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Approaches for Complex and Integrated Refurbishment to Improve Energy Efficiency and Spatial Comfort of the Existing Post-War Mass Housing Stock in Serbia

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Abstract: The research presents approaches to the complex refurbishment of multi-family buildings constructed during the mass construction period in Serbia. These buildings comprise a quarter of Serbia's housing stock, are characterized by high energy consumption for heating, and have major spatial and organizational deficiencies: small apartments, outdated and inflexible spatial organization, and the absence of elevators. The subject of the research is the application of the methodology of complex and integrated refurbishment by adding volume to existing multi-family buildings with the goal of achieving higher energy efficiency while remodeling and modernizing residential units and improving vertical building communications. The research presents a comparative analysis of the energy performance and spatial organization of the existing building and three variants of building improvement: Case 1 (without volumetric additions), Case 2 (with volumetric additions—relocating vertical communications), and Case 3 (with volumetric additions—expanding usable living space). Based on the Knaufterm simulations, the energy savings for heating energy consumption compared to the existing state are 81% in Case 1, 89% in Case 2, and 87% in Case 3. Based on predefined parameters of spatial comfort, a comparative analysis of spatial comfort in residential units was conducted for all three improvement variants.

Keywords: sustainability; complex and integrated refurbishment; multi-family past-war housing stock; volumetric additions; energy retrofit; housing comfort; thermal comfort; spatial comfort; building simulation

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1. Introduction

1.1. European Energy Policies and Objectives

Buildings are responsible for around 40% of energy consumption and 36% of CO_2 emissions in the EU, making them the single largest energy consumer in Europe [1]. The renovation of existing buildings with the primary aim of reducing energy consumption has become a very contemporary topic in recent years. Considering that almost 50% of the EU's final energy consumption is used for heating and cooling, of which 80% is used in buildings, the achievement of the EU's energy goals is linked to the EU's efforts to renovate its building stock by giving priority to energy efficiency, making use of the "energy efficiency first" principle [2]. "The 'energy efficiency first principle' means taking utmost account of cost-efficient energy efficiency measures in shaping energy policy and making relevant investment decisions" [3]. The Directive on the Energy Performance of Buildings contains clear objectives related to long-term strategies for the renewal of the building stock in Europe. In addition, the European Green Deal provides guidelines on how to transform all sectors of the economy by ensuring the complete zero emission of greenhouse gases by 2050. One of the guidelines of the European Green Deal refers to the renewal of existing building stock in order to improve energy efficiency and reduce energy consumption [4]. The EU countries agreed to almost double their annual energy savings obligations in the coming years. Under the recast Directive, EU countries will be required to achieve an average annual energy savings rate of 1.49% from 2024 to 2030, up from the current requirement of 0.8%, driving energy savings in critical sectors such as buildings, industry, and transport [5]. To pursue the ambition of energy gains and boost renovation in the EU, the EU Commission in 2020 published the strategy "A Renovation Wave for Europe—Greening our buildings, creating jobs, improving lives." Across the EU, deep renovations that reduce energy consumption by at least 60% are carried out in only 0.2% of the building stock per year [6].

1.2. Serbian Energy Policies and Objectives

Even though Serbia is not an EU member, the governments of the Western Balkans committed to the "Green Agenda for the Western Balkans" as a concrete plan to expand the European Green Deal to Southeast Europe. The Green Agenda for the Western Balkans is a regional development strategy aimed at addressing the challenges of climate change and green transition while assisting Western Balkan countries in aligning their environmental regulations with European standards and norms [7]. The objectives of the Green Agenda in Serbia are as follows: enhancement of the strategic and legislative framework, co-financing the implementation of innovative pilot projects in practice, and mobilization of additional funding for expanding projects that contribute to Serbia's green transformation. In this way, the project will contribute to the green transformation of the economy and society in Serbia [7]. No official date is available on refurbishment actions and their results in Serbia [8]. The Government of the Republic of Serbia defines strategies through a series of documents aimed at balancing three key factors of sustainable development: sustainable development of the economy, industry, and technology; sustainable development of society based on social equity; and environmental protection with rational use of natural resources [9–11]. One of the most important aspects of this policy is the exploitation of buildings, as this sector has a high saving potential of primary energy consumption. Renovation of the existing building stock has a large untapped potential for energy savings and implementation of measures to increase energy efficiency [12].

1.3. Research Question and Objectives of the Study

Energy retrofitting of existing buildings involves improving the thermal envelope of the building to enhance its energy performance. When it comes to renovating existing residential multi-family buildings, it is necessary to conduct multiple analyses of the building to identify all its deficiencies. In addition to assessing the thermal performance of the building envelope, it is important to analyze the spatial and organizational characteristics of the apartments and the functionality of the building's communication systems. The research focuses on defining various approaches for the complex renovation of existing multi-family buildings, which include energy retrofitting and modernization of apartments, as well as improving the building's communication systems.

One quarter of the multi-family residential buildings in Serbia were built in the period from 1946 to 1970 [13]. The first regulations regarding thermal protection in Serbia emerged in the late 1960s [14]. Consequently, it is characteristic of these buildings that they lack adequate thermal insulation according to today's thermal regulations. The residential stock built before these regulations is relevant for research inquiries into energy improvements through thermal envelope retrofitting. These buildings have functional and spatial–organizational deficiencies due to their initial design aimed at providing small apartments for as many people as possible, resulting in inadequate spatial unit dimensions and rigid spatial organization [15]. Moreover, these buildings have high energy consumption for heating [15].

This research presents an analysis of the spatial–organizational, functional, and energy improvement of a multi-family residential building constructed in Serbia during the period of mass construction after World War II. The research analyzes the application of the methodology of complex and integrated refurbishment by adding volume to existing multi-family buildings to achieve high energy efficiency, modernize residential units, and improve vertical building communications. The research aims to review the advantages and limitations of applying volumetric addition strategies for housing comfort improvement in multi-family residential buildings built during the mass construction period.

1.4. The Concept of Comfort and the Conditions of Comfort

Comfort is the well-being of a person based on their subjective perception of several external parameters, and it is also related to the health of the occupants. As such, it is a basic requirement that the building needs to fulfill. Because of its subjectivity, this perception is influenced by not only physical conditions but also physiological (e.g., age, gender) and intermediary conditions (e.g., clothing). Comfort, therefore, is exceedingly difficult to quantify in exact values that satisfy everyone [16,17]. A lot of research and practice has focused on studying the components of comfort and identifying the criteria for comfort [17,18].

The Regulation on Energy Efficiency of Buildings RS 61/2011 defines the conditions that influence the achievement of residential comfort: The conditions of comfort are all those conditions in a building (thermal, air, visual, and acoustic) in which a person feels comfortable [19].

Thermal comfort represents the psychological state that corresponds to a pleasant feeling of thermal conditions in a space where thermal balance of the body is achieved. The objective parameters of thermal comfort include air temperature, mean radiant temperature of surfaces, air movement velocity, and air humidity [19].

Air comfort represents the conditions that ensure an adequate amount of clean air in a building, thereby providing air quality that is free from health risks for the occupants [19].

Visual comfort represents the conditions that enable good visibility as well as accurate and quick perception with minimal strain on the eyes [19].

Acoustic comfort represents the conditions in which the noise level in a room is such that it does not cause a sense of discomfort [19].

According to Alfirević, in contrast to the previously mentioned terms of comfort, spatial comfort has not been clearly defined, even though it is one of the key terms when discussing human needs and functionality of space in architecture. Along with being widely used in practice and the fact that a clear scientific determination of this term is still lacking, its use is understood as the equivalent of the comfort of a certain space [20]. Numerous authors have shared the opinion that spatial comfort results from the good quality of functional organization of space [20]. In his research, Alfirević systemizes physical parameters that contribute to the achievement of the feeling of spatial comfort. The physical parameters are as follows [20]:

1. distance between space boundaries—the boundaries of space can be perceived (are perceptible) when they determine the domain up to which the view can extend or be anticipated, when they cannot be viewed, but their location can be assumed. If a boundary disturbs the view, in the sense that it is close to the view's position, it creates the impression of blocking the space and "confining" the person in it;
2. space configuration—when the rooms are united in a single space following the principle of open space and when they can be connected flexibly as the need might be, when the rooms are positioned in a linear order following the principles of enfilades or are in cyclical order, as is the case in circular connection;
3. openness of space—towards the surroundings is the principle based on the idea of grouping and orientation of space towards the motifs in the surroundings. The concept results from the aspiration of the creator to use a high aesthetic level of viewpoints from the interior (in one or more directions) but also to achieve the perception of a larger spatial comfort through visual connection of the interior and the exterior;
4. shape of space—can be of importance in achieving spatial comfort if we consider the aspects of its regularity and interior organization (density of furniture in space) [20].

1.5. Complex and Integrated Refurbishment

One of the most important advantages of renovating existing residential buildings is extending their lifespan and improving the building's comfort.

For the refurbishment of buildings, it is important to apply the principle of adaptability. Strategies for designing adaptable existing buildings are flexibility, or enabling minor shifts in space planning; convertibility, or enabling changes in use within the building; and expandability, or adding space to a building. The criteria considered for assessing the potential for adaptation of existing buildings are as follows: external space (availability of construction sites and existing infrastructure), internal space (size of spaces and rooms, relationships between them, and communication routes in the layout), and spatial and structural characteristics [21].

Apart from traditional methods of energy-retrofitting existing buildings, the question of comprehensive improvement is becoming increasingly relevant, which includes both energy and spatial–functional renovation and enhancement. The approach of renovating existing buildings by adding new structures has significant functional advantages that distinguish it as one of the more important methods for comprehensive building renewal. This primarily refers to the possibility of adding specific functional elements to the existing building that were previously lacking, such as elevators, emergency staircases, or terraces, which can enhance the spatial–functional quality of the building and improve the comfort of its occupants [22].

The question of investing in the renovation of multi-family buildings is closely tied to ownership considerations. According to statistics, 98.3% of homes in Serbia are privately owned [23]. The subject multi-family residential stock was built between 1946 and 1970 during the socialist period when the state financed the construction of buildings. In the early 1990s, mass privatization began, with the sale of socially owned apartments to previous tenants, which brought a series of severe consequences for the housing sector, one of the most significant being the rapid deterioration of the residential fund. The causes can be found in inadequate regulations, a lack of enforcement mechanisms, low levels of compliance with these regulations, weak government institutions, and a housing culture inherited from the socialist era [24]. The social status of households and a strong, united, and resilient residential community play a crucial role in such extensive renovations. In this context, municipal policy support in the form of subsidies and grants is of essential importance [25]. The key challenges in achieving sustainable housing renovation often revolve around conflicting sustainability goals and conflicting stakeholder interests. To tackle these challenges effectively, an innovative approach toward sustainable housing renovation is essential. This innovative approach includes the process of innovation (linear versus organic) and the typology of innovation (product versus process and business versus social) toward sustainable housing renovation are discussed [26]. Apartment owners should be involved in sustainable renovation design for multi-family buildings. Some research suggests frameworks for the initial stages of socially sustainable renovation design, facilitating the occupants' active and timely engagement by establishing suitable participation mechanisms in a structured manner [27].

1.6. Sustainable Refurbishment

The motivation for renovating existing buildings is linked to the three pillars of sustainability: environmental, social, and economic aspects. The key environmental strategy is to reduce energy consumption from fossil fuels and lower greenhouse gas emissions. The primary economic strategy is to decrease the cost of the energy used for heating. The key social strategy is to improve the users' quality of life [21,28].

The ecological aspect is primarily related to reducing the energy required for heating buildings and decreasing carbon dioxide emissions. Energy consumption is the main source of greenhouse gas emissions, so by improving the energy efficiency of existing buildings, the energy required for heating is reduced, which directly impacts the reduction of greenhouse gas emissions.

This study examines the potential for using prefabricated lightweight wooden assemblies in the complex and integrated refurbishment of the existing multi-family housing stock. Prefabrication provides a satisfying solution for numerous factors affecting modern construction practices, contributing to faster construction, reduced labor costs, improved safety, sustainability, and waste reduction. By using prefabrication, projects can achieve greater efficiency and address the challenges posed by traditional construction methods [29].

This research focuses on the application of environmentally friendly materials and products for building renovation. This involves the use of natural materials (wood, stone mineral wool) and products based on natural materials (wood-based products, gypsum boards, stone façade panels, etc.), as well as materials that can be recycled without emitting toxic substances during the recycling process (aluminum).

It is crucial to emphasize that by utilizing existing buildings and extending their lifespan through renovation rather than demolition and new construction, significant natural resources can be conserved. This has both environmental and financial benefits. The demolition of old buildings and the construction of new ones require a substantial amount of energy to be embedded in the new building. In addition to these issues, substantial amounts of waste are generated from demolishing the old building and constructing the new one.

The economic aspect of sustainable renovation revolves around the interplay between cost reduction for heating and energy savings, along with the conservation of natural resources. Energy efficiency improvements in existing buildings lead to significant reductions in the energy needed for heating, thereby lowering heating costs.

Expanding the building's usable area by adding volumes, forming extensions on free facades, or constructing additional floors on the roof can increase the heated floor area. Although such complex interventions demand substantial initial investments, economic analysis can demonstrate their profitability and viability. This is particularly true for constructing additional floors, which could house extra residential units that could be sold or rented out, effectively recovering the initial investment. Moreover, adding functional elements is an essential benefit that requires greater investment but raises the building's value and accessibility. These elements enhance the building's security and directly impact its commercial value.

Additionally, it contributes to social benefits by ensuring accessibility for people with disabilities, elderly individuals, and families with children. Improving the quality, appearance, security, and accessibility of a building positively affects the quality of life for its occupants. Increasing the usable floor area and spatial reorganization of residential units are of utmost importance for enhancing the users' comfort and quality of life.

It becomes evident that the benefits arising from the energy improvement of an existing building cannot be strictly categorized under just one aspect of sustainability, as they can be observed on multiple levels that interconnect and complement each other.

2. Materials and Methods

The research methodology has several steps. The first step involves analyzing the types of existing multi-family housing built in the period of mass construction after World War II in Serbia based on a predefined classification [15]. The existing multi-family residential building consisting of three units with separate entrances was selected for the research. This building was chosen because it aligns with the typical characteristics of the building type described in the "Atlas of multi-family buildings in Serbia" [15] and based on which the energy performance class for this type of building was calculated in the "National typology of residential buildings in Serbia" [13].

The second step involves the analysis of the spatial organization, function, and energy performance of a selected multi-family free-standing building with three units.

The third step presents three variants of building improvement. Case 1 involves improving the thermal insulation of the entire building envelope without any spatial, organizational, or functional changes to the building. Cases 2 and 3 present variants of complex and integrated refurbishment using volumetric additions, which include energy, spatial, organizational, and functional improvements of the building. Case 2 represents a variant of complex renovation, which includes relocating vertical communications outside the existing building to increase the usable residential area and enable the creation of dual-oriented apartments. This variant was chosen for analysis because, in this case, the thermal envelope area is reduced, while the usable heated area is increased. Case 3 represents a variant of complex renovation, which involves increasing the usable space of apartments without relocating the existing staircase. Apartments in this variant remain single-oriented, but their usable area is increased. These two variants were selected to conduct a comparative analysis of energy improvement possibilities and energy consumption savings for heating, as well as an analysis of the spatial–organizational characteristics of apartments in both improvement options. The energy performance of all variants is evaluated using Knaufterm software, which is the most used calculation tool for calculating energy performance and determining the energy performance class of a building in Serbia. The energy needed for space heating in all cases was calculated by applying the seasonal method according to EN ISO 13790 [30] based on a one-zone model.

The fourth and last step includes a comparative analysis of the results of the energy simulations and a comparative analysis of the spatial comfort of the variants of building improvement. The advantages and limitations of applying the volumetric addition strategy to the existing building are determined. The research methodology is depicted in Figure 1.

2.1. Multi-Family Housing Stock Built in the Period from 1946 to 1970 in Serbia

According to the results of a study conducted in 2012 within a more comprehensive research project aimed at forming the national methodology and respective typology of residential buildings in Serbia, based on previous research projects carried out with the methodology developed within the European Project TABULA (Typology Approach for Building Stock Energy Assessment), 25% of the total stock of residential multi-family buildings in Serbia was built in the period from 1946 to 1970 [14,15]. This period is characterized by intensive housing construction, the dynamic growth of cities, the development of new settlements, and block construction [14,15].

The classification of multi-family buildings according to architectural–urban planning parameters and building characteristics includes the following types:

- A free-standing building on a separate plot does not border neighboring buildings on any side;
- A free-standing building consisting of two or more identical units with separate entrances (*lamellas*), in an open city block;
- A building in a row, within a series of different buildings in a closed city block, borders neighboring buildings on one or two sides;
- A high-rise free-standing building with more than 10 floors on a separate plot does not border neighboring buildings on any side [14,15].

According to the established typology of multi-family buildings, in the construction period from 1946 to 1970, the most represented type was free-standing buildings, with a share of 10.95%, followed by free-standing buildings formed of two or more identical units, with a share of 7.46% of the total stock of multi-family residential buildings (see Figure 2) [14,15]. The buildings built in this period have common characteristics: the architectural form of the buildings was compact and geometrically regular, the façade was simple, and the windows were small. The buildings were built in a traditional way, in a massive construction system, with brick as the dominant material. Similarities are also noticeable in the spatial organization: the kitchen includes a dining space, and there is no separate dining room. The central position of the entrance to the building, the position of the staircase, and the absence of an elevator are also consistent in these types of buildings and represent their common characteristics. Such similarities between the types, which do not exist in any other period, derive primarily from the post-war housing policy, which aimed to provide the minimum housing space in the shortest possible time for many people using known constructive systems and traditional building techniques [14,15]. Rational solutions, common to all buildings, are the result of regulations for residential construction that aim to define the minimum dimensional and technical standards. As thermal insulation appeared only at the end of the 1960s, buildings from this period do not have an adequate solution for thermal conductivity [14]. However, the simple cubic forms and simple materialization of the building envelope make them extremely suitable for energy renovation because significant improvements can be achieved with simple measures [14,15].

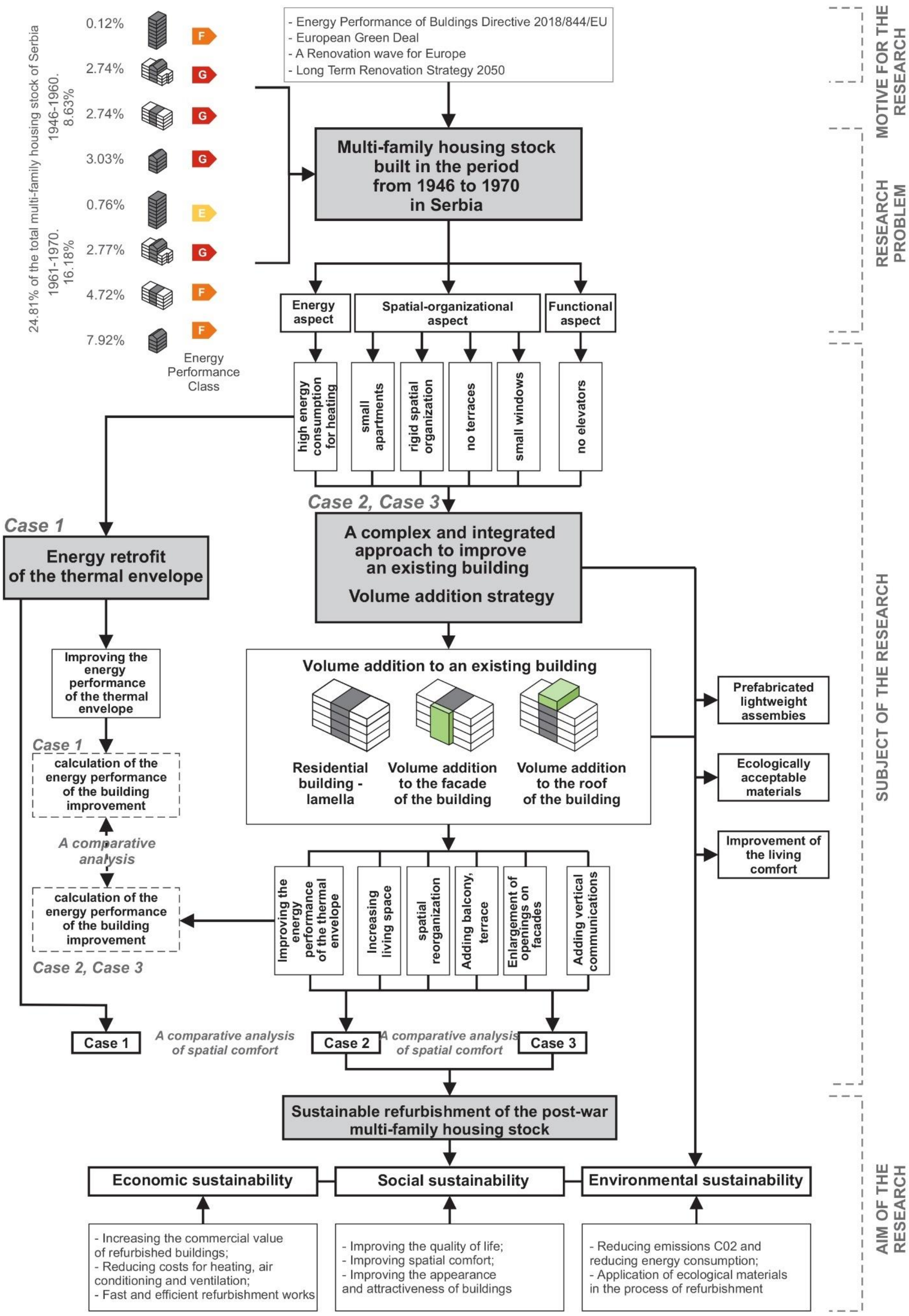


Figure 1. The research methodology diagram.

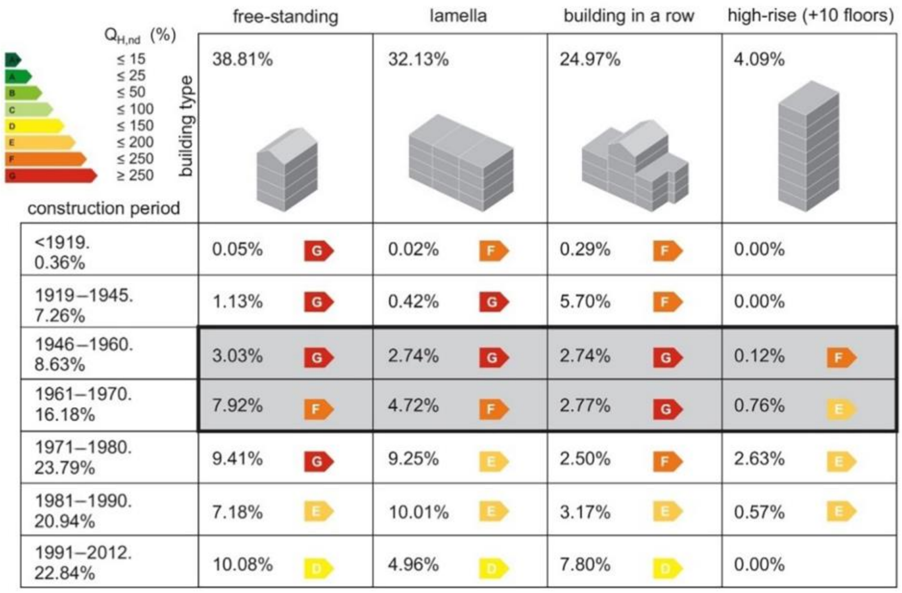


Figure 2. Statistical representation of types of multi-family housing according to time periods of construction on the territory of the Republic of Serbia and calculated energy performance classes. Adapted from [15].

2.2. Various Aspects of the Complex and Integrated Refurbishment of a Building Using the Strategy for Volumetric Addition

The sustainable renovation goal is to improve living conditions in existing multi-family residential buildings and achieve high energy efficiency standards. Various parameters affect the heating energy calculation: the materialization and quality of the building envelope, the ratio of the volume of a building to the area of the building envelope (shape factor), the total usable heated area, and the "exposure" of the building [19]. In common practice, improvement measures are based on bettering the conductivity characteristics of building envelopes through the addition of insulation layers and window replacement, a process that can have several qualitative levels [31]. The focus of this research is to investigate a more complex approach based on the application of volumetric additions to the volume of a building. This method, apart from changing the thermal characteristics of an envelope, changes the shape factor and increases its useful living space, enabling the redefinition of the existing apartments of minimal dimensions and outdated and rigid spatial organization [32]. Based on previous results, it can be concluded that an increase in the number of floors reduces energy use for heating per square meter, because it increases the share of apartments situated in the central part of the building (as seen by the height of the building), which have better energy performance of dwellings on the ground and the last floor [33]. According to previous research focusing on the impact factors of a building's shape on final building energy use, correlations exist between the size and shape of the non-heated staircase area and the overall size and shape of the building in the context of total energy consumption for heating [34].

The functional characteristics of the building, such as inadequate vertical communications, can also be improved by applying volumetric additions. A vertical volumetric addition on the roof of a building increases its useful living space (see Figure 3), which can be commercialized presenting an economic base for overall intervention. An increase in the number of floors of a building is possible only if the preliminary load-bearing analysis shows that a building is suitable for such an intervention.

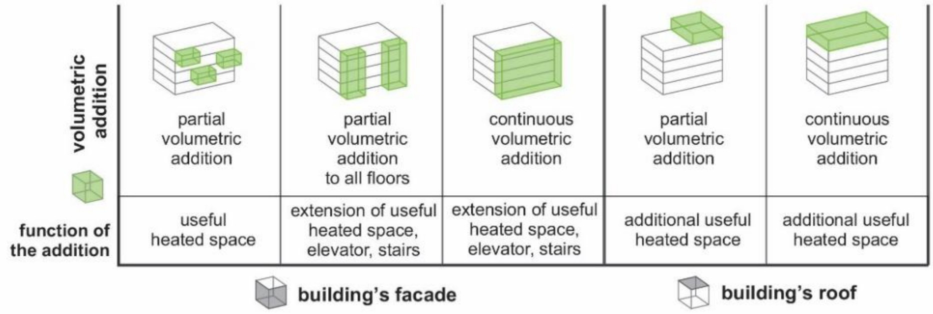


Figure 3. Variants of volumetric addition to an existing building.

The strategy for adding volumetric extensions to facades and on the roof of an existing building in a complex and integrated renovation depends on the building type, structural strength of all described building types, and construction site size and accessibility. As free-standing buildings were built in an open city block, there is sufficient surrounding space that is necessary for this renovation approach. Regarding free-standing buildings consisting of two or more identical units, it is not possible to apply this strategy to dilatation spaces and walls between them. In such buildings, there is a possibility of volumetric addition to the side facades of its end units. As these buildings were also built in an open city block, there is free space around them. In the case of buildings in a row in a closed city block, two facades are free, but in general, as these buildings were built on the regulation line, extension on the street façade is not allowed. Interventions to increase the volume of such a building are possible on the courtyard façade, but due to the applied sustainable refurbishment approach, which implies the use of prefabricated lightweight panels, the possibility of interventions on this façade is not considered because it is inaccessible to cranes (see Figure 4). High-rise, free-standing buildings with more than 10 floors were not taken into consideration because their percentage share in the total multi-family housing stock in Serbia is small.

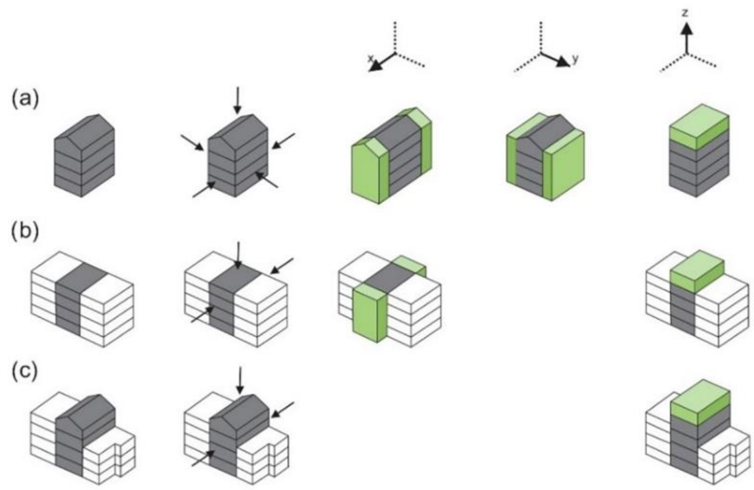


Figure 4. Possible directions of volumetric addition according to types of multi-family residential buildings: (**a**) free-standing building, (**b**) free-standing building consisting of two or more identical units, and (**c**) building in a row.

This research analyzes the possibility of applying the strategy of volumetric additions to multi-family free-standing building consisting of three units.

2.3. The Selected Residential Multi-Family Free-Standing Building Consisting of Three Units

A multi-family residential building with three units was selected for the research. This building was constructed in 1964 in an open city block in Belgrade, Serbia. There are three identical buildings constructed simultaneously, interconnected by side walls (see Figure 5). More buildings in the immediate and wider vicinity were constructed during the same period and belong to the same multi-family residential buildings.

Figure 5. Grouping of three identical multi-family residential buildings.

The multi-family residential building has a cubic form with shallow recesses in the façade that house balconies (see Figure 6). The building comprises a basement and five floors. The basement is used as a storage space, while all other levels are designated for residential purposes. According to the original technical documentation, the building has 24 cm thick transversal load-bearing hollow brick walls. The ceiling is a reinforced concrete structure 14 cm high. The 24 cm thick brick façade walls are plastered. The building features a traditional wooden pitched roof with a very low slope covered with sheet metal.

Figure 6. The existing conditions of the selected multi-family building.

The selected building consists of three units, and each unit has its own staircase. There are two entrances to the building. One entrance provides access to two units, while the other entrance is reserved for one unit. The building does not have elevators. The side units of the building are symmetrical. Most of the apartments have access to a small loggia. All apartments have a one-sided orientation. The spatial organization is the same on all floors. According to the original documentation, most of the apartments on the upper floors had loggias (see Figure 7).

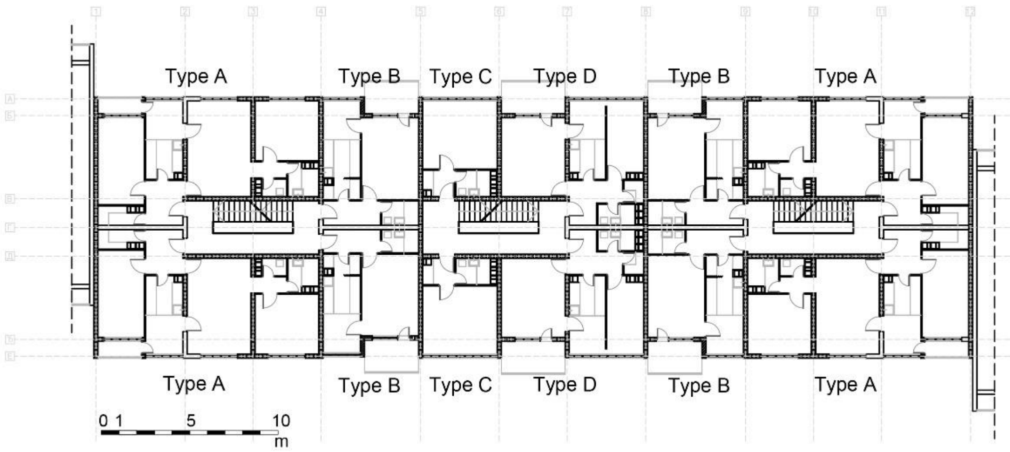


Figure 7. Typical floor plan according to the project.

The spatial organization of the side-positioned units consists of two larger apartments (Type A) with a usable area of 66.55 m^2, and two smaller apartments (Type B) with a usable area of 33.9 m^2, positioned around the staircase located in the central part, which lacks natural lighting. The apartments have an outdated and rigid spatial organization. There is no clear division between the day and night zones. The living room and kitchen are positioned in the central part of the apartment, while the bedrooms are located on the left and right sides of the living room.

The spatial organization of the centrally positioned unit consists of two smaller apartments (Type C) with a usable area of 21.65 m^2, and two larger apartments (Type D) with a usable area of 43.9 m^2, positioned around the staircase located in the central part, which lacks natural lighting (see Figure 7).

The thermal envelope of the building consists of all elements that separate the heated from the unheated parts of the building, or different comfort zones within the building, where heating may be temporarily interrupted due to the non-use of certain spaces [19]. The building's heated area includes the apartments on all floors, while the stairwell and basement are not heated. The apartments are heated by a central district heating system with steel radiators. According to the Knaufterm software calculation of heat transfer coefficients for the entire thermal envelope and of its elements that are next to unheated spaces, they are significantly higher than in energy-efficient buildings (see Table 1).

Table 1. Elements of the building envelope of the existing building.

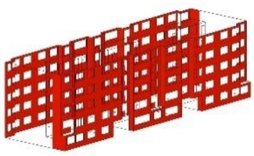
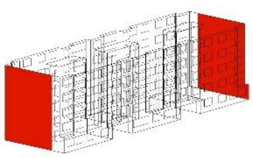
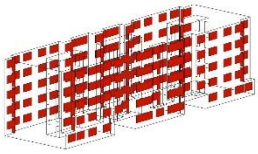
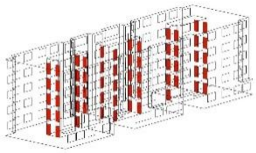
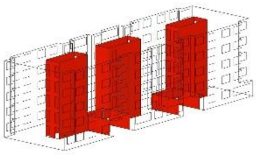
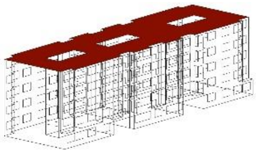
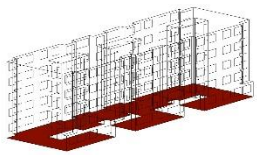
3D View of Envelope Segment	Name of Segment	Assembly Layers	Surface (m^2)	Umax (W/m^{2}K)	Umax (W/m^{2}K)
	Façade walls	1. Lime mortar 20 mm 2. Brick 200 mm 3. Lime mortar 20 mm	1105.78	0.4	2.012 > Umax
	Walls on dilatation	1. Lime mortar 20 mm 2. Brick 200 mm 3. Lime mortar 20 mm	313.7	0.5	1.862 > Umax

Table 1. *Cont.*

3D View of Envelope Segment	Name of Segment	Assembly Layers	Surface (m^2)	Umax (W/m^2K)	Umax (W/m^2K)
	Windows	Wooden single window with double glazing	547.12	1.5	3.3 > Umax
	Doors to unheated space	Metal non-insulated doors	107.25	1.6	5.5 > Umax
	Walls facing unheated space	1. Lime mortar 20 mm 2. Brick 200 mm 3. Lime mortar 20 mm	895.42	0.55	1.704 > Umax
	Constr. under unheated space	1. Lime mortar 20 mm 2. Concrete 140 mm	658.9	0.4	3.65 > Umax
	Constr. above unheated space	1. Parquet 20 mm 2. Cement screed 50 mm 3. Concrete 140 mm	662.74	0.4	1.848 > Umax

The thermal envelope segments of the selected building do not meet the criteria set in the Regulation on the Energy Efficiency of Buildings for maximum heat transfer coefficient values [19]. Based on this significant observation, the building serves as an excellent example for a research study that will focus on the thermal envelope of the building to achieve better energy performance results.

It is noticeable that some residents have independently implemented certain energy improvements, but the study will consider the original state of the existing building without subsequent interventions. In the selected building, as well as in similar examples of multi-family residential buildings, each apartment is individually owned, and each owner decides and approaches the energy retrofitting of their segment of the thermal envelope. This often leads to partial and discontinuous application of thermal insulation on the façade walls, which directly affects the aesthetic appearance of the building and raises the issue of an inadequately resolved thermal envelope, a common occurrence in existing practice. In practice, it is challenging to reach a consensus among all apartment owners to address the issue of building reconstruction.

This building belongs to the G energy efficiency class, which is the lowest on the scale of energy efficiency classes for residential buildings (see Figure 8). It can be concluded that it would be extremely desirable to carry out energy efficiency renovation to reduce the total energy for heating and, therefore, improve the energy efficiency class.

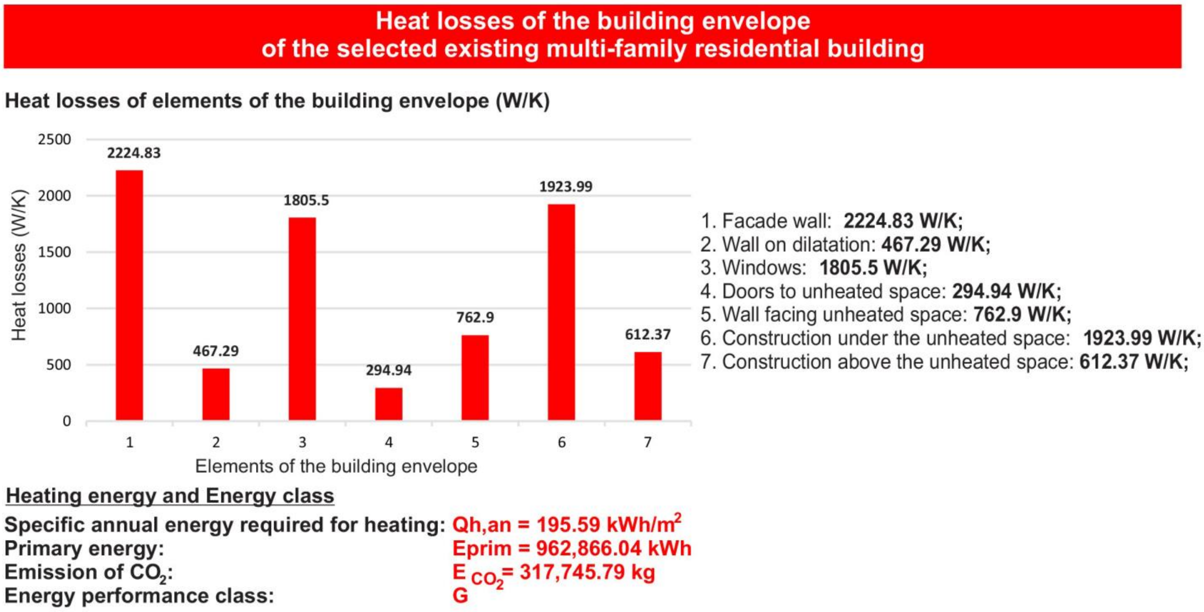


Figure 8. Heat losses of the building envelope of the selected existing multi-family residential building.

2.4. Case 1—Energy Efficiency Retrofit of the Building Envelope of the Existing Building without Volumetric Additions

Case 1 represents a variant of the energy efficiency retrofit of the existing building through interventions on the thermal envelope and on its elements that are next to unheated spaces without volumetric additions or expanding the useful space. In order to achieve the best possible energy performance of the building, it is necessary to perform energy retrofitting at every position of the thermal envelope, considering that none of the thermal envelope positions currently meet the allowed maximum heat transfer coefficient values for existing buildings according to the Rulebook on Energy Efficiency [19] (see Table 2).

Table 2. Energy efficiency retrofit of the elements of the existing building envelope: Case 1 (without volumetric additions).

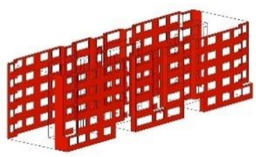
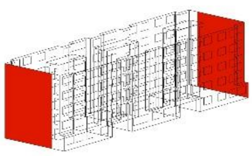
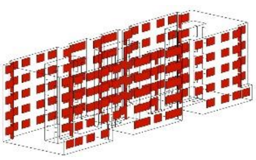
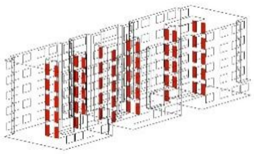
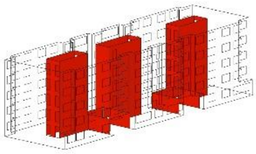
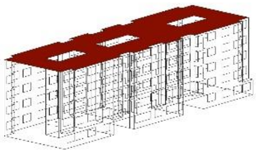
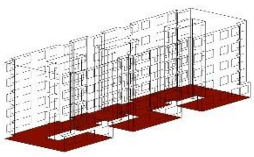
3D View of Envelope Segment	Name of Segment	Assembly Layers	Surface (m^2)	Umax (W/m^2K)	Umax (W/m^2K)
	Façade walls	1. Lime mortar 20 mm 2. Brick 200 mm 3. Lime mortar 20 mm 4. Thermal insulation mineral wool 100 mm 5. Façade plaster—Knauf Kati	1105.78	0.4	0.29 < Umax
	Walls on dilatation	1. Plasterboard 12.5 mm 2. Thermal insulation mineral wool 50 mm 3. Lime mortar 20 mm 4. Brick 200 mm 5. Lime mortar 20 mm	313.7	0.5	0.484 < Umax
	Windows	Aluminum frame with improved thermal break, low-emission two-layer glass package with krypton 4 + 12 + 4	547.12	1.5	1.4 < Umax

Table 2. *Cont.*

3D View of Envelope Segment	Name of Segment	Assembly Layers	Surface (m^2)	Umax (W/m^{2}K)	Umax (W/m^{2}K)
	Doors to unheated space	Insulated steel doors	107.25	1.6	1.5 < Umax
	Walls facing unheated space	1. Lime mortar 20 mm 2. Brick 200 mm 3. Lime mortar 20 mm 4. Thermal insulation mineral wool 50 mm 5. Plasterboard 12.5 mm	895.42	0.55	0.472 < Umax
	Constr. under unheated space	1. Lime mortar 20 mm 2. Concrete 140 mm 3. Thermal insulation mineral wool 80 mm 4. Plasterboard 12.5	658.9	0.4	0.372 < Umax
	Constr. above unheated space	1. Parquet 20 mm 2. Cement screed 50 mm 3. PVC foil 4. Reed insulation 20 mm 5. Concrete 140 mm 6. Thermal insulation mineral wool 80 mm 7. Plasterboard 12.5 mm	662.74	0.4	0.291 < Umax

Based on the mentioned interventions on all positions of the thermal envelope of the reference building, significant results have been achieved in reducing heat losses and energy required for heating. The same percentage of savings was obtained for primary energy as well as for reducing carbon dioxide emissions. Based on the energy required for heating per square meter, the building falls into the C energy performance class (see Figure 9). It can be concluded that through interventions aimed at energy improvement in all positions of the thermal envelope, outstanding results in energy savings for heating can be achieved. This energy improvement allowed the building to transition from a very low to a very high energy class, which was the goal of this improvement variant.

2.5. Approaches for Complex and Integrated Refurbishment in the Selected Residential Multi-Family Building

The research presents two approaches to complex refurbishment of the existing building using the strategy of volumetric addition. The first approach involves completely relocating the circulation areas of the building to create a gallery-type building. The existing building's dimensions are reserved exclusively for residential purposes, with the goal of providing a dual orientation for the apartments. New staircases, elevators, and access communication galleries are planned as additional volumes on the longitudinal façade of the building. The second approach to the complex refurbishment involves enlarging the residential units by adding volume while retaining the existing staircase inside the building and adding an elevator to each unit of the building. In this case, the heated area of the apartments is increased, but the one-sided orientation of the apartments is maintained. Both conceptual solutions in these renovation variants include the addition of an extra floor (see Figure 10). The goal of these approaches to the complex refurbishment of a building is to enhance spatial comfort and improve the building's energy performance.

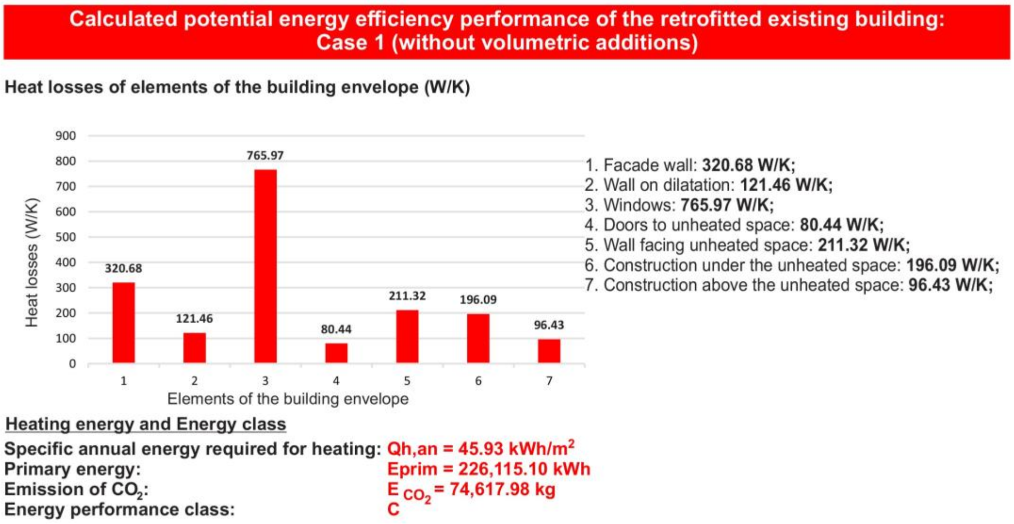


Figure 9. Calculated potential energy efficiency performance of the retrofitted existing multi-family residential building: Case 1.

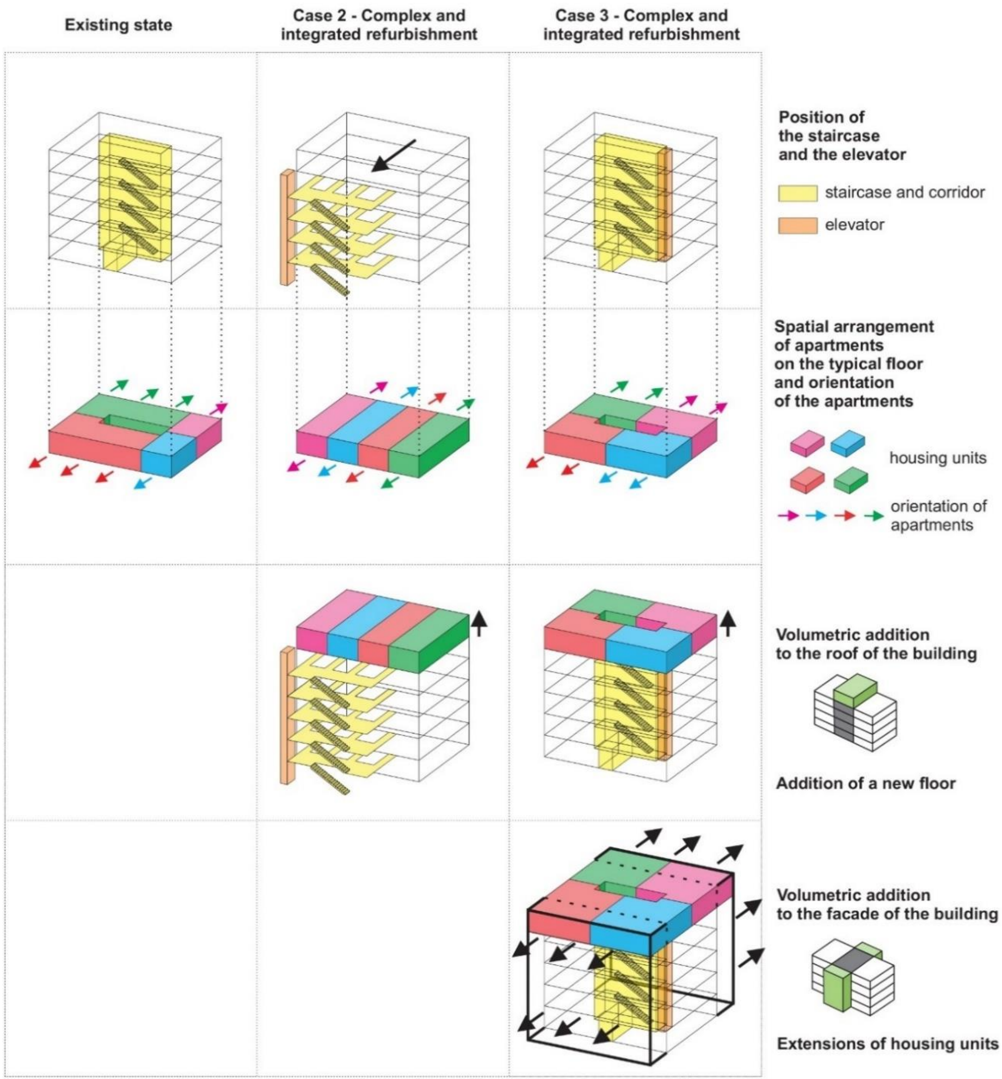


Figure 10. Diagram of interventions on variants for the improvement of the existing multi-family residential building.

2.6. Case 2—Complex and Integrated Refurbishment of the Existing Building

Case 2 represents a variant of a complex and integral refurbishment of the existing building by proposing communication galleries with two staircases and two elevators as additional volumes on the longitudinal façade, which would increase the usable living space of residential units (see Figure 11).

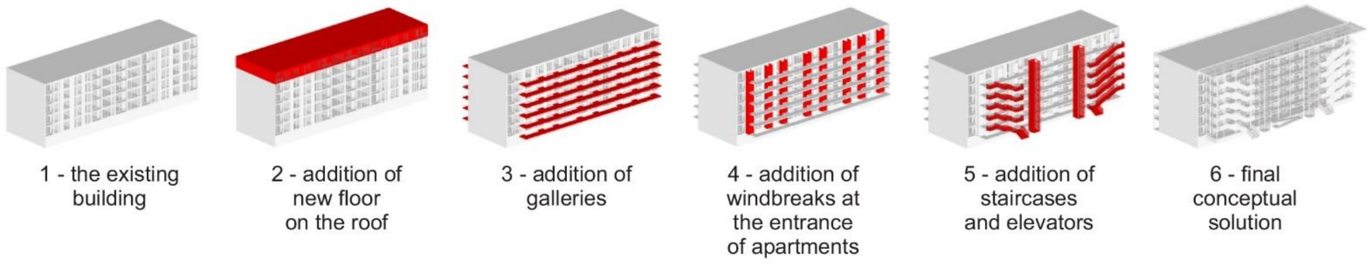


Figure 11. Iterations of the spatial and functional renovation of the existing building.

The architectural conceptual design includes the addition of an extra floor for residential purposes. The design incorporates balconies supported by independent columns and foundations on strip footings. The balconies serve different purposes: on one side, they function as communication spaces connecting the apartments to the newly formed staircases and elevators. On the other side of the building, the balconies serve as open relaxation areas, providing each apartment with access to a spacious balcony (see Figures 12 and 13).

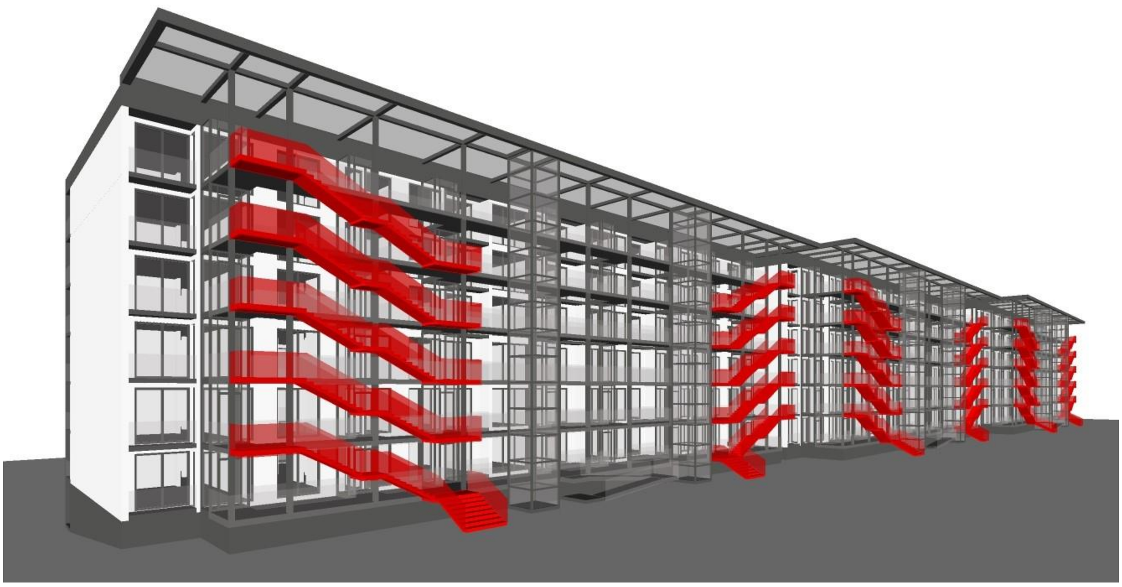


Figure 12. Three-dimensional view of the eastern façade of the conceptual architectural solution for complex and integrated refurbishment of the existing building: Case 2.

The most significant interventions are planned in the spatial organization of the floors, where the existing staircases are removed and, in their place, intermediate structures are formed. The entire floor is now residential, and the project design includes the formation of eight residential units on each floor. The apartments have dual orientations. On one side of the façade, an entrance to the apartments is provided with the addition of a windbreak, serving as an intermediate space between the heated interior and the outdoor area and functioning as a thermal barrier (see Figure 13).

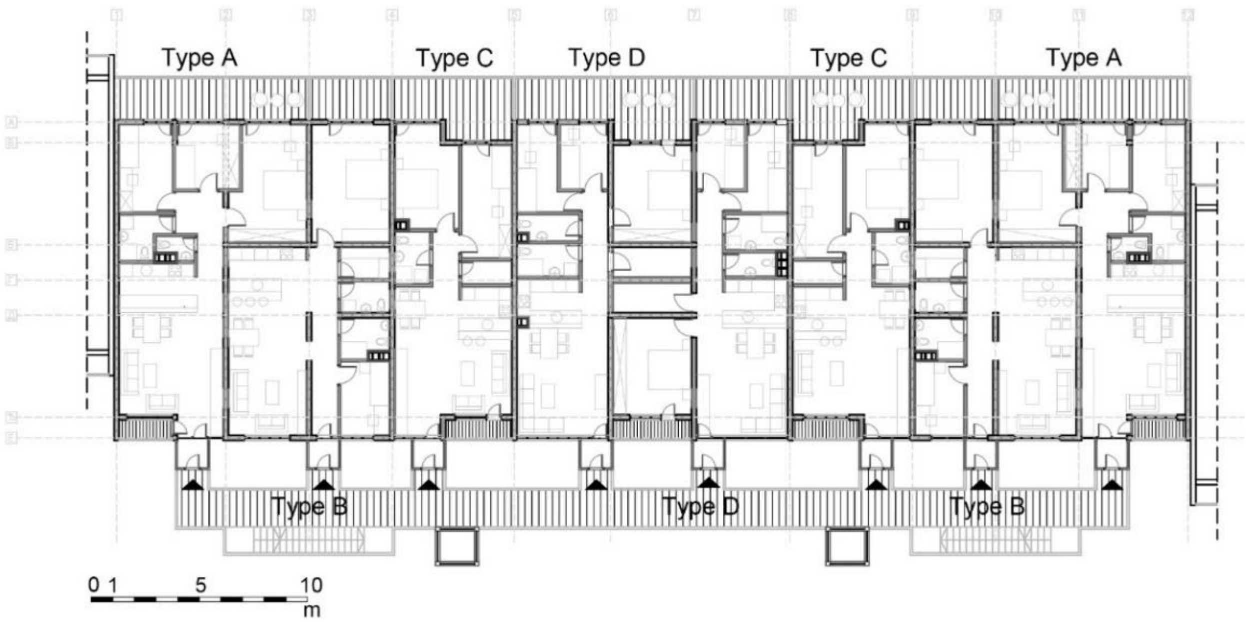


Figure 13. Typical floor plan of the complex and integrated refurbishment of the existing building: Case 2.

Analyzing one unit of the building in its existing state, it currently consists of a centrally located staircase and four apartments: two larger ones with a useful area of 66.55 m^2 and two smaller ones with a useful area of 33.9 m^2. The apartments have a one-sided orientation. In the conceptual design, the load-bearing transverse walls are retained to maintain the stability of the building, while the partition walls are removed, and reorganization is carried out to create three apartments with dual orientation. The spatial organization is based on dividing the apartments into a daytime zone (entrance, living room, kitchen, and dining area) and a nighttime zone (bedrooms and bathroom). The living room, kitchen, and dining area form one integrated zone without separating the walls between them. The bedrooms are oriented towards the facades for natural lighting. The newly designed apartments have larger areas than the existing ones. The largest apartment (Type A) has a heated useful area of 85.2 m^2 and includes three bedrooms. The other two apartments have two bedrooms, each with a clear division between the day and night zones, and their useful areas are (Type B) 81.5 m^2 and (Type C) 70.2 m^2 (see Figure 14).

By applying complex and integrated renovation, alongside spatial and functional improvements, the primary goal is to achieve the energy efficiency of the building. Therefore, the aim of this variant is the energy improvement in all positions of the thermal envelope and the use of highly rated, energy-efficient prefabricated lightweight assembly systems in the added parts of the existing building extension.

In Case 2, the thermal envelope of the building has fewer segments and covers a smaller area compared to the existing state and Case 1. This is because the internal staircase, which was unheated, has been eliminated in this variant, resulting in a fully compact heated zone, which directly impacts the energy performance of the building. Interventions have been made on all existing segments of the thermal envelope to achieve the allowed maximum heat transfer coefficient values for existing buildings, according to the Rulebook on Energy Efficiency [19]. The new positions in the thermal envelope (façade walls of the added part and a flat roof) are designed as prefabricated lightweight assemblies with an exceptionally low heat transfer coefficient (see Table 3).

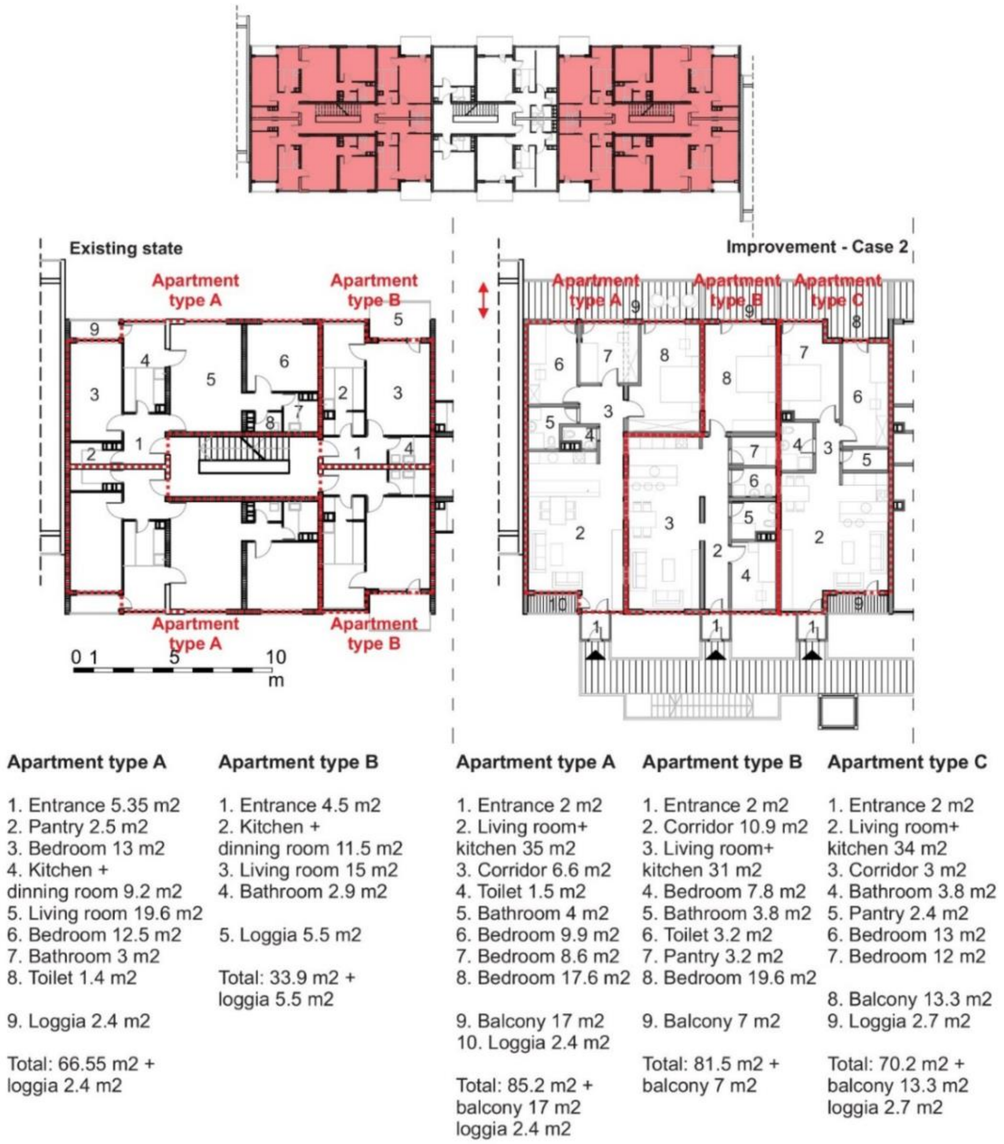


Figure 14. Apartments at the side entrances to the building (**above**); spatial organization of four apartments around the stairs in the existing state of the building (**bottom left**) and spatial organization of three apartments through complex and integrated refurbishment of the existing building: Case 2 (**bottom right**).

Table 3. Elements of the thermal envelope of Case 2—Energy renewal of the existing multi-family building using the strategy of volumetric additions—Relocation of communication functions.

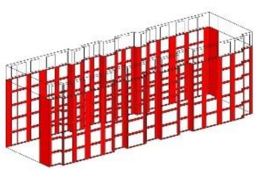
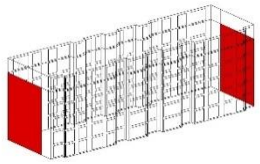
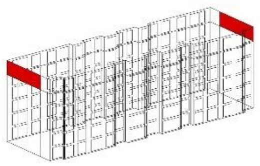
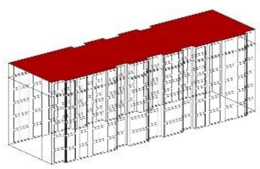
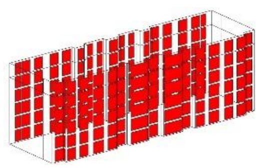
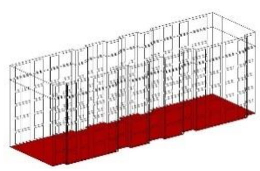
3D View of Envelope Segment	Name of Segment	Assembly Layers	Surface (m^2)	Umax (W/m^2K)	Umax (W/m^2K)
	Façade walls 1	1. Lime mortar 20 mm 2. Brick 200 mm 3. Lime mortar 20 mm 4. Thermal insulation mineral wool 150 mm 5. Façade plaster Knauf Kati	843.28	0.4	0.203 < Umax

Table 3. *Cont.*

3D View of Envelope Segment	Name of Segment	Assembly Layers	Surface (m^2)	Umax (W/m^2K)	Umax (W/m^2K)
	Façade walls 2	1. Plasterboard 12.5 mm 2. Vapor barrier 3. Wooden beam 10/160 mm + mineral wool 160 mm 4. Plasterboard 12.5 mm 5. Thermal insulation mineral wool 100 mm 6. Vapor barrier 7. Façade plaster Knauf Kati	192.43	0.4	0.1 < Umax
	Walls on dilatation 1	1. Plasterboard 12.5 mm 2. Thermal insulation mineral wool 100 mm 3. Lime mortar 20 mm 4. Brick 200 mm 5. Lime mortar 20 mm	303.83	0.5	0.283 < Umax
	Walls on dilatation 2	1. Plasterboard 12.5 mm 2. Vapor barrier 3. Wooden beam 10/160 mm + mineral wool 160 mm 4. Plasterboard 12.5 mm 5. Wooden substructure 40/40 mm + mineral wool 40 mm 6. Vapor barrier 7. Plasterboard 12.5 mm	65.12	0.5	0.200 < Umax
	Flat roof	1. Plasterboard 12.5 mm 2. Wooden beam 50/40 mm 3. Vapor barrier 4. Wooden substructure 100/220 mm + mineral wool 220 mm 5. Vapor barrier 6. Plywood 18 mm 7. Thermal insulation mineral wool 100 mm 8. Plywood 18 mm 9. Hydro isolation 10. Gravel 100 mm	715.27	0.2	0.118 < Umax
	Windows	Aluminum frame with improved thermal break, low-emission three-layer glass package with krypton 6 + 16 + 6 + 16 + 6	978.11	1.5	1.1 < Umax
	Constr. above unheated space	1. Parquet 20 mm 2. Cement screed 50 mm 3. PVC foil 4. Reed insulation 20 mm 5. Concrete 140 mm 6. Thermal insulation mineral wool 100 mm 7. Plasterboard 12.5 mm	715.27	0.4	0.248 < Umax

With significant interventions that resulted in a more compact volume of the heated space, a reduction in the number of positions of the thermal envelope, a decrease in the surface area of the thermal envelope, and extensive enhancement of the thermal envelope, the building has transitioned from the lowest to an exceptionally high energy performance class (see Figure 15). This achievement was the primary goal of this improvement variant, which serves as an example of a deep renovation of an existing building.

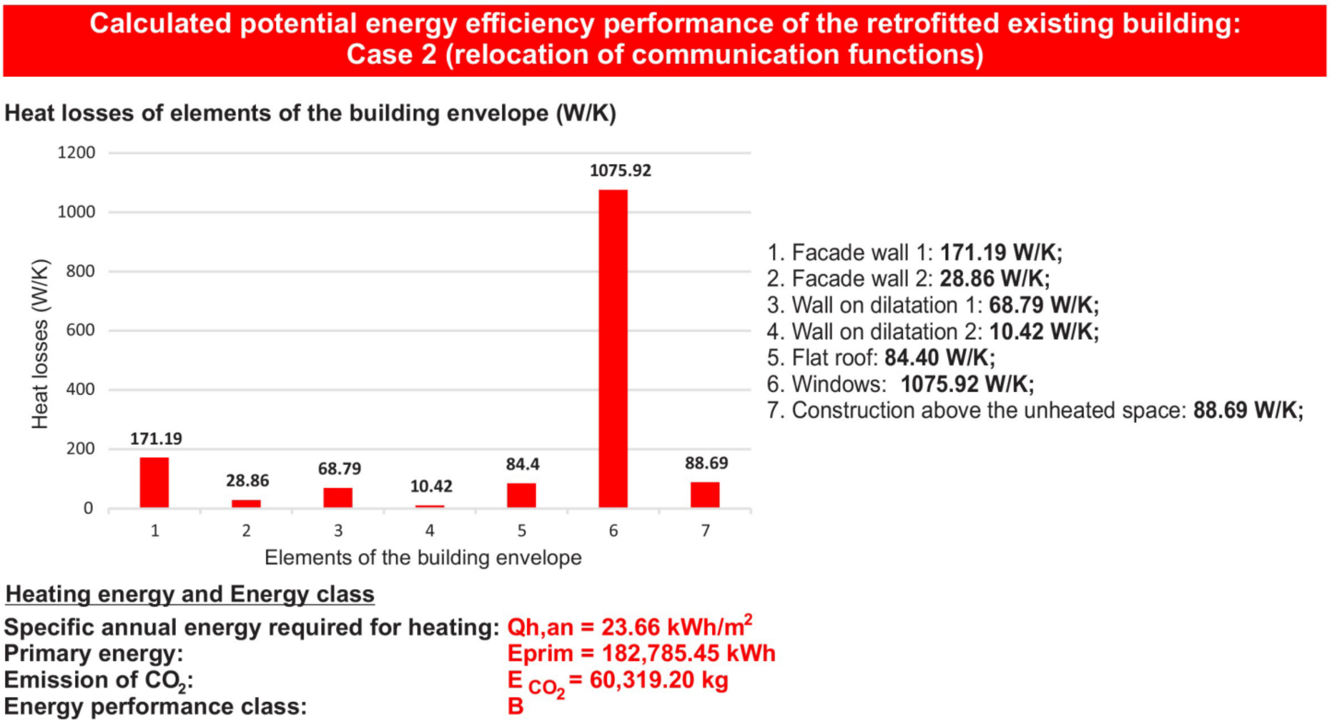


Figure 15. Calculated potential energy efficiency performance of the retrofitted existing multi-family residential building: Case 2.

2.7. Case 3—Complex and Integrated Refurbishment of the Existing Building

Case 3 represents a variant of a complex and integral refurbishment of the existing building by proposing volumetric additions on longitudinal facades, which would increase the usable living space of residential units from a spatial and organizational aspect, and the addition of elevators from a functional point of view.

The staircase has been retained in the central part of every unit of the building, and a lift has been added next to each staircase. In this variant, the same number of apartments as in the existing state have been retained, but the spatial organization of the apartments has been modified. Due to the small dimensions of the apartments, a strategy of adding volume has been implemented to increase the usable area of the apartments. On the longitudinal facades, the useful area of the apartments has been expanded by adding extensions. The architectural conceptual design includes the addition of an extra floor for residential purposes (see Figures 16 and 17).

Analyzing one unit of the building, the central staircase and four apartments have been retained. A lift has been added next to the staircase. Instead of two larger apartments with a usable area of 66.55 m^2 and two smaller apartments with a usable area of 33.9 m^2, the solution includes four apartments with similar sizes: 62.5 m^2 and 63.7 m^2. The apartments have a one-sided orientation. In the conceptual design, the load-bearing transverse walls are retained to maintain the stability of the building, while the partition walls are removed and reorganization is carried out to create four more comfortable apartments than the previous ones. The spatial organization is based on dividing the apartments into a daytime zone (entrance, living room, kitchen, and dining area) and a nighttime zone (bedrooms and bathroom). The living room, kitchen, and dining area form one integrated zone without separating the walls between them. The bedrooms are oriented towards the facades for natural lighting. The newly designed apartments have larger areas than the existing ones (see Figure 18).

The most important aspect of the complex and integrated refurbishment is increasing the energy efficiency of the existing building to improve its energy class and reduce energy losses for heating as much as possible. In Case 3, the thermal envelope of the building has more segments and covers a bigger area compared to the existing state and Case 1. This is because of volumetric additions to the longitudinal façade walls and to the roof. Interventions have been made in all existing segments of the thermal envelope to achieve the allowed maximum heat transfer coefficient values for existing buildings, according to the Rulebook on Energy Efficiency [19]. The new positions in the thermal envelope (façade walls of the added part, flat roof, and internal walls facing unheated spaces) are designed as prefabricated lightweight assemblies with an exceptionally low heat transfer coefficient (see Table 4).

Figure 16. Three-dimensional view of the eastern façade of the conceptual architectural solution for complex and integrated refurbishment of the existing building: Case 3.

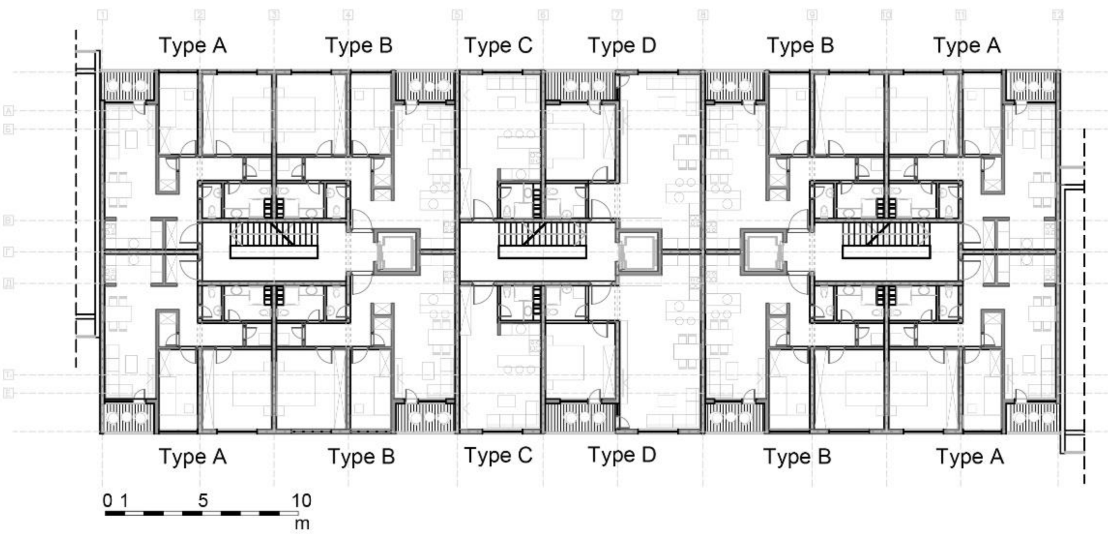


Figure 17. Typical floor plan of the complex and integrated refurbishment of the existing building: Case 3.

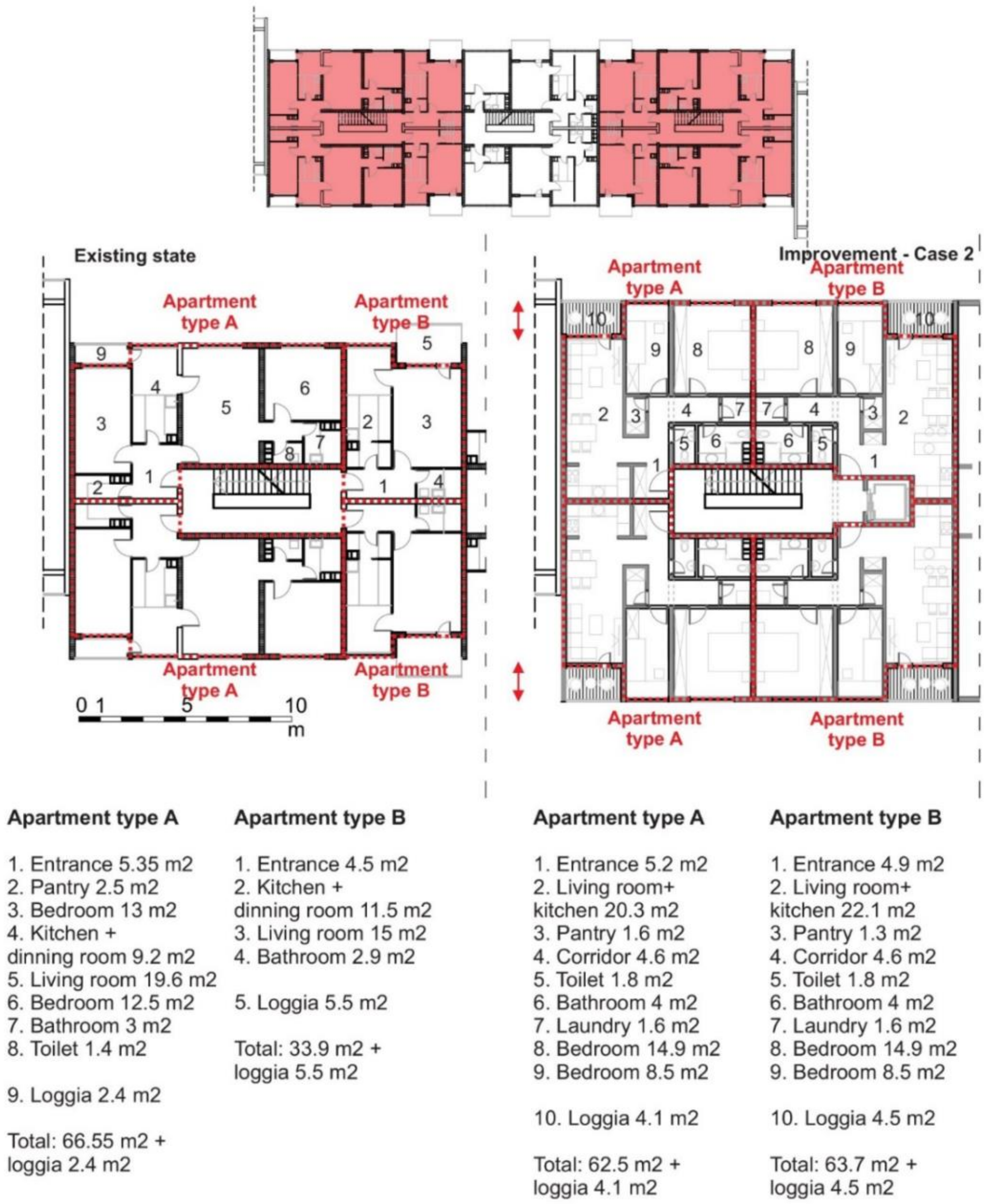


Figure 18. Apartments at the side entrances to the building (**above**); spatial organization of four apartments around the stairs in the existing state of the building (**bottom left**) and spatial organization of three apartments through complex and integrated refurbishment of the existing building: Case 3 (**bottom right**).

Table 4. Elements of the thermal envelope of Case 3—Energy renewal of the existing multi-family building using the strategy of volumetric additions—Extensions of living space.

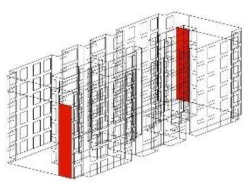
3D View of Envelope Segment	Name of Segment	Assembly Layers	Surface (m^2)	Umax (W/m^2K)	Umax (W/m^2K)
	Façade walls 1	1. Lime mortar 20 mm 2. Brick 200 mm 3. Lime mortar 20 mm 4. Thermal insulation mineral wool 150 mm 5. Façade plaster Knauf Kati	83.6	0.4	0.203 < Umax

Table 4. *Cont.*

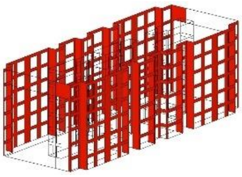
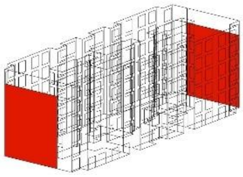
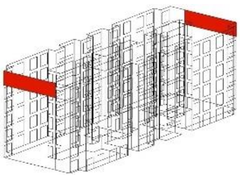
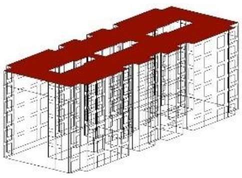
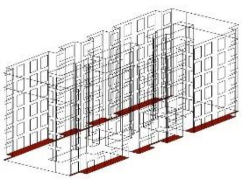
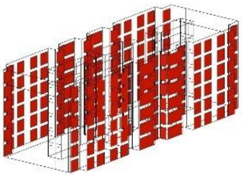
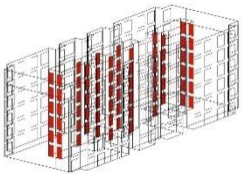
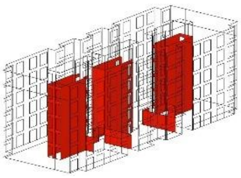
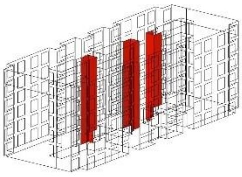
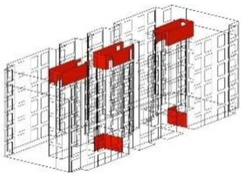
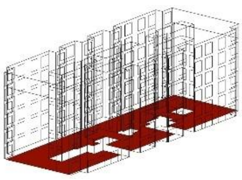
3D View of Envelope Segment	Name of Segment	Assembly Layers	Surface (m^2)	Umax (W/m^{2}K)	Umax (W/m^{2}K)
	Façade walls 2	1. Plasterboard 12.5 mm 2. Vapor barrier 3. Wooden beam 10/160 mm + mineral wool 160 mm 4. Plasterboard 12.5 mm 5. Thermal insulation mineral wool 100 mm 6. Vapor barrier 7. Façade plaster Knauf Kati	1135.29	0.4	0.145 < Umax
	Walls on dilatation 1	1. Plasterboard 12.5 mm 2. Thermal insulation mineral wool 100 mm 3. Lime mortar 20 mm 4. Brick 200 mm 5. Lime mortar 20 mm	342.11	0.5	0.283 < Umax
	Walls on dilatation 2	1. Plasterboard 12.5 mm 2. Vapor barrier 3. Wooden beam 10/160 mm + mineral wool 160 mm 4. Plasterboard 12.5 mm 5. Wooden substructure 40/40 mm + mineral wool 40 mm 6. Vapor barrier 7. Plasterboard 12.5 mm	68.42	0.5	0.200 < Umax
	Flat roof	1. Plasterboard 12.5 mm 2. Wooden beam 50/40 mm 3. Vapor barrier 4. Wooden substructure 100/220 mm + mineral wool 220 mm 5. Vapor barrier 6. Plywood 18 mm 7. Thermal insulation mineral wool 100 mm 8. Plywood 18 mm 9. Hydro isolation 10. Gravel 100 mm	799.65	0.2	0.118 < Umax
	Construction above external space	1. Parquet 20 mm 2. Cement screed 50 mm 3. PVC foil 4. Reed insulation 20 mm 5. Plywood 24 mm 6. Vapor barrier 7. Wooden substructure 100/200 mm + mineral wool 200 mm 8. Vapor barrier 9. Plywood 18 mm 10. Thermal insulation mineral wool 100 mm 11. Vapor barrier 12. Plasterboard waterproof 15 mm	148.26	0.4	0.099 < Umax

Table 4. *Cont.*

3D View of Envelope Segment	Name of Segment	Assembly Layers	Surface (m^2)	Umax (W/m^2K)	Umax (W/m^2K)
	Windows	Aluminum frame with improved thermal break, low-emission three-layer glass package with krypton 6 + 16 + 6 + 16 + 6	964.89	1.5	1.1 < Umax
	Doors to unheated space	Insulated steel doors	171.88	1.6	1.5 < Umax
	Walls facing unheated space 1	1. Plasterboard 12.5 mm 2. Thermal insulation mineral wool 80 mm 3. Lime mortar 20 mm 4. Brick 200 mm 5. Lime mortar 20 mm	800.27	0.55	0.333 < Umax
	Walls facing unheated space 2	1. Plasterboard 12.5 mm 2. Thermal insulation mineral wool 80 mm 3. Lime mortar 20 mm 4. Concrete 200 mm 5. Lime mortar 20 mm	304.02	0.55	0.357 < Umax
	Walls facing unheated space 3	1. Plasterboard 12.5 mm x2 2. Vapor barrier 3. Wooden substructure 80/180 mm + mineral wool 180 mm 4. Vapor barrier 5. Plasterboard 12.5 mm x2	190.02	0.55	0.216 < Umax
	Constr. above unheated space	1. Parquet 20 mm 2. Cement screed 50 mm 3. PVC foil 4. Reed insulation 20 mm 5. Concrete 140 mm 6. Thermal insulation mineral wool 100 mm 7. Plasterboard 12.5 mm	662.74	0.4	0.248 < Umax

Due to different types of wall structures, the position of the inner wall facing unheated space is divided into three segments in this analysis. The first two internal walls facing the unheated space are the existing internal walls of the building, which differ in the type of wall construction material and which, according to the energy calculation of the existing state, do not meet the maximum permitted heat transfer coefficient for this position. Therefore, it is necessary to carry out interventions in these positions by adding thermal insulation material. Based on the mentioned interventions in all positions of the thermal envelope and by adding new positions in the thermal envelope, significant results were achieved in terms of reducing heat losses and the energy required for heating (see Figure 19).

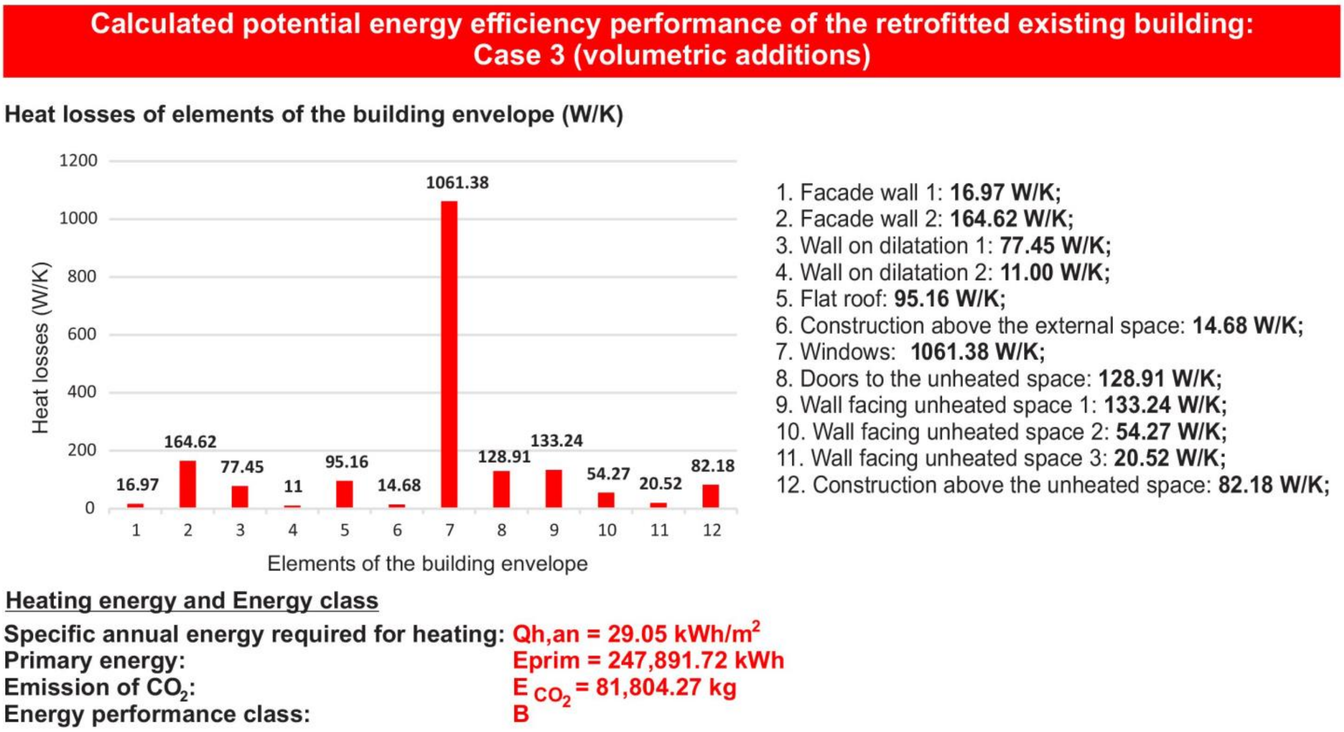


Figure 19. Calculated potential energy efficiency performance of the retrofitted existing multi-family residential building: Case 3.

3. Results

Based on the analysis of three variants for improving the energy performance of the existing building, a comparative analysis of the energy performance of the current state of the building and the three improvement variants can be conducted (see Figure 20).

The first improvement variant involves enhancing all components of the thermal envelope to achieve better energy performance for the building. The surface area and volume of the building remained the same as in the current state. With this improvement, excellent results were achieved, with an 81% reduction in specific annual heating energy consumption compared to the current state. Similar savings were obtained for primary energy consumption and CO_2 emissions.

The second improvement variant represents a complex and integrated renovation where the surface area and the number of thermal envelope positions are reduced while the volume of heated space is increased. Due to the higher compactness of the heated space volume, better results were obtained compared to Case 1, despite almost doubling the surface area of the heated space. The specific annual heating energy consumption is reduced by 89% compared to the current state. A similar percentage of savings (84%) is achieved for primary energy consumption and CO_2 emissions. The energy performance class of Case 2 is better than Case 1 due to the increased surface area of the heated space and greater energy savings for heating.

The third improvement variant also represents a complex and integrated renovation, but with the addition of volume on the longitudinal facades, while the unheated stairwell space remains in its original position. This results in a larger number of thermal envelope segments and the largest surface area of the thermal envelope. Similarly, the heated area in this case is larger than in the previous variants. The results of this improvement variant are similar to Case 2, with an 87% reduction in specific annual heating energy consumption compared to the current state. The same level of savings is achieved for primary energy consumption and CO_2 emissions (80%). This variant achieves an energy performance class B, the same as in Case 2, which is an excellent result compared to the energy performance of the current state.

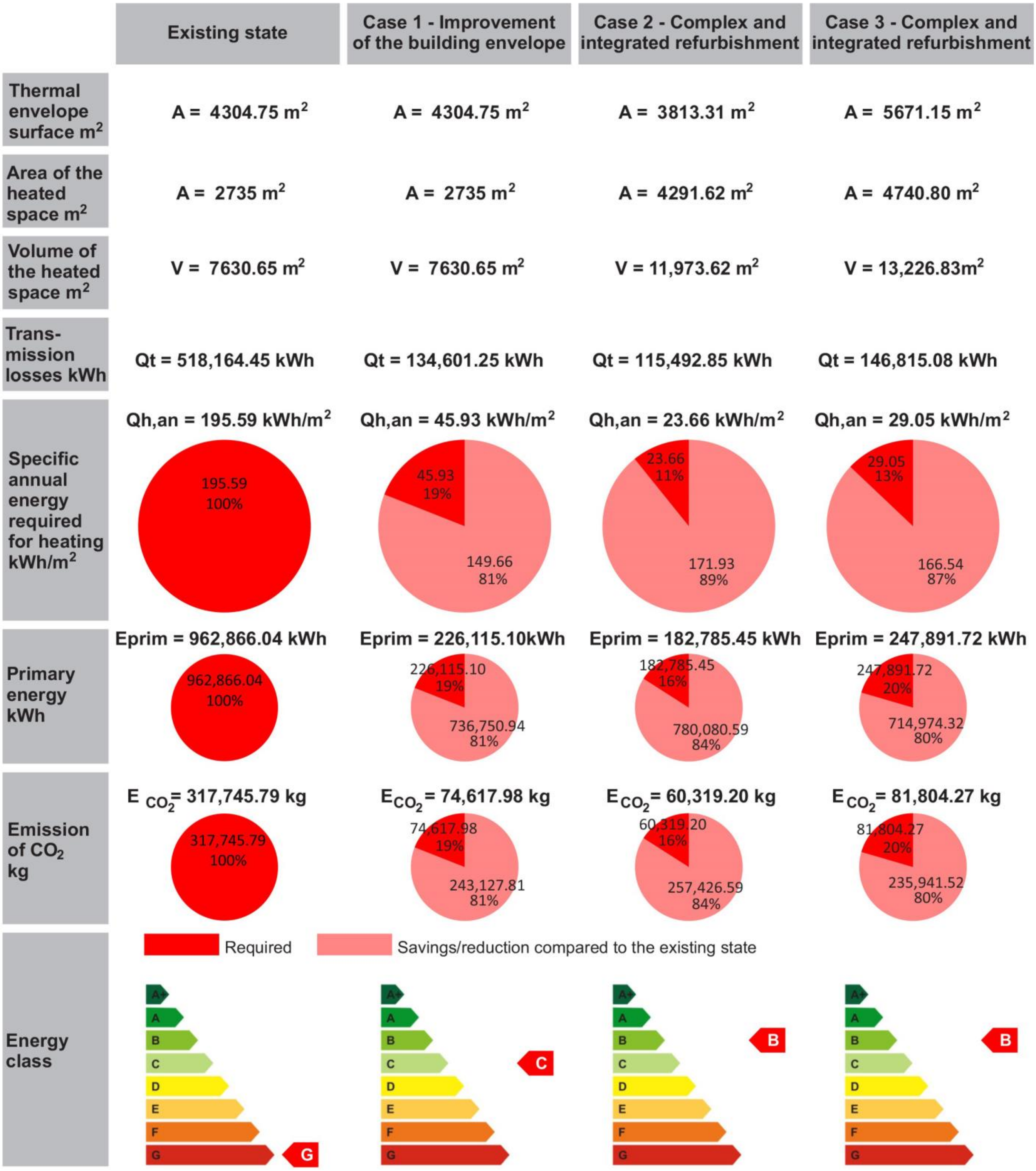


Figure 20. A comparative analysis of the energy required for heating and related emission of carbon dioxide in the existing state and three cases of energy improvement in the existing residential multi-family building.

4. Discussion

Based on the analysis of three variants for the improvement of the existing multi-family residential building, a comparative analysis of functional and spatial–organizational parameters can be conducted (see Figure 21). The positioning of vertical communications (staircases and elevators) has influenced the number, orientation, and area of the apartments on the typical floor of the improvement variants of the existing building.

A comparative analysis of energy, functional, and spatial-organizational parameters of the existing state and three cases of improvement in the existing residential multi-family building				
	Existing state	Case 1 - Improvement of the building envelope	Case 2 - Complex and integrated refurbishment	Case 3 - Complex and integrated refurbishment
Energy Class	G	C	B	B
Area of the heated space m^2	A = 2735 m^2	A = 2735 m^2	A = 4291.62 m^2	A = 4740.80 m^2
Number of floors	5	5	6	6
Number of apartments	58	58	48	72
Apartments' size	20 apartments - 66.55 m^2 10 apartments - 43.9 m^2 18 apartments - 33.9 m^2 10 apartments - 21.65 m^2	20 apartments - 66.55 m^2 10 apartments - 43.9 m^2 18 apartments - 33.9 m^2 10 apartments - 21.65 m^2	12 apartments - 85.2 m^2 12 apartments - 81.5 m^2 12 apartments - 70.2 m^2 12 apartments - 78.47 m^2	24 apartments - 62.5 m^2 22 apartments - 63.7 m^2 12 apartments - 30.5 m^2 12 apartments - 56.5 m^2 2 apartments - 37.3 m^2
Apartments' orientation	The apartments are oriented on one side	The apartments are oriented on one side	The apartments are oriented on two sides, with windows on the east and west sides	The apartments are oriented on one side
Position of the staircase	Inside the building	Inside the building	Outside the building	Inside the building
Position of the elevator	No elevator	No elevator	Outside the building	Inside the building

Figure 21. A comparative analysis of energy, functional and spatial–organizational parameters of the existing state and three cases of improvement of the existing residential multi-family building.

In the current state of the building and Case 1, there are four types of apartments with different areas (66.55 m^2, 43.9 m^2, 33.9 m^2, 21.65 m^2), and all apartments are single-oriented.

In Case 2, the apartments have significantly larger areas (85.2 m^2, 81.5 m^2, 70.2 m^2, 78.47 m^2) compared to the existing state, as they have a dual orientation. The drawback of this improvement variant is the lack of smaller apartments for families with fewer members or for singles.

In Case 3, the apartment areas were slightly increased compared to the existing state by adding volume to the longitudinal facades, resulting in extensions to the apartments. The drawback of this improvement variant is that the apartments have a single orientation.

Based on the analysis of the physical parameters of spatial comfort from the literature through the variants of improvement for the existing building, it can be concluded that Case 2 satisfies the physical parameters defined by Alfirević [20] (see Figure 22).

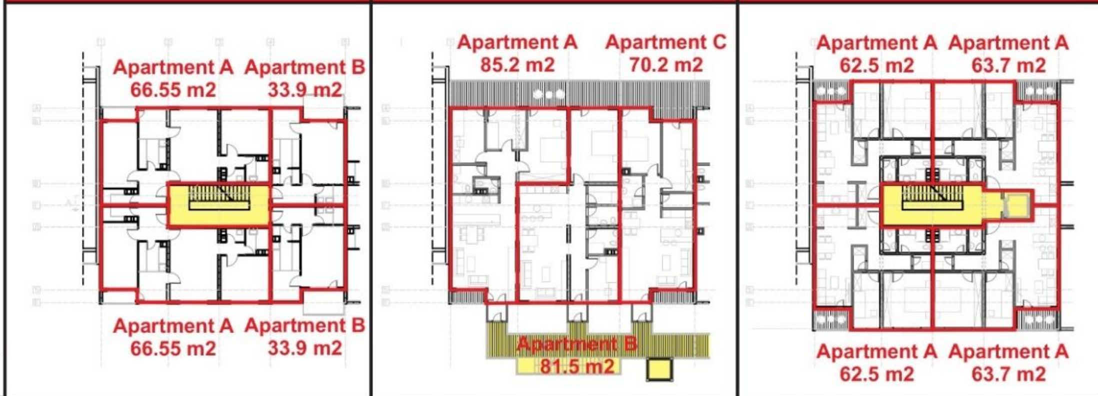
The parameter "distance between space boundaries" is fulfilled in Cases 2 and 3, because the kitchen and living room form a single zone without partition walls that would restrict the view. The view is not blocked, and distinct functions are combined in one space.

The parameter "space configuration" is fulfilled in Cases 2 and 3, because the kitchen and living room are united in a single space following the principle of open space and positioned in a linear order according to the principles of enfilades.

The parameter "openness of space" is fulfilled in Case 2 because the apartments have a dual orientation, which affects the visual connection between the interior and exterior to achieve greater spatial comfort.

The parameter "shape of space" is fulfilled in Cases 2 and 3 because a clear distinction in the spatial organization of the daytime and nighttime zones of the apartments has been achieved.

It can be concluded that the dual orientation of apartments, the clear separation of the living and sleeping areas, and the formation of a multi-functional open space without partition walls have a significant impact on the spatial comfort of living.



Physical parameters of spatial comfort	Case 1 - Improvement of the building envelope	Case 2 - Complex and integrated refurbishment	Case 3 - Complex and integrated refurbishment
distance between space boundaries		- living room and kitchen are not separate rooms, boundaries (walls) do not disturb the view	- living room and kitchen are not separate rooms, boundaries (walls) do not disturb the view
space configuration		- open space: living room and kitchen - rooms are positioned in a linear order following the principles of enfilades	- open space: living room and kitchen
openness of space		- two side oriented apartments - achieved the perception of a larger spatial comfort	
shape of space		- clear division into day (living room, kitchen and dinning room) and night (bedrooms) zones	- clear division into day (living room, kitchen and dinning room) and night (bedrooms) zones

Figure 22. A comparative analysis of physical parameters of spatial comfort of three cases of improvement of the existing residential multi-family building.

5. Conclusions

The research results show significant potential for energy savings in all three analyzed approaches to energy retrofitting. In all three improvement cases, high energy performance classes were achieved. However, Cases 2 and 3 reached a better energy performance class than Case 1, despite the increased useful heated surface area and heated volume of the building. The increased space also influenced the improvement of both the spatial–organizational and functional characteristics of the building in Cases 2 and 3.

By applying a complex and integrated refurbishment approach, multiple benefits can be achieved. Besides energy retrofitting by improving the energy performance of the building envelope, the spatial and functional enhancement of the building is also a focus of this renovation approach. The advantages of implementing the volumetric extension strategy in an existing building in this research can be observed through several aspects: the method of realization, the use of natural materials, and the results achieved in terms of living comfort. In this way, it becomes evident that the strategies arising from a comprehensive and integrated improvement in the existing building cannot be strictly classified into just one aspect of sustainability, but they can be observed at several interconnected levels. By conducting interventions on the entire building envelope, increasing the usable space of the building, improving its functionality, enhancing the energy performance of the building envelope, using materials and products of natural origin, and applying innovative construction techniques that involve environmentally friendlier materials and prefabrication, which are more time-efficient and environmentally cleaner than conventional construction techniques, exceptional results can be achieved.

The problems accompanying complex and integrated refurbishment would be the duration of the work and the accommodation of tenants in the meantime, the issue of ownership relations, and the housing community's consent for such work to be done.

Further research should proceed in several directions. One research direction should focus on the analysis of the stability of existing multi-family residential buildings constructed between 1946 and 1970 and static assessments of the feasibility of adding volume to existing buildings. Another research direction should be centered on the economic justification of such extensive renovations. Research on the economic viability of complex renovations should include an analysis of initial investments, calculations of energy consumption savings for heating, long-term heating cost reduction, and an assessment of the building's value before and after complex refurbishment. The third research direction should address the investigation of relationships and the roles of stakeholders in complex renovation of existing buildings. Issues related to ownership, building occupants, the unity and resilience of the residential community, municipal and city policies regarding subsidies and incentives for building renovations, and various renovation and development funds require extensive research and the definition of a framework and model for conducting such renovations.

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