters of the gable eaves canopies. The posts of the timber-frame structure of the attic gable wall stand directly on the highest beam of the first-floor wall. On the gable walls, the passing arrangement of the beams in relation to the longitudinal walls forces (in order to achieve a single eave level) the need for soffits. Thermal insulation of the attic is routed along the ceiling, and then between the structure of the retracted knee wall, between the rafters and on the maypole ceiling.

The double-pitched rafter-collar wooden roof with a dormer over the staircase has slopes of 45°, with a "softened" girt eave section with a slope of 30°. Mineral wool roof insulation is put on between the rafters, between the mayflies, in the retracted knee walls and on the first floor ceiling along the eaves. The roof covering is double-layered wooden shingles. The terrace in front of the living room has concrete and stone foundation walls, on which a light wooden ceiling with openwork boarding was laid. Fig. 1 shows first floor plan and cross-section. Fig. 2 shows construction solutions and Fig. 3 shows a view of the building from the north and south.

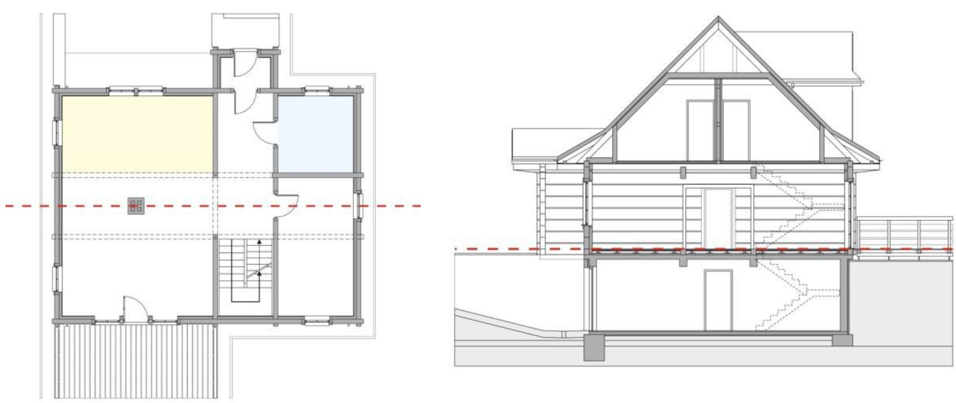


Fig. 1. First floor plan and cross-section (source: author's design).

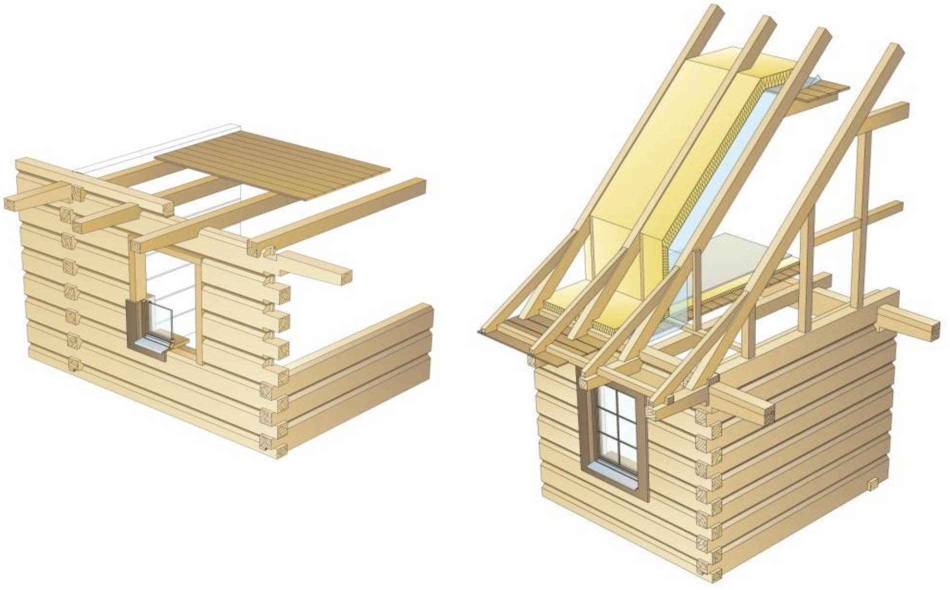


Fig. 2. Construction solutions (source: author's design).

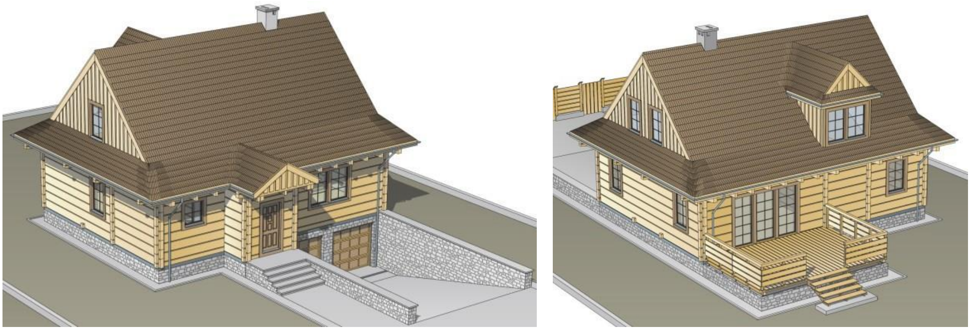


Fig. 3. View of the building from the north and south (source: author's project).

4.5 Energy analyses

The massive log building, which was subjected to energy efficiency analyses, has the following parameters:

- southern orientation (southern elevation located perpendicular to the north-south axis),
- shielding the building from the wind for the location in Krakow,
- temperature zoning of utility rooms,
- technological contact solutions with eliminated thermal bridges,
- air tightness of the enclosure at the level of n_{50} = 0.6 [ac/h] floors designed as massive concrete screeds, which are a significant heat-accumulating mass,
- a buffer zone above the usable attic, above the mayflies - insulation of the usable attic routed along the rafters to the level of the mayflies bracing the roof trusses and then between the mayflies,

- window joinery with improved thermal insulation parameters, with a heat transfer coefficient U of 0.9 [W/m^{2}K],
- windows installed in the thermal insulation layer of the wall, with a 4 cm wide thermal insulation board rebate formed around the frames,
- mechanical ventilation with heat recovery in a recuperator with an efficiency of 85% and the value of fresh air volume flow per person with increased values,
- gas heating with a dual-function furnace with an efficiency of 90%,
- air conditioning system was abandoned in the building - instead, night ventilation was assumed in the summer,
- domestic hot water with a target temperature of 55° C,
- energy-efficient lighting.

By achieving the above-mentioned parameters of the building, despite the fact that the requirements for the size of the heat transfer coefficient for the exterior walls are not met - logs without additional thermal insulation - the results of the energy efficiency analyses show that the building is an energy-efficient building.

Examples of energy efficiency analyses are shown below.

4.6 Internal energy gains

An analysis determining the total annual internal gains in the building was divided into gains from lighting, appliances, occupants, gains from the sun and from heating and cooling shows that the largest amount of energy gained in the reference building is provided by gains from the sun (Fig. 4). This is due to the large area of glazing falling on the south elevation.

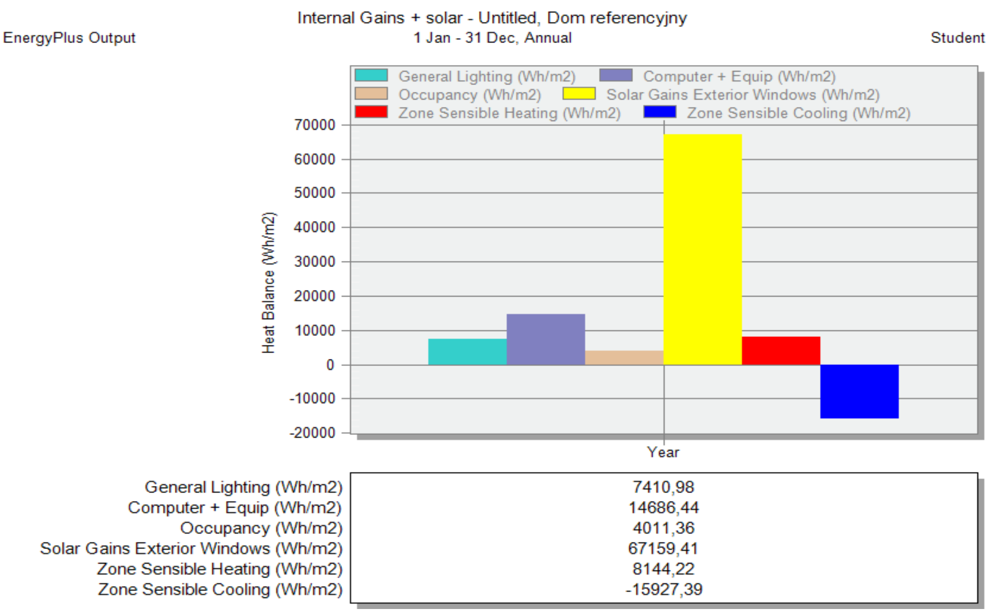


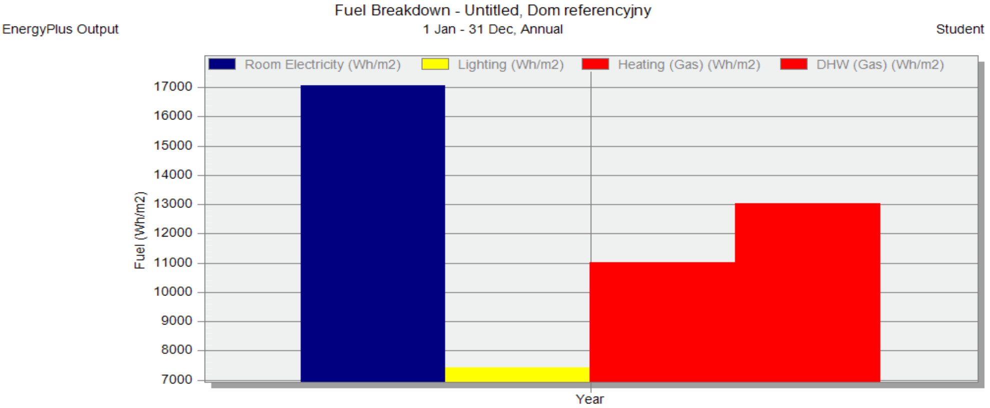
Fig. 4. Chart of internal gains and gains from the sun (source: own research).

https://doi.org/10.1051/matecconf/202439620011

4.7 Air tightness

The air tightness of a building refers to the amount of air that penetrates through gaps and openings in the building shell. The lower the amount of air that penetrates through gaps, the lower the loss of heat and cold, leading to a reduction in the energy required to maintain an adequate temperature inside the building.

Airtightness is particularly important for low-energy buildings, such as passive and energy-efficient buildings, where minimizing heat and cooling losses is crucial to a building's energy efficiency. Comparative analyses of different levels of building air tightness show that increasing a building's air tightness to 0.6 ac/h significantly increases energy efficiency [4], [5]. (Fig. 5).



Room Electricity (Wh/m2)	17065,63
Lighting (Wh/m2)	7424,54
Heating (Gas) (Wh/m2)	11030,29
DHW (Gas) (Wh/m2)	13042,05

Fig. 5. Graph of the final energy of the building with an enclosure leakage of 0.6 ac/h (source: own research).

4.8 Recuperation

Recuperation is the process of recovering heat from ventilation air, which is used to heat the cold air entering the building. This makes heating the air more efficient and economical, reducing the energy costs of heating the building. The advantage of the recuperation system is that it allows up to 90% of heat to be recovered from ventilation air, resulting in energy savings and lower building heating costs. In addition, thanks to the exchange of air in the rooms, it is possible to maintain an adequate level of humidity, which affects the comfort and health of building users.

The lack of recuperation significantly increases final energy consumption for the building. (Fig. 6).

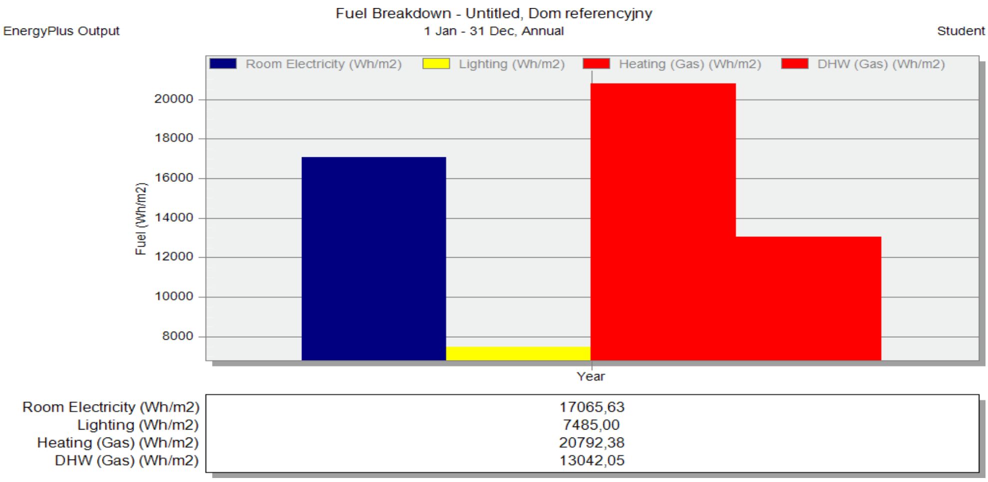


Fig. 6. Graph of final building energy for a building with no heat recovery in a recuperator (source: own research)

Only sample analyses are presented above. A full set of multivariate energy analyses allows multi-criteria optimization of a building in terms of its energy efficiency.

4.9 Accessibility for people with special requirements

The building has several features to facilitate accessibility for people with special requirements. The entrance to the building allows people with mobility disabilities to enter the building. On the first floor there is a toilet sized to accommodate wheelchair users. A stairlift is recommended to eliminate vertical barriers to circulation spaces, if necessary. The building does not use devices and other technical means to serve the hard of hearing and visually impaired. Accessibility is provided by the support of fellow residents.

5 Conclusions

In the article, the authors conducted an analysis of a typical single-family building using massive timber log technology, located near Krakow. The purpose of the analysis was to see if a building of this type, can achieve the standard of a building with almost zero energy consumption. The authors added to their innovative concept the criteria of comfort of use and closely related to comfort of use, the criterion of accessibility for people with special needs. The results of the analysis show that a single-family building made of massive timber logs can achieve the standard of a building with almost zero energy demand, but provided that comprehensive measures are carried out Additional user comfort criteria are aimed at the satisfaction of the building's users, which directly contributes to improving the quality of work performed and improving health and well-being. The results of the analysis can be implemented for other similar buildings with the same use.

The design of single-family residential buildings as energy-efficient buildings is becoming a widespread necessity, driven by environmental, economic and social considerations, as well as by existing laws. The design of such buildings requires a reorganization of the design process toward so-called Integrated Energy Design. This involves the use of appropriate design support tools and shifting the main burden of design decisions to the earliest possible design stage. These tools are software in the BIM standard, linked to programs that enable a series of simulations of a building's energy performance for a virtual model.

The final level of a building's energy performance is influenced by several complementary and interdependent architectural and construction solutions that are recommended for energy-efficient buildings. The more such solutions are applied in the design and during implementation, the better the final energy performance of the building will be. Some of the recommended design solutions can be described as mandatory, and some as complementary - this means that failure to apply them does not disqualify the project as energy-efficient but may make it more difficult to achieve the highest energy standards.

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