Chapter 4
Scientific Research Related to Building Renovation

Maja Lešnik, Vesna Žegarac Leskovar and Miroslav Premrov

4.1 State of the Art of the Existing Building Renovation

Many studies and literature reviews focusing on a variety of scopes and objectives associated with building renovation have been recently conducted. They represent a comprehensive source of information and an appropriate basis for further investigation. The existing literature deals with the topic related to building renovation from different perspectives, scopes and goals as already explained in Chap. 2. The classification contained in different literature reviews may vary, mainly on account of being made for various purposes. For the purpose of the research, further presented in Sect. 4.3, the relevant state of the art is divided into two categories: categorization according to *sustainability aspects* and categorization according to the *scale of consideration*.

4.1.1 State of the Art—Categorization According to Sustainability Aspects

When renovating buildings, it is necessary to apply a holistic approach to sustainability including its *social*, *economic* and *environmental* aspects [1]. The basic targets of sustainability aspects and their evaluation attributes are presented in Table 4.1.

As established in the research conducted by Abdul Hamid et al. [2], energy efficiency, which belongs to the environmental sustainability aspect, is one of the leading aspects and objectives considered in the available literature regarding building renovation. Energy efficiency is also the main objective of our research presented in Sect. 4.3, which does not disregard the importance of other closely related aspects. Thus, a brief presentation of the relevant literature follows in the text below. Among numerous perspectives, the assessment involves the energy

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Table 4.1 Sustainability aspects, their targets and evaluation attributes

	Environmental	Economic	Social
Targets	Energy efficiency Source consumption Environmental impacts	Cost-effectiveness Economic viability Economic rationality	Indoor environmental quality (IEQ) Accessibility[a] Adaptability[a] Health and comfort Loading on the neighbourhood[a] Maintenance Safety/security[a] Sourcing of materials and services Stakeholder involvement[a]
Evaluation attributes	Building operating energy Consumption of water Waste Emission of CO_2 and other pollutants Life-cycle assessment (LCA)	Operating costs Rental costs Asset value Life-cycle cost (LCC) Payback time	Thermal comfort Air quality Relative humidity Visual comfort Acoustic comfort

[a]Some of the social aspects cannot be easily evaluated or measured employing different parameters

efficiency, environmental impacts, the economic aspect and the indoor environmental quality (IEQ). Many reviewed references consider more than one single aspect and often even treat several aspects as jointly intertwined. Additionally, according to Ascione et al. [3], the selected objectives are usually in mutual contradiction and should be therefore taken into account simultaneously.

4.1.1.1 Environmental Aspect of Building Renovation

The environmental aspect of sustainability generally covers numerous topics related to preservation of natural systems, biodiversity, management of natural resources, impacts to the environment, climate impacts, etc. The environmental aspect of building renovation aims mainly at reducing resource consumption and environmental burdens [1] (Table 4.1). Since the scope of the environmental sustainability aspect is too large to be fully covered respecting the aim of our further research, only the energy efficiency and environmental impacts which are closely related to building renovation will be discussed.

Energy Efficiency

Energy efficiency is one of the leading perspectives within the environmental sustainability aspect and is therefore frequently explored in the literature. Improving the energy efficiency of existing buildings is usually associated with the implementation of various renovation measures, considered in many research studies, which will be further discussed in Sect. 4.1.2.3.

Several studies demonstrate that the majority (80–90%) of negative environmental impacts occur during the building use stage and are due to the building operating energy. Reducing the operational energy is therefore one of the main targets of sustainable building renovation [1]. The energy efficiency of building renovation is usually described as energy savings where the energy saved in the form of heat or electricity is calculated as a difference in the annual energy consumption [4]. For the purpose of a more general evaluation, the energy saved is usually converted into primary energy. Unlike other sustainability aspects such as the IEQ, the energy efficiency of buildings is rarely measured and mostly calculated or simulated [2]. It is worth mentioning that simulation assumptions exert considerable impact on the results of the energy balance analysis, as emphasized by Dodoo et al. [5]. The research discusses the outdoor microclimate, the building thermal envelope and the household electrical equipment parameters. The divergence in the results due to input parameters is more noticeable when energy-efficient buildings are taken into account instead of conventional ones. The research proves that the estimation of heat gains from electrical appliances has a significant influence on calculation of the building's space heating. In addition to internal gains, the indoor temperature set point along with the efficiency of the ventilation heat recovery unit has a great impact on the energy balance of the building and the energy efficiency measures [6].

Another important aspect affecting the building energy consumption is user behaviour which is one of the issues often disregarded in the literature regarding building renovation [7]. The above human factor is also one of the main reasons for the gaps occurring between the expected—calculated and the actual energy consumption [8].

A considerable effort has lately been made to provide early stage decision support tools and strategies to guide the energy-efficient renovation process [9–11]. Decision-making is a complex process, involving several different aspects and part takers. A survey of existing tools and methodologies of building renovation with a focus on the preliminary investigation phase was conducted by Thuvander et al. [9]. The above-mentioned phase is the time when the main directions and goals are defined. The survey points out that although there are many tools supporting sustainable construction, only few are suitable for building renovations. However, a recent literature survey conducted by Nielsen et al. [10] exhibits continuous development of decision support tools which can be used for building renovation. The majority of reviewed tools (81%) included environmental sustainability criteria, 72% contained economic criteria, 63% had social criteria and 40% covered all three criteria.

Environmental Impact

Environmental impact has recently become an ever more emerging component of the environmental sustainability aspect with respect to which the life-cycle assessment analysis (LCA) has become a widely applied technique used to determine environmental impacts of the building as well as those of numerous other products and systems through their entire lifespan. The scope of application of the life-cycle assessment analysis (LCA) is constantly growing not only in the sense of evaluating new buildings but also in assessing building renovation. The review of relevant literature conducted by Vilches et al. [12] identified a lack of studies on building renovation using the LCA approach since only in few of the researches, energy consumption and greenhouse gas emissions prove to be the most considered impact categories of the life-cycle assessment analysis (LCA), followed by eutrophication or acidification, while other impact categories like toxicity are not typically addressed. Additionally, a lack of studies with a focus on the analysis of environmental, economic and social consequences resulting from the extension of the building's lifespan due to renovation is observed.

Another approach, the energy approach, suitable for environmental impact evaluation was emphasized by Andrić et al. [13]. The energy approach accounts for different forms of energy and resources and measures the quality differences among various types of energy. The method enables a comparison of different types of energy and resources using the same comparative basis. The literature survey summarizes the results of several studies with regard to different types of buildings, demonstrating that the greatest impact of all building life-cycle phases exerted on the energy consumption and greenhouse gas emissions goes to the building operational phase [12, 13]. In both, the life-cycle assessment analysis (LCA) and the energy approach, the life cycle of the building is generally divided into four life-cycle phases; building construction, building operation, building renovation and the end of life-cycle [13]. According to the EN 15804:2012 [14], an additional product stage including raw material supply, transport and manufacturing can also be considered within the LCA.

4.1.1.2 Economic Aspect of Building Renovation

According to Simson et al. [15], building renovation projects are mostly driven by potential economic benefits. Economic viability can be evaluated with different evaluation attributes, presented in Table 4.1. Among them, the net present value (NPV), internal rate of return (IRR), simple payback period (SPP) and discount payback period (DPP) are the most applicable [16]. Additionally, the life-cycle cost (LCC) analysis is an important method which can be used to simulate the life-cycle economic analysis.

The above-mentioned underlying economics of building renovation call for their cost-effectiveness as a part of a long-term plan based on assessments of renovation measures and strategies, in addition to evaluation of their energy efficiency and environmental viewpoints. The selection of appropriate renovation measures depends on the selected goals defined as financial, energy and environmental savings in a research conducted by Tan et al. [17]. The authors prefer using financial and environmental savings, expressed as CO_2 emission reduction and the NPV, to using energy savings as an objective function in the optimization process. For example, cost-effectiveness based on several renovation measures applied to typical 1970s multi-family buildings in Sweden is assessed by Dodoo et al. [18]. The influences of the proposed renovation measures on energy savings in addition to electricity savings along with investment costs are considered in the study. A focus is laid on cost-effectiveness of the proposed individual and package measures on the basis of the NPV method. The results also indicate that energy efficiency and cost-effectiveness are not always in accordance with each other. For instance, replacement of windows considered in the research proves to be the best single final energy saving. However, the window with $U = 0.9$ W/(m^{2}K) is cost-effective only under a sustainability scenario including a real discount rate of 1% and the annual real energy price increase of 3%.

Ballarini et al. [19] conducted another research, considering the cost-effectiveness of renovation measures applied to Italian building stock. A cost-benefit analysis was conducted based on global costs, including the present value of the initial investment costs (e.g. renovation costs), the present value of the annual costs (e.g. running costs) and disposal costs. The heat generator replacement demonstrates the lowest global cost, particularly in buildings located in warm climates. On the other hand, the most satisfying renovation measures regarding energy savings, such as building envelope insulation combined with the window and the heat generator replacement, are cost-effective only in the case of the oldest of the researched buildings located in colder climates and above all, in the smallest of the buildings considered in the study.

4.1.1.3 Social Aspect of Building Renovation

Social sustainability aspect of building renovation evaluates subjective user satisfaction and objective parameters of health and indoor climate [1]. The main social targets described in EN 15643-3 [20] are presented in Table 4.1. Sometimes they are labelled as non-energy benefits, since they may not have direct financial or environmental implications but are vital for the health, well-being and comfort of the users. For the purpose of further investigation, the following text discusses only the IEQ.

Indoor Environmental Quality (IEQ)

The focal point of many research articles is set on the energy efficiency and environmental impacts of renovation strategies; however, the findings of Craft et al. [21] suggest additional consideration of the impact building renovation exerts on the occupants' health and well-being. The IEQ is a vast topic including thermal, visual and acoustic comfort besides the indoor air quality (IAQ) [22]. According to the literature review on the IEQ conducted by Al horr et al. [23], thermal comfort is the most important IEQ parameter. It is influenced by several environmental parameters, such as air temperature, relative air humidity and air velocity, and personal factors such as human metabolic rates and insulation through clothing. Moreover, visual comfort is also vitally important for the well-being and productivity of the occupants, since it includes good lighting conditions and views from the indoor areas. Accordingly, architectural design plays an important role in reference to appropriate daylighting and thereby on the occupants' well-being [24]. Finally, acoustic comfort in buildings defined as the capacity to protect occupants from noise and offer an acoustically suitable environment is often not considered as a high priority in building design, which leads to several post-occupancy issues although the problem sphere of acoustic comfort is recognized [23]. The research identified the building materials, equipment and occupants as the main sources of indoor air pollutants. The IAQ can be increased either by increasing the ventilation rate or by reducing the source of pollution within and outside the building. Additionally, the topic of sick building syndrome (SBS) can be added to the afore-mentioned factors [23]. SBS is a group of health problems which can be caused by unsuitable temperature, humidity, chemical and biological pollution, closure of natural openings, use of improperly tested materials, furniture, equipment, etc.

According to the literature survey conducted by Abdul Hamid et al. [2], the IEQ is the most frequently measured sustainability aspect. For instance, the impacts of the energy renovation on the IEQ in several multi-family buildings were measured and compared in the research conducted by Leivo et al. [25]. The findings underline the importance of assessing thermal conditions and ventilation for the optimal IEQ and energy savings. Additionally, the user aspect regarding the visual connection with the surroundings along with the quality of daylight proves to be one of the most important features of living spaces, producing influence not only on the occupants' well-being but also on the market value of real estate units [26]. Improving the IEQ, particularly in office and public buildings, results in the increase of the users' productivity level, which in turn increases the economic benefit [16].

4.1.2 State of the Art—Categorization According to the Scale of Consideration

Based on the survey of the existing literature, we additionally classified the latter according to the scale of consideration into the *urban-scale* category representing the building stock, the *building-scale* category including different building typologies and the *component-scale* category discussing several renovation measures. Furthermore, the renovation measure of building extension is thoroughly analysed in the literature belonging to the component-scale category.

4.1.2.1 Urban Scale

Some existing studies [27] emphasize the importance of focusing on multiple buildings and a multi-year renovation rather than on individual buildings constructed within a certain time period. Accordingly, available literature highlights national or European existing building stock renovations [28, 29], while others deal with the selected segments of the building stock, for example, historical buildings [30, 31]. The results obtained by this kind of research usually serve the purposes of energy policy development and that of energy-efficient renovation scenarios for building stocks.

Brøgger et al. [28] conducted a recent state-of-the-art literature review regarding building stock models which serve to estimate the energy-saving potential in a diverse building stock. The findings of the review identified the highest occurrence of the archetype approach which makes use of representative buildings. However, the authors questioned the representativeness of the buildings and the subsequent adequacy in view of making typology-based generalizations. The above approach was also used in the international projects IEE-TABULA and EPISCOPE, where the residential building typologies have been created in 20 European countries, as explained in [32]. The building typologies were classified according to the size and age of buildings, with a further step of comparing the building energy performance. Average representative buildings of each building typology, size and age were defined in order to enable the projection of the energy performance to the entire residential building stock. The developed classification of the residential building stock was further used within numerous studies assessing the energy-saving potential of building stocks [33–35]. A real example building and average building models were established for the Danish residential building stock, according to the IEE-TABULA project, within a research conducted by Kragh et al. [33]. The first one can be used by building owners as it demonstrates typical energy-saving initiatives, and the latter is suitable for establishing a space heating balance model. Moreover, a comparison between the energy balance simulation using average designed building models and the official statistics on energy consumption in Denmark shows negligible divergence of 4%, which proves that the approach is useful for the energy-saving estimation. The same approach was used in a research conducted by Dascalaki et al. [34] for a residential building stock in Greece and a study by Ballarini et al. [19] for an Italian residential building stock.

Csoknyai et al. [35] conducted an assessment of the building stock energy performance and energy-saving potential of Eastern European countries, based on similar building stock characteristics due to their common historical and economical background. The primary energy saving achieved by deep energy-efficient renovation, aiming at nearly zero energy use with the inclusion of extensive thermal insulation of the building envelope, the replacement of windows and doors, modernization of the heating and domestic hot water systems along with installation of renewable energy systems conducted in the research, results in the energy-saving potential between 67.8 and 77.2%.

A special part of the building stock represents historical buildings which require special attention during a renovation process. In some countries like Italy, historical buildings represent a considerable share of the entire building stock which cannot undergo a traditional renovation process [31]. Renovating such buildings is a complex process where a number of criteria must be balanced. The main features distinguishing historic and traditional buildings from the rest of the building stock are their physical characteristics (complex and irregular geometry, lack of insulation and vapour barriers, natural non-standardized materials, etc.) and conservation principles, as explained by Webb [30]. In their research, they conducted a review of the main criteria, followed by the analysis methods and the decision-making process used to assess the energy-efficient renovation of historical and traditional buildings. According to the results, conservation and energy consumption are the main criteria discussed in the available literature. Simultaneously, a shift in the viewpoint regarding energy-efficient renovation as a treat to the character of historic and traditional buildings towards the opportunity of protecting them is identified. An overview of the Italian historical buildings energy-efficient renovation focusing on renovation actions, conducted by Galatioto et al. [31], demonstrates several suitable and feasible approaches in line with the historical value restrictions. As affirmed by the authors, the most difficult renovation action proves to be the improvement of the envelope thermal properties, which calls for this action to be conducted according to the “case-by-case” approach.

4.1.2.2 Building Scale

A considerable part of available literature focuses on renovation of individual buildings or groups of buildings due to more accurate results in this line of research. The studies comprise various types of buildings and sustainability aspects of building renovation which have been previously discussed in Sect. 4.1.1.

Different types of buildings require distinguished consideration of renovation measures and strategies applicable to building renovation. Types of buildings in this research are defined according to the building use which significantly influences the energy consumption of existing buildings. Two general categories considered are residential and non-residential buildings, which does not exclude a possible further division of the two. After all, one of the basic differences between residential and non-residential buildings in addition to design, size, etc., lies in the occupancy schedule [36].

Residential Buildings

Available studies on building renovation mainly deal with residential buildings which represent the largest share among all types of buildings. Residential buildings account for 75% of the entire Europe’s building stock, where 64% represent single-family houses and the remaining 36% comprise multi-family buildings [36].

In a recently conducted research by Abdul Hamid et al. [2], publications regarding renovation of multi-family buildings in temperate climates are thoroughly reviewed according to several categories; status determination, renovation strategies and renovation measures. The survey of the status determination category, which is useful for legislation or policy implementation and decision-making during a building renovation process, indicates that energy performance is the most explored aspect, followed by the IEQ. The methods frequently used in this kind of research are mostly interviews or surveys, followed by simulations or calculations, and measurements. Furthermore, the survey of renovation strategies includes methodologies, methods, protocols and approaches but does not encompass environmental certification systems (e.g. LEED, BREEAM). Strategies are analysed according to the established and most recurring sustainability aspects, i.e. economic, social and environmental. Moreover, many of the reviewed references in the research can be classified into more than one category of sustainability. The last considered category examines literature relative to various renovation measures and strategies. Energy efficiency proves once again to be the most recurrent aspect considered in the reviewed literature regarding renovation measures, along with the IEQ and economy. The analysed research works predominantly consider renovation measures taken on different building components, which will be further discussed in Sect. 4.1.2.3.

Unlike non-residential buildings, where the users have limited control over thermal and ventilation conditions, user behaviour in residential buildings proves to be of vital importance. The impact of user behaviour on the energy efficiency of residential buildings is addressed in the research conducted by Balvedi et al. [37]. Better understanding of the user behaviour is crucial for understanding of the human–building interaction which represents energy-saving potential. The best method of evaluating user behaviour in residential buildings is physical monitoring, which is frequently conducted with the purpose of developing mathematical models, further applied within building performance simulations.

Single-family houses represent the largest share of the residential building stock and therefore offer a large potential for reducing the energy consumption of the entire residential building stock. The main renovation measures applicable to single-family houses are comparable to those taken in the case of multi-family houses. However, the financial viewpoint remains the main challenge when deciding for renovation. According to Ekström et al. [38], there are two main categories of motivators for building renovation, with the first one being regulation and the second the operational costs of the homeowners. The research involves the life-cycle cost analysis (LCC) carried out to evaluate several cost-effective renovation packages towards the passive house level of single-family houses in Sweden. The outcomes of the research indicate possible final energy savings by at least 65% if compared to the energy need prior to renovation. Correspondingly to multi-family buildings, the minority of case studies considering single-family renovation include measures to be taken before and after renovation. A relevant example is a research conducted by Bjørneboe et al. [39] which is based on an existing single-family building renovation process, taking into consideration the realistic financial condition of the building owners. The main aim of the renovation was not merely to reduce the energy consumption but mostly to upgrade the building elements durability, the IEQ, improved function and the value of the house.

Non-residential Buildings

A country-by-country review of the energy performance of buildings [36] demonstrates that the non-residential building stock accounts for 25% of the entire Europe's building stock. However, the average energy consumption in non-residential buildings is estimated to be 40% higher than the equivalent value for the residential sector. Therefore, improvement of the energy efficiency of non-residential buildings should receive equal attention to that paid to the residential sector. Offices and wholesale buildings make up the largest share of the floor space area among non-residential buildings. Office buildings are presumed to have similar heating and cooling conditions to those in residential buildings although their daily occupancy span is much shorter. Similar usage pattern corresponds to educational buildings which account for less than 20% of the entire non-residential floor space area. One of the differences between residential and non-residential buildings is the basic use pattern which significantly influences the energy demand. Additionally, non-residential buildings are more complex units regarding the number of occupants, greater diversity of contaminants, heating, ventilation and air conditioning (HVAC) systems and limited personal control over thermal and ventilation conditions [22].

The authors of a critical literature review on renovation of commercial and institutional buildings [40] observed a lack of comprehensive studies focusing on improving the energy performance of operating buildings. The contemporary energy efficiency approaches including technical, organizational and behavioural aspects were examined. Although the focus of the above-mentioned research is set predominately on active measures, the survey emphasizes the need for additional research focusing on behavioural-based approaches in improving the energy performance of commercial and institutional buildings.

The analysis of the building envelope insulation, ventilation system and lighting fixture-based renovation of three industrial buildings suggests that it is not always profitable to renovate only from the energy savings point of view since considering also the costs of maintenance and repair work proves to be profitable in the long run [15]. The benefit of installing controlled mechanical ventilation systems with heat recovery as one of the most effective renovation measures suitable for non-residential buildings is recognized also in the research conducted by Ferrari and Beccali [41] and Ascione et al. [3].

Similar to office and public buildings, good IEQ is very important in educational buildings. A literature review conducted by Irulegi et al. [7] underlines the changes in user behaviour, referring to the use of computers and other technologies, and thereby, the increase of internal gains in poorly ventilated buildings, which can lead to overheating problems during summer and shoulder periods. In a multi-step and multi-objective optimization of the energy-efficient renovation process of an educational building conducted by Ascione et al. [3], the authors consider the objective functions of the indoor thermal discomfort together with the energy need for heating and cooling for three groups of energy renovation measures: building envelope, heat generation and renewable energy sources. Installation of an air-source heat pump along with the full roof PV system proves to be the most profitable configuration of renovation measures for applying the methodology to the case study building. While most of the literature focuses on envelope and system properties to increase the energy efficiency and air quality in educational buildings, the reference [24] considers the so-called Architectural Energy Retrofit (AER) strategy which emphasizes passive renovation measures with special regard to architectural design of the school building having a specific conservation value.

4.1.2.3 Component Scale

The majority of research studies examine the influence of various renovation measures and strategies on the energy-saving and economic potential, on environmental implications and the IEQ, regardless of the size of consideration (building stock, group of buildings, individual buildings, etc.), sustainability aspect or type of building. Among them, renovation of the building envelope is the most frequently investigated group of renovation measures, followed by renovation of active technical systems (e.g. HVAC systems) [2].

Under the component scale, several renovation measures are discussed. As explained in Sect. 2.1, renovation measures can be divided according to the area of their application. In this state of the art, only three (*renewal of the building thermal envelope, renewal or addition of active technical systems* and *building extension*) will be discussed. Moreover, the majority of the reviewed literature refers to more than one of the listed groups of renovation measures. According to Ruparathna et al. [40], renovation measures can also be divided according to the type of intervention into passive and active measures, where interventions dealing with the building envelope are usually associated with passive measures, while renovation or replacement of building systems, electrical appliances and lighting are labelled as active measures.

Renewal of the Building Thermal Envelope

As emphasized in Sect. 2.1, renovation measures improve both, the building's physical condition and its functional performance, e.g. the energy demand behaviour and the occupants' health and well-being.

Choosing appropriate renovation measures, as discussed by Mikučionienė et al. [4], depends on the chosen criteria. Sustainability of renovation measures in the research was evaluated according to the following criteria: energy efficiency, environmental impacts, economical rationality, comfort and duration under the life-cycle duration analysis (LCD). The selected individual renovation measures considered in the research are the following: insulation of external walls, insulation of the roof, heat substation renovation and installation of the mechanical heat recovery ventilation. The selected five separate renovation measures and packets of energy efficiency measures were applied to a case study building, with the purpose of demonstrating the use of the developed distribution decision three method. The results of applying this method to a public building in Lithuania demonstrate that the best general sustainability criteria when taking separate renovation measures are achieved with exterior walls insulation, followed by the heating system renovation. The first measure provided the best results in the energy efficiency and duration under the LCD criteria, while the second enabled the best performance according to economical rationality. However, the best general sustainability is achieved by applying a packet including all of the listed renovation measures.

According to Abdul Hamid et al. [2], only few studies conduct field measurements before and after renovation. Moreover, the measurements focus mainly on the IEQ. Alonso et al. [42] conducted one of the researches focusing on monitoring the IEQ applicable to energy-efficient renovation, which was a part of REFAVIV research on the façade energy-efficient renovation. The research data collected by monitoring the user behaviour, the IEQ, the building design, the construction system, etc., were implemented in a dynamic analysis model which was used to assess the impacts of the proposed renovation measures. Significant differences between the assessed user behaviour and the reference usage profiles suggested by the legislation were observed, which can exert substantial impacts on the accuracy of energy balance calculations. The renovation measures applied to two case study dwellings in Madrid with a view to increasing indoor comfort and energy efficiency during winter periods were the building envelope insulation, infiltration reduction, omitting thermal bridges and using passive solar gains. On the other hand, applying solar shading and nighttime ventilation are the most recommendable renovation measures for achieving thermal comfort in dwellings during summer periods, which proves to be the most problematic issue in the case study buildings.

The effects of simple energy-efficient renovation on the IEQ for Slovakians multi-family buildings were analysed within the research conducted by Földváry et al. [43]. The parameters of IEQ in the existing and renovated pairs of buildings were measured and compared. The measures applied in the case study included additional thermal insulation of external walls, roofs and basement ceilings along with balancing of the existing heating system. No changes were made to the windows, since most of them had already been replaced beforehand. The findings of the research indicate lower occupant satisfaction with the post-renovation IEQ, associated with lower air exchange rates occurring due to the increased airtightness of the building envelope. To avoid adverse impacts of the energy-efficient renovation on the IEQ, measures including ventilation improvement should be implemented, as stressed by the authors of the research.

An important frequently disregarded aspect within renovation projects which focus mostly on the use of renewable energy sources, energy-efficient technologies and insulation materials is seen in the energy behaviour of buildings, derived from the architectural form and microclimate of the building's surrounding, as emphasized by Eliopoulou and Mantziou [24]. Within their research, an alternative building renovation, called AER, strategy was developed and applied to an energy-consuming school complex. An effort was made to interlink the energy efficiency and architectural perspectives since the building is protected as an architectural monument. Based on the analysis of the current building's energy performance and the users' comfort level, the following renovation measures were taken into consideration: partial thermal insulation of the envelope, optimization of daylighting, seasonal modification of the heated volume combined with the introduction of buffer zones, cross and night ventilation, shading with greenery and cool paving materials. In addition to 44% energy savings and cost-optimal benefits resulting from applying only architectural passive measures to the existing building, several non-energy benefits are also highlighted.

The envelope quality plays an important role also in the energy-efficient renovation of historical buildings, where the currently available best practice according to Galatioto et al. [31] proves to be special insulation plasters and interior insulation of the walls. One of the possible ways of increasing thermal performance of the building envelope, as emphasized by Hilliaho et al. [44], is adding a glazed façade to the existing building. The research conducted on a case study building in Sweden investigated the effects of added glazing on the energy efficiency and the IEQ of the renovated building. The result of calculations and measurements demonstrates a decrease in the energy need for heating with savings ranging from 5.6 to 25.3%, depending on the design. In addition, indoor comfort during summer periods was considered with a suggestion of increasing the cavity airflow and adding solar shading in order to decrease thermal discomfort relative to summer periods.

As emphasized in several research studies [45] and review articles [2, 29], the effects of building renovation on the energy, cost efficiency, environmental impacts and IEQ are not solely dependent on the selected renovation measures but vary significantly according to the location and climate conditions. Most of the available research related to energy efficiency of several renovation measures and strategies is conducted for buildings in cold and temperate climates, where the major part of operational energy is used for heating. However, some of the available researches deal also with buildings in hot climates [45, 46] where the energy demand for cooling is much stronger. A study conducted on residential buildings in Israel by Friedman et al. [45] demonstrates limited usefulness of well-established renovation measures applied to the building envelope. The research acknowledges the benefit of insulating the roof as a cost-effective renovation measure even though the estimated payback period is 15–30 years, making this measure unattractive to most homeowners. On the other hand, external wall insulation as one of the most effective renovation measures taken in cold and temperate climates does not prove to be economically viable in mild Mediterranean weather conditions and hot climates of Israel. A review of passive envelope measures for improving the energy efficiency of buildings in United Arab Emirates, conducted by Friess and Rakhshan [46], reveals an enormous energy-saving potential. With the measures including thermal insulation of building envelope, up to 20% of energy consumption can be saved in the residential context. On the other hand, up to 55% of energy consumption can be reduced by using the appropriate glazing type and orientation in office buildings. Moreover, the use of natural ventilation can reduce the energy demand from 30% in villas up to 80% in high-rise office buildings using mixed-mode ventilation systems.

The increase in the energy demand for cooling as a result of overheating during summer and shoulder periods, not only in hot but recently also in temperate climates, is becoming ever more important. To address this issue, a literature review of active and passive cooling methods for dwellings was conducted by Oropeza-Perez and Østergaard [47] who identify and discuss three of the most used active cooling methods (fans, evaporative coolers and heat pumps) and ten of the most used passive cooling methods regarding several energy flows in the building energy balance (internal gains, inside and outside heat transfer through the envelope and a mix of all of them). The results of the developed decision-making programme applied to dwellings demonstrate a high level of dependence of the cooling method availability on climate conditions and the economic aspect. With reference to climate conditions, passive methods such as cooling shelters, wind towers and solar-assisted AC can provide comparable indoor thermal comfort to that resulting from the active ones. However, their economic feasibility proves to be rather low.

Renewal or Addition of Active Technical Systems

Renovation of active technical systems in the building such as space and water heating, space cooling, ventilation and lighting systems together with renewable energy systems is, according to Abdul Hamid et al. [2], one of the most frequently investigated groups of renovation measures. While mechanical ventilation with heat recovery takes the position of the most researched renovation measure regarding ventilation, natural ventilation techniques prove to be poorly examined.

A review of technologies and assemblies for improving energy performance of commercial and institutional buildings' main components, conducted by Ruparathna et al. [40], deals separately with the building envelope, mechanical components and lighting systems. The HVAC system is recognized by the authors as the most energy-consuming component of the building. However, the efficiency of the HVAC system depends on various factors, such as the indoor temperature set point, air infiltration, window type, the window-to-wall ratio and internal loads. Utilizing natural ventilation together with heat and moisture recovery is recognized by the authors of the research as a popular approach for improving the energy efficiency of the HVAC systems. According to some studies [48], proper selection and optimization of the HVAC systems in commercial buildings can provide energy savings up to 25%. Another measure, emphasized by Ruparathna et al. [40], is thermally activated building system (TABS) which uses thermal mass of massive floors and ceilings for heat storage and peak-shifting behaviour. Furthermore, the most frequently used methods to increase the energy efficiency of lighting systems are lamps with higher luminous efficacy, task-based lighting design, daylight-linked lighting systems and occupancy sensors [49].

In addition to the above-mentioned renovation and upgrading of the HVAC and lighting systems, the study by Ferrari and Beccali [41] deals also with installation of a photovoltaic (PV) plant as a renovation measure applied to an office building in Milan. The case study points to the building primary energy reduction achieved via the implementation of a PV plant on the roof and the façades, amounting to 5% of the current rate. Moreover, the research findings denote renovation measures not including the thermal envelope as the most cost-effective. As such, installation of controlled mechanical ventilation systems with heat recovery reduces the primary energy consumption by up to 15%. However, from the economic viewpoint, the implementation of this renovation measure is usually not affordable.

The advantage of technical systems over the building envelope improvement for the energy-saving potential and the potential of the investments targeting renewable energy systems, which figure among the most cost-effective alternatives, was recognized also by Niemelä et al. [50]. Within their research, a cost-optimal energy analysis of deep renovation for typical Finnish apartment buildings was conducted. The findings of the research suggest comparable energy savings when applying cost-optimal renovation measures and those required by the legislation. Special attention was paid to modern heat pump systems which deliver best economic viability and energy performance. Among them, the ground source heat pump proves to be the most globally cost optimal.

Next, a study by Dodoo et al. [18] focusing on a cost-optimal energy analysis of a deep renovation process targeted at typical Swedish apartment buildings, examined renovation measures regarding both, the envelope improvement and the technical system renovation. Among the discussed renovation measures, heat recovery ventilation system and the improved new windows show higher energy efficiency than the improved thermal envelope insulation.

An assessment of renovation measures for three typical industrial halls based on the energy efficiency and renovation budget was conducted by Simson et al. [15]. The renovation measures applied focus on the building envelope insulation and the ventilation system renovation options. The ones involving insulation of the building envelope contribute to energy efficiency but require more than 20-year-long payback periods, which is not economically reasonable. However, conversion of the existing ventilation system into a heat recovery ventilation system and replacing the existing lighting system with the energy efficient one prove to be suitable for all case study buildings. The benefits of introducing a heat recovery ventilation system, particularly in non-residential buildings, are emphasized in other studies [3, 4, 40, 41] as well.

Building Extension

In addition to increasing the level of sustainability of existing buildings, there is also a high requirement for new usable surfaces in urban centres, especially in large central, northern and western European cities [36]. As already discussed in Sect. 2.1, building extension with a structural upgrade module is one of the renovation measures suitable for increasing the energy efficiency of existing buildings and providing usable surfaces at the same time. Therefore, a further level of energy performance renovation can be seen in building extensions which could be considered as one of possible ways of increasing urban density.

The idea is supported by the researchers in Refs. [26, 51], addressing the problem of extensive land consumption due to a lack of available building areas. The advantage of available building spaces such as attics, in particular, can be of assistance in controlling land consumption. According to the research conducted by Puglisi and Invernale [26], up to 18% of projects carried out in the period from 2014 to 2016 in Italy were related to attic reconstruction. According to the research conducted by Pukhkal et al. [51], up to 12.7% of the energy considered for m^2 of the treated floor area can be saved by adding a mansard floor if the building envelope is insulated by adding the appropriate amount of thermal insulation which would retain the total energy need for heating of the existing non-renovated building.

In addition to increasing the existing building's functionality and energy efficiency, the structural upgrade module creates additional vertical load impact on the existing structure, as presented in Fig. 3.18. Due to the prescribed reserve in the load-carrying capacity, as explained in Sect. 3.2.5, the existing structural elements are presumed to be able to overtake this additional load impact. A further literature review and best practice on extending buildings with prefabricated timber structural upgrade modules from the structural point of view will be presented in Sect. 4.2.3. With regard to the limited load-bearing capacity of existing buildings the selection of timber as a construction material for upgrades is particularly suitable, in comparison to other building materials, on account of its low weight, its cost and energy efficiency. According to the research in [52], ¼ of existing buildings in urban centres are strong enough to carry additional storeys made of timber structure, which represents a large potential for building renovation with timber upgrade modules.

In addition to the ever more emerging phenomenon of attic extensions in common practice, the attempts to explore such solutions are recorded in few research studies [53–61]. However, according to Lee et al. [11], there is a lack of design guidelines for energy-efficient upgrades, which is mostly due to the fact that they have to be adjusted to individual buildings and tend to require extensive planning efforts.

An effort to promote lightweight timber building extensions is recorded also within design competitions [52]. A variety of interesting architectural and structural solutions of upgrading existing buildings with lightweight timber structures were developed. However, most of them focused on the design of upgrade modules without previous consideration of the energy efficiency or structural condition of existing buildings.

One of the first studies exploring the possibility of integrating additional floors within energy-efficient building renovation was conducted by Konstantinou and Knaack [53, 54]. Adding floors was only one of the measures considered when developing the so-called toolbox approach, applicable to early stage decision support for renovation projects. An interesting approach towards designing prefabricated modular units with regard to the load-bearing structure of the existing building was developed by Soikkeli [55]. The impact of the location of the load-bearing structure of the existing building was limited by the installation of an array of beams, distributing the load of the modular units over the old structure. Moreover, the installed construction was additionally recognized as a possibility of covering the costs of building renovation. A lightweight attic extension system for Vienna's social housing from the 1950s to 1970s was developed within the research project "Attic Adopt 2050", discussed by Jaksch et al. [56, 57]. The goals of the study were to develop a low-cost timber-based prefabricated system applicable to a great number of buildings of the same type, to create additional living spaces and to increase urban density. The fact that many buildings erected in that period have a similar architectural and constructional design, not only in Vienna but also in other parts of Europe, was considered in the evaluation of the case study building load-bearing capacity. Although an attempt to develop a systematic, energy-efficient solution was made, the impact of the added structure on the energy efficiency of the entire upgraded buildings was not taken into account.

The first complex research focusing on development of timber-glass upgrade modules was conducted by Špegelj et al. [59]. The optimal lightweight timber-glass modules from the viewpoint of energy efficiency in regard to possible geometries of the existing buildings were developed. Variations of the module façade length ratio (a/b) and the three selected net floor areas ($A_1 = 200\ \text{m}^2, A_2 = 400\ \text{m}^2, A_3 = 600\ \text{m}^2$) for single-storey modules with south-oriented glazing were investigated. In the following research [58], four different upgrade modules, covering different shares of the roof of the two case study buildings in the Slovenian town of Velenje, were applied in order to verify their influence on the energy need for heating and cooling of the entire renovated building. The results of the research indicate a positive impact of different upgrade modules on the total energy consumption of the renovated building.

The extension of the presented researches conducted by Špegelj et al. [58, 59], who developed additional two-storey timber-glass upgrade modules of several net floor areas, aspect ratios (a/b), thermal transmission values (U) and glazing sizes (AGAW) applied to three case study buildings of different building types and number of storeys with the aim of designing most optimal solutions, was discussed in the researches [60, 61] which will be further presented in Sect. 4.3.

At the end, it needs to be stressed that the existing literature fails to record compound studies researching the interdisciplinary field of the energy efficiency, functional performance and construction-based renovation which is a basic objective/goal of an optimal solution for a building renovation. The only study involving multidisciplinary approach to structural and energy efficiency analysis of historical buildings was conducted by the authors Ceroni et al. [113]; however, their research work offers no variants of solution to the problem of building renovation. Related facts from the energy points of using such upgrade structural timber-glass modules will be therefore analysed in Sect. 4.3.

4.2 State of the Art—Structural Renovation

Structural renovation of buildings needs to be dealt with in a comprehensive manner, i.e. from the combined viewpoints of architectural, energy-efficient and structural renovation along with the aspect of living comfort. Building renovation often brings about changes in the functional use, which in turn leads to alterations in the imposed load acting on the floor in the sense of additional load impact on the existing load-bearing floor elements. Subsequently, the total building mass also undergoes an increase causing additional vertical load impact on the load-bearing wall elements, while it results on the other hand in increased inertial seismic load. As part of energy efficiency renovation, Sect. 3.2.5 discusses a case of structural upgrade module which increases both the vertical load acting on the existing structure and, as a consequence of the higher mass, the inertial seismic load. Seismic load impact aspect requires acting of the floor element as a horizontal diaphragm evenly distributing inertial loads on the load-bearing wall elements. The latter requirement is not always easily met when renovating old timber floors since the floor elements act rather flexibly on account of the low module of elasticity of timber and due to relatively small floor heights. This is the reason why it is not possible to treat them as stiff diaphragms.

The following course of discussion will therefore be based on separate treatments of the floor strengthening, from the perspective of the increase in the bending load-bearing capacity and stiffness as from that of the horizontal stiffness with the aim of ensuring the acting of the diaphragm stiffness. In addition, we will address strengthening of the wall elements after the event of changing the purpose of the renovated building. As next, the focus will be laid on the structural module upgrade which can substantially increase the vertical load impact on the existing wall elements (Fig. 3.18) and cause significant changes to seismic load impact on the building, as shown in Fig. 3.19.

4.2.1 Strengthening of Floor Elements

The current section discusses only old floors, subject to renovation, which fail to satisfy constructional requirements regarding static resistance to the potentially increased vertical load and call for ensuring the horizontal stiffness of floors as diaphragms to enable evenly distributed transfer of horizontal inertial loads in the case of the seismic load impact. Our detailed analysis goes solely to strengthening old timber floors as it is mainly this type of floor that has the lowest stiffness due to their extremely low modulus of elasticity. Two different methods will be discussed with respect to the strengthening:

– Out-of-plane bending strengthening which increases the bending stiffness against the vertical load impact,

– In-plane strengthening which increases the horizontal diaphragm stiffness in the seismic behaviour.

With the aim of retaining as much of the authentic structural features of the visible strengthened floor element as possible, renovation design of the floor as a composite structural system proves to be the simplest way of increasing the load-bearing capacity and stiffness. The main drawbacks of the original element can be eliminated by adding another construction element that needs to be structurally attached to the basic one. In order to increase the load-bearing capacity and stiffness, two types of structural strengthening will be discussed in the suggested composite structural system manner:

– Strengthening in the compressive zone of the floor element:

  (a) replacing the wooden planks with a concrete slab,
  (b) replacing the wooden planks with a CLT plate.

– Additional strengthening of the floor element in the tensile zone:

  (a) bonding of FRP/CFRP strips to the bottom side of the timber beam,
  (b) adding glazing to the bottom side of the timber beam.

4.2.1.1 Types of Old Timber Floors

Old timber floors can be structurally divided into two large typologies:

(a) Solid timber floor elements, Fig. 4.1a.
(b) Framed floors with load-bearing elements (timber beams) placed at a constant distance and covered with wooden planks. Sound insulation material is inserted between the timber beams, mainly in the form of different fillings, with a purpose of ensuring a certain level of sound insulation, Fig. 4.1b.

High-density and easy-to-install materials were mainly used to insure the highest possible level of sound insulation. According to Kolbitsch [62], materials used for timber roofs filling are mostly (considering the decreasing density):

– Clay with a density of about 1800 kg/m^3,
– Sand and gravel with a density of about 1400 kg/m^3,
– Construction waste (crushed masonry, usually thermically strengthened or burnt) with a density of about 1400 kg/m^3,

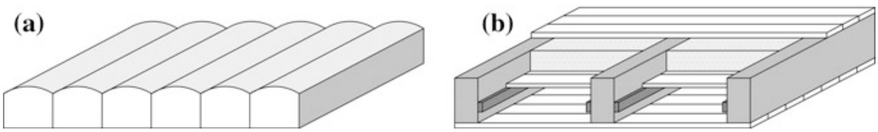


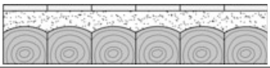
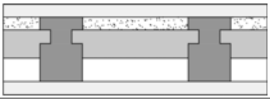
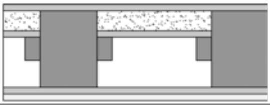
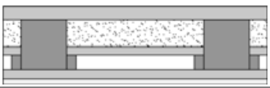
Fig. 4.1 **a** Solid timber floor, **b** timber-framed floor

– Slag (without sulphur) with a density of about 850 kg/m^3,
– Black coal ash with a density of about 750 kg/m^3.

Observed from the purely sound insulation perspective, the main point of adding such fillings is achieving bigger mass, particularly with regard to its percentage in reference to the load-bearing elements. On the other hand, excessive non-load-bearing structure mass increase is an inconvenience in the sense of the building statics as it adds to the vertical load acting on the existing load-bearing elements. The results relevant to different types of load-bearing floors with different fillings are found in Lißner and Rug [63] and presented in Table 4.2.

As obvious from the given data, the weight ratios vary from 20 to 65% with the filling weight surpassing 0.5 kN/m^2 in all variants. Taking modern renovation approaches described in the following chapter parts along with using up-to-date sound-insulating materials, whose density is much lower than in the past, will result in the increased imposed load being at least partially compensated by means of replacing the sound-insulating materials.

Table 4.2 Floor weights and filling weight percentages [63]

Timber floor type	Floor area weight (kN/m^2)	Filling	Filling volume per area usage (m^3/m^2)	Filling area weight (kN/m^2)	Weight percentage of the filling (%)
	2.24	Slug	0.075	0.64	28.5
	2.07	Sand	0.04	0.56	27.1
	2.2	Construction waste	0.046	0.64	29.3
	2.2	Sand	0.062	0.87	39.5
	2.88	Ash	0.078	0.59	20.3
	1.5	Slug	0.079	0.67	44.8
	2.2	Clay	0.079	1.42	64.6

Although timber floors can have random geometric properties, for example, timber joist cross sections differing from a rectangular cross section, Brezar [64] analysed the so-called 4-m syndrome in European buildings, claiming that the most common span of European rooms is 4 m, which is a consequence of different practical criteria such as easy transport or handle ability. Moreover, as pointed out by Brezar [64], the typical timber floor beam cross-sectional dimension is 180 mm × 240 mm with the beam spacing of approximately 900 mm. Unuk et al. [65] therefore numerically analysed such typical old floor elements with the beam quality of C24 where the space between the spacer boards and timber joists is filled with a mixture of sand and gravel, as schematically presented in Fig. 4.2. The wooden flooring is fitted on spacer boards which are oriented perpendicularly to the timber joists and have an axial distance of about 1 m. The function of the lower wooden boards is to simply hold the floor filling in place. The density of the fill (sand and gravel) was chosen to be 1300 kg/m^3. The calculated total imposed load of the timber floor element was 155 kg/m^2.

The obtained results for maximal available imposed load on the timber floor depending on the floor span are graphically presented in Fig. 4.3. The results are presented according to different ultimate (ULS) and serviceability limit states (SLS) criteria prescribed by Eurocode 5 [66]. Furthermore, bending (ULS bending) and shear stress criteria (ULS shear) were respected for the ULS, as well as instantaneous (SLS start) and final deflection (SLS finish) for the SLS.

According to the calculated results, the final deflection criterion proves to be decisive for the beam spans higher than approximately 3.5 m. However, in the case of the 5 m span, for example, the maximal impact load is set at 2.5 kN/m^2, rapidly decreasing with the span, converging to zero already at the height of 6.5 m. This actually means that only the imposed load can be resisted by the floor element in this case. What is more, changing the purpose of the building often encompasses further reconstruction, which usually results in an increased imposed load prescribed by Eurocode 1 [67]. For instance, category C3, defined as an area without obstacles for moving people, has a prescribed imposed load of 5 kN/m^2. Figure 4.3 evidently points out that only floors whose span is lower than approximately 4.2 m can be used in cases where the floor element definitely has to be strengthened to

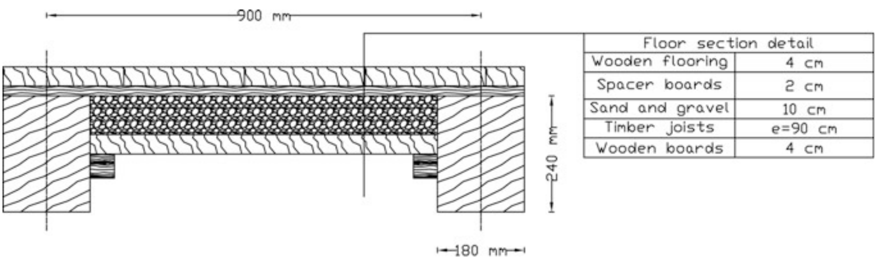


Fig. 4.2 Typical cross section of old floor elements used in the numerical study in Unuk et al. [65]

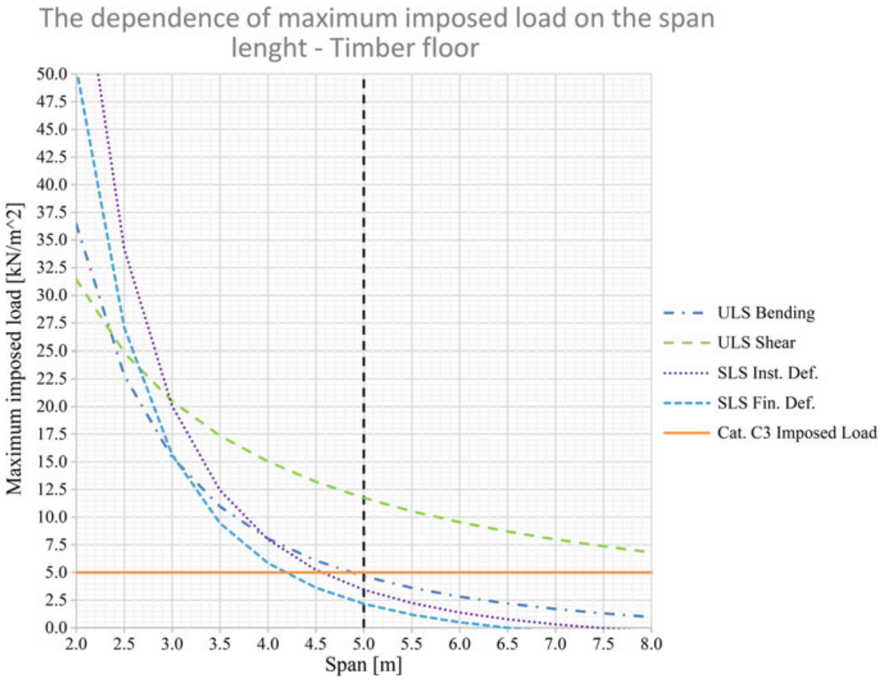


Fig. 4.3 Maximum allowable imposed load depending on the beam span [65]

bear the prescribed imposed load acting at higher existing spans of the roof. Some alternative strengthening methods to enlarge the out-of-plane bending stiffness will be presented in further sections.

4.2.1.2 Out-of-Plane Bending Stiffness Strengthening

The floors in old residential buildings usually consist of timber beams placed in the tensile zone and of timber planks simply connected to the timber beams, Fig. 4.1b. In order to increase the bending and shear resistance of the floor elements, two main successive steps of reconstruction are to be taken and will be further considered, as schematically presented in Fig. 4.4:

– Wooden planks are removed and replaced with a concrete slab or with a cross-laminated timber (CLT) plate.
– Timber beams are additionally reinforced with carbon-fibre-reinforced polymer (CFRP) strips glued to the bottom of the beam.

Firstly, it is necessary to present the basis of such out-of-plane strengthening concepts which will be further theoretically analysed according to the schematical stress distribution in the strengthened timber beam cross section in Fig. 4.4. The timber beam cross section schematically presented in Fig. 4.4 is strengthened:

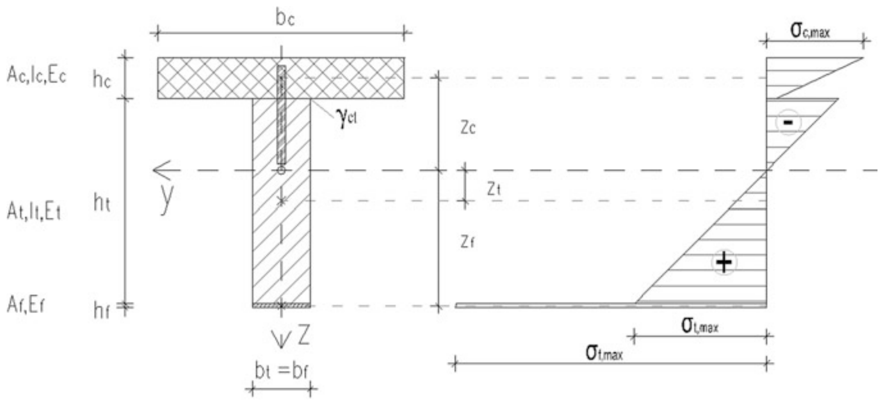


Fig. 4.4 Linear elastic stress distribution in the beam cross section [69]

– In the compressive zone with a concrete or CLT slab to increase the compressive resistance of the beam element,
– In the tensile zone with carbon-fibre-reinforced polymers (CFRP) to increase the tensile resistance of the beam element.

Structural behaviour of timber–concrete/CLT composite members, governed by the shear connection with mechanical fasteners anchored between the timber beam and the concrete/CLT, can be predicted by the elastoplastic model presented by Frangi and Fontana [68] or a simplified elastic model appropriate for everyday engineering practice. For design purposes and the parametric study, a simplified design method for mechanically joint elements according to Annex B of EN 1995-1-1 (2005) (Moehler's formulation) was implemented. In the calculations, care was taken to ensure that the potential tension area in the concrete slab is neglected, according to EN 1995-2 (2004). The expression of the so-called ɣ-method was used in the equations with the following fundamental assumptions:

– Bernoulli's hypothesis is valid for each subcomponent.
– Material behaviour of all subcomponents is linear elastic.
– The distances between the dowels are constant along the beam.
– The slip modulus is taken in the elastic region for the SLS as K_{ser} and in the plastic region for the ULS as K_u.

Respecting all these four assumptions, we assure a linear elastic stress distribution along the vertical axis of the beam cross section with a strong discontinuity in the connecting areas, as schematically presented in Fig. 4.4, and the effective bending stiffness $(EI_y)_{eff}$ of the composite timber–concrete/CLT beam element reinforced with CFRP strips can be written in the approximate form of:

$$(\mathrm{EI_y})_{\mathrm{eff}} = E_c \cdot \left(\frac{h_c^3 \cdot b_c}{12} + \gamma_{ct} \cdot A_c \cdot z_c^2\right) + E_t \cdot \left(\frac{h_t^3 \cdot b_t}{12} + A_t \cdot z_t^2\right) + E_f \cdot \left(A_f \cdot z_f^2\right) \tag{4.1}$$

where γ_{ct} is the stiffness coefficient in the timber–concrete/CLT connecting area, E_t is the modulus of elasticity of timber, E_c is the modulus of elasticity of concrete/CLT, and z_i is the distance from overall neutral axis to the centre of gravity of each subcomponent. E_f and A_f present the modulus of elasticity and a cross section of CFRP strips glued to the bottom side of the existing timber beam in the case of additional tensile strengthening of the existing beam. It is evident from Eq. (4.1) that structural behaviour of the described floor construction importantly depends also on the connection between the timber beam and the concrete slab, i.e. on the fasteners used, which is approximately simulated with the coefficient γ_{ct}. The primary interest of all studies is to increase the bending stiffness which will be further presented by various alternative or consequent steps.

(a) *Out-of-Plane Bending Strengthening with a Concrete Slab*

Using the existing timber floor, we can develop an efficient composite system made of timber members in the tensile zone, a concrete layer in the compression zone and a timber–concrete connection between both the elements, schematically presented in Fig. 4.5. The benefits of such reconstruction–strengthening procedures, sometimes applicable even to newly constructed buildings, are increased stiffness and load-bearing capacity, better sound insulation and fire resistance as well as cost and environment-related advantages gained when the existing supporting timber structure is used as framework [70].

Owing to the negative impact humidity has on the strength of timber, it is of outmost importance to install hydro-isolation in the flat area between the concrete slab and the timber beam in order to prevent humidity invasion from the first to the latter. Afterwards, the timber beam equipped with hydro-isolation undergoes the process of installation of the steel dowels which connect the concrete slab to the

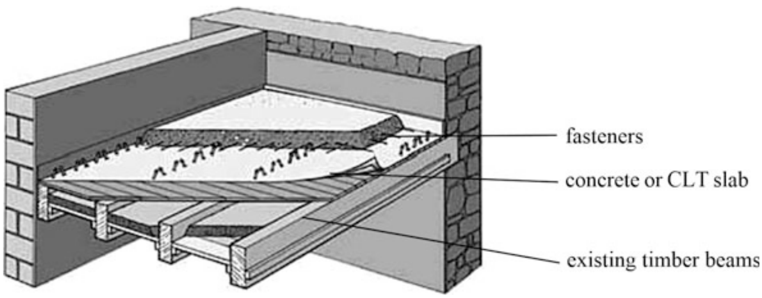


Fig. 4.5 Type of reconstruction of old timber floors with a concrete slab placed in the compressive zone [70]

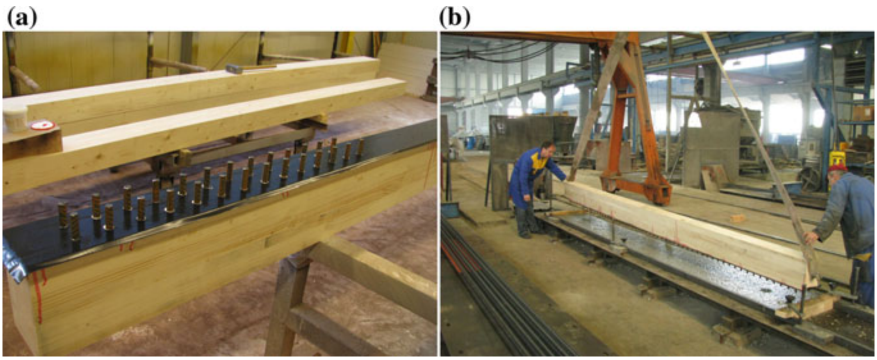


Fig. 4.6 **a** Installation of the steel dowels onto the timber beam and **b** laying of the timber beam onto the concrete slab [70]

timber beam (Fig. 4.6a). Next, a minimum depth of a reinforced concrete slab is poured onto the timber beams with the installed steel dowels by simply laying the timber beam with steel dowels onto the concrete plate (Fig. 4.6b).

Many experiments showed that the use of steel fibre-reinforced concrete (SFRC) instead of a classic concrete displays better characteristics, regardless of the type of fasteners connecting the concrete slab and the timber beam. The experimental study involving the use of steel fibre-reinforced concrete by Holschemacher et al. [71], for example, demonstrated a 27% higher final load-bearing capacity of the fasteners and a few times higher ductility, in comparison with the classically reinforced concrete. Practical examples of this kind of reconstruction procedure performed on the existing timber floor can be found in many European cities (e.g. Leipzig and Tübingen), as presented by Kenel [72], Holschemacher et al. [71] and Schanzlin [73].

In a sense to analyse the load-bearing capacity increase depending on the concrete slab, the existing timber beam from Fig. 4.2 is upgraded with the concrete slab of quality C20 according to the Eurocode 2 [74], schematically presented in Fig. 4.7. The existing wooden planks in the upper zone are removed and substituted with the concrete slab of a thickness of 50 mm. Moreover, the existing sand and gravel filling between the timber beams is removed and replaced with an additional

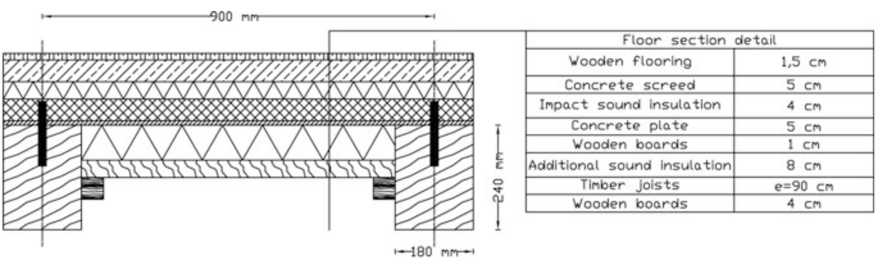


Fig. 4.7 Existing timber beam strengthened with the concrete slab [65]

sound insulation layer. The area mass of such strengthened floor is now approximately 283 kg/m^2. The mechanical connectors between the concrete and timber part are steel dowels with a diameter of 20 mm and a spacing of 10 cm. The connectors were only used for stiffness calculations and were not structurally checked. The calculations were performed in compliance with the so-called gamma method from Annex B of Eurocode 5 [66].

Two different ULS bending criteria are considered in the numerical procedure, one before creep and one after creep (of both materials). The ULS criteria depend only on timber strength, as the calculation showed that the concrete compression strength is never exceeded. The concrete tensile strength is neglected in the calculation procedure, i.e. considered to be zero; therefore, it is estimated that the concrete slab fails under the maximal tensile stress. The uncracked concrete height was calculated iteratively (if the first step of the calculation showed tensile stresses in the concrete plate). The new height or uncracked section height is used to recalculate the floor bending stiffness of each iteration step, although γ, the coefficient of composite action between both materials according to Eq. (4.1), is calculated only for the uncracked concrete height. The obtained numerical results for the maximal available imposed load depending on the beam span are graphically presented in Fig. 4.8.

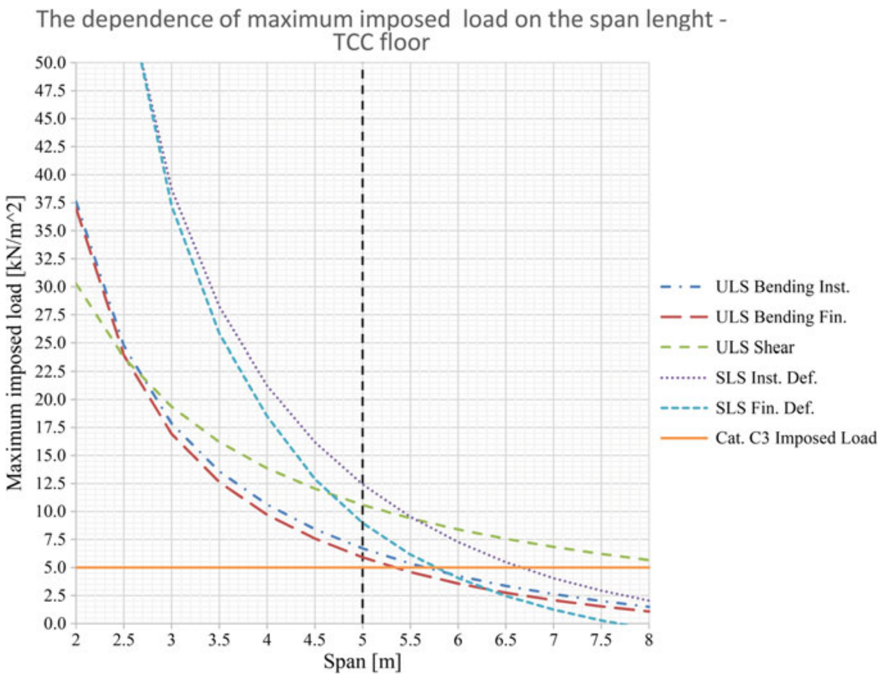


Fig. 4.8 Maximum allowable imposed load depending on the beam span for timber–concrete composite floor element [65]

It is obvious from the given results that in contradiction to the non-composite floor element (Fig. 4.3), the ULS bending stress criteria are decisive, except for the spans bigger than 6.5 m. The unstrengthened element was considered within the SLS criteria. The fact that the failure criteria have been changed in comparison to the non-strengthened floor element can be attributed to the fact that by using the concrete slab, the flexural stiffness according to Eq. (4.1) is essentially increased. Taking under observation only the values for the maximal possible imposed load, we can detect that the values compared with the unstrengthened samples (Fig. 4.3) essentially increased. For example, the value reached 2.5 kN/m^2 for the span of 5 m (Fig. 4.3), with the present value of approximately 6.0 kN/m^2 for the strengthened samples (Fig. 4.8). Moreover, it can be detected that the maximal possible span is not increased in the same manner. For instance, by considering the strengthened element in residential buildings, it is possible to reach a span of about 6.7 m with the imposed load of 2 kN/m^2, prescribed by Eurocode 1 [67]. With the unstrengthened sample, however, the span of about 5.2 m is attained, Fig. 4.3. In the case of the C3 building category of Eurocode 1 [67] with the prescribed imposed load of 5 kN/m^2, it is possible to reach the span of 5.3 m with the strengthened element, while the unstrengthened sample results in only a 4.2 m span. Hence, it can be concluded that the bending resistance of the composite floor is limited by the timber strength or timber height, as the concrete compression strength is not even nearly exceeded. This is a consequence of the concrete slab only stiffening the compression zone of the composite section and having no influence on the tensile resistance which primarily depends on the timber beam tensile resistance. As the timber strength or height cannot be increased to obtain better results in the sense of bending resistance, it is necessary to additionally strengthen the tensile zone of the timber beam. This solution will be presented through the method of reinforcement with the CFRP strips (strengthening case c) glued to the bottom side of the existing timber beam.

Until now, only the influence of the concrete slab on the load-bearing capacity and the bending stiffness was discussed. However, it is important to consider also the positive influence of the concrete slab on the sound and fire resistance of the floor element. The latter will not be analysed at this stage, but it can be found in Kaufmann et al. [75] who suggest that the sound resistance, in particular, can be essentially improved by using the concrete slab instead of the removed wooden planks in the upper area of the floor element.

(b) *Out-of-Plane Bending Strengthening with a Cross-laminated Timber (CLT) Panel*

Another possibility to improve the bending resistance of a timber floor element in a sense of increasing the compressive resistance of a cross section is seen in inserting a CLT panel instead of the removed wooden boards, as schematically presented in Fig. 4.5, with a difference of using CLT instead of concrete. Such solution is treated as a less invasive approach into the existing floor structure, with another advantage—that of a better CO_2 footprint. Respecting Eq. (4.1) and similar to the case with the concrete slab, the increasing of the available bending resistance strongly depends on the connection between the CLT plate and the timber beam and has the same limitations as the out-of-plane bending strengthening approach. The reason lies in the fact that the tensile resistance of the composite floor element does not increase if no additional reinforcement is placed in the tensile zone of the beam.

This strengthening solution is comparable to the previously described method with the concrete slab; however, there are still some important differences in a view of structural, building physic and ecological aspects:

– Additional mass in this method is essentially lower on account of the lower density of CLT ($\rho \approx 500$–$600\ \mathrm{kg/m^3}$) according to the concrete slab ($\rho \approx 2500\ \mathrm{kg/m^3}$).
– Sound resistance is essentially higher in the model involving the concrete slab [75].
– CO_2 storage is better in the example of the CLT panels [75].

The existing floor element from Fig. 4.7 is now analysed for the proceeding of strengthening with the 60-mm CLT panel with, as schematically presented in Fig. 4.9. Other components have the same dimensions and material characteristics as in the case with the concrete slab strengthening.

Numerical results using the same calculation approach as for the 50-mm-thick concrete slab are graphically presented in Fig. 4.10. A difference to point out is seen in the considered imposed load being essentially lower, 1.8 kN/m^2, in comparison to the value associated with the concrete slab, 2.8 kN/m^2. Both, the Ultimate and the serviceability limit state conditions, according to the Eurocode 5 [66], were considered to prescribe the limits.

In comparison with the concrete slab graph (Fig. 4.8), the results observed for the CLT plate are better and demonstrate higher allowable imposed load acting on the strengthened floor. For example, the maximal allowable imposed load with a 5 m span is 6 kN/m^2 for the concrete slab and approximately 7.5 kN/m^2 for the CLT panel. The maximal allowable floor span for residential buildings with the prescribed imposed load of 2 kN/m^2 is 6.6 m when using the concrete slab or 7.2 m when the floor is strengthened with the CLT panel instead of the concrete slab.

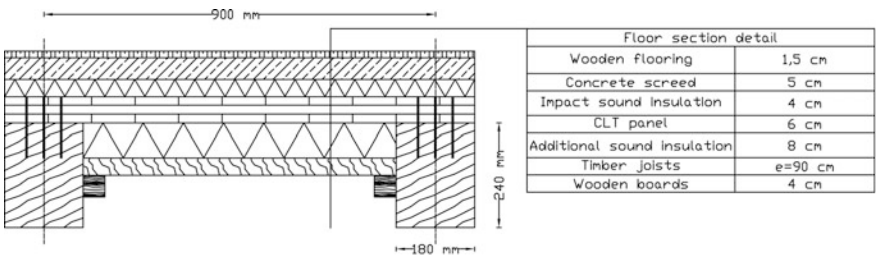


Fig. 4.9 Existing timber beam strengthened with the CLT panel [76]

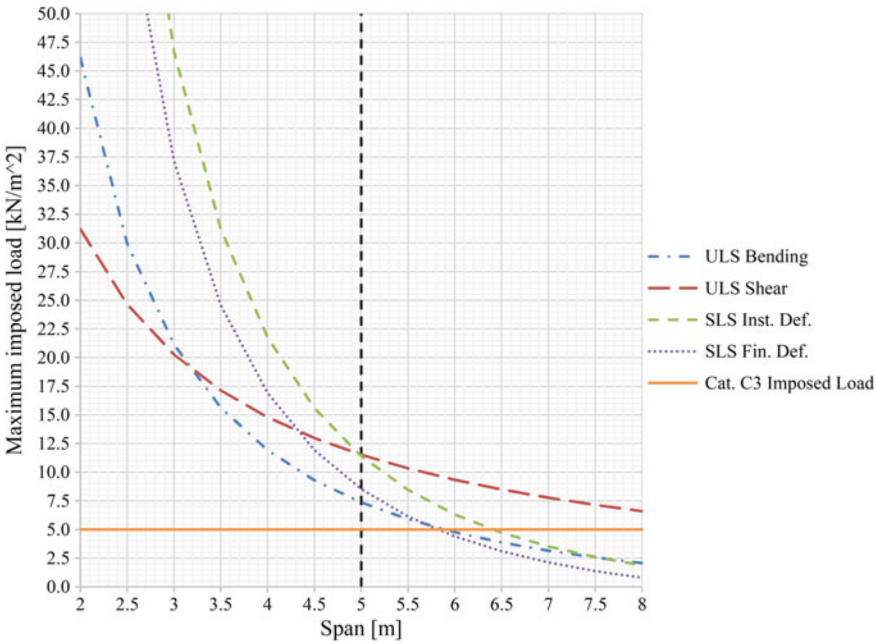


Fig. 4.10 Maximum allowable imposed load depending on the beam span for the timber–concrete composite floor element [76]

(c) *Out-of-Plane Bending Strengthening with CFRP Strips*

As presented in (a) and (b), there are limitations as to increasing the bending resistance of a refurbished composite floor element with a concrete or a CLT slab when the tensile failure mechanism appears. Consequently, in such cases, it is necessary to additionally increase the tensile resistance of the existing timber element which can be performed with different solutions:

- By inserting classic steel strips or bars to the bottom surface of the existing timber beam,
- By inserting fibre-reinforced (FRP), carbon-fibre-reinforced (CFRP) or glass fibre-reinforced (GFRP) polymers glued to the bottom surface of the timber beam, as schematically presented in Fig. 4.11.

It is well known that the materials chosen for reconstruction (concrete, CFRP strips and the adhesive) are less eco-friendly than timber. A particularly adverse effect is observed in the exposure to the CFRP and the dust due to ageing in the closed space, which may be seriously harmful to the user of the building. According to the given facts, the strengthened floor elements are thus less eco-friendly than the original elements with timber planks; nevertheless, with such subsequent preservation of the timber beams, we still can keep the original features of the building. Another drawback is a currently rather high cost of employing CFRP, in

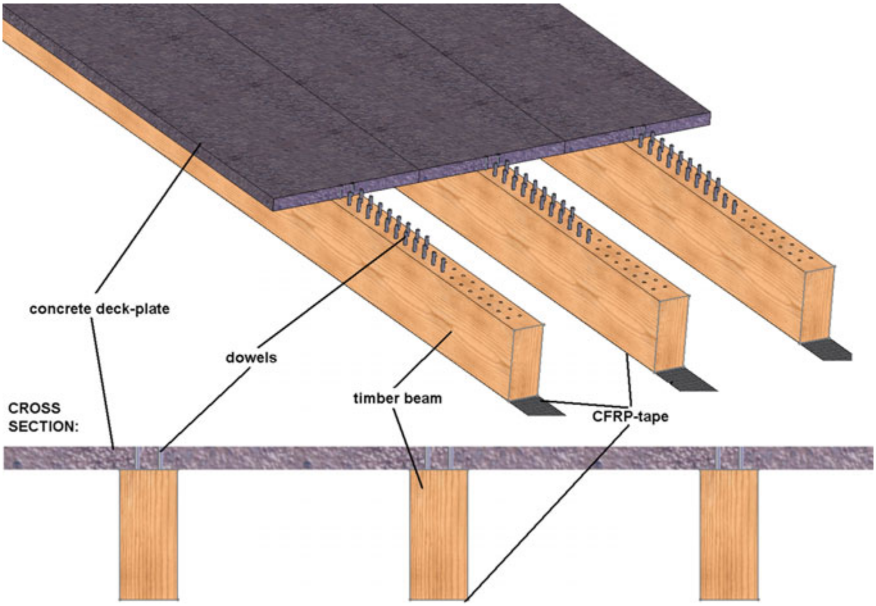


Fig. 4.11 Types of reconstruction of old timber floors with a concrete slab and additionally with CFRP strips [70]

comparison with other strengthening materials such as steel bars or strips. However, the main advantage of using CFRP strips, compared to other optional case-relevant materials of strengthening (e.g. steel plates), is their corrosion resistance, in addition to lightweight and flexibility which allow for convenient and easy transport to the place of erection. Continuously decreasing prices of these materials make the new technology more economical and interesting. Therefore, the use of CFRP for repair and strengthening of timber elements opens new perspectives regarding timber structures design [70].

There are many available experimental as well as numerical studies concerning the influence of FRP or CFRP strengthening on timber beam bending load-bearing capacity and stiffness, carried out by Dagher and Breton [77], Johns and Lacroix [78], Johns and Racin [79], Bergmeister and Luggin [80], Kent and Tingley [81], Dourado et al. [82]. Stevens and Criner [83] additionally conducted an economic analysis of fibre-reinforced polymer (FRP) glulam beams. The results showed practical applicability of FRP reinforced elements, especially to bridges of greater spans, where beam dimensions can be substantially reduced using the FRP solution presented. The above-mentioned FRP elements can also be adopted for the renovation process of strengthening in old buildings. An extended state of the art of such further studies on strengthening interventions on timber floors is presented in Franke et al. [84] and Gubana [85].

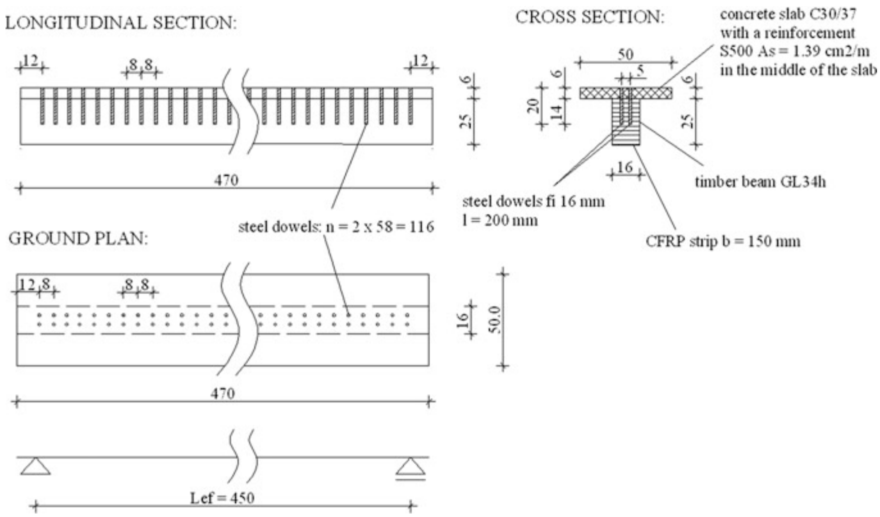


Fig. 4.12 Geometry of the test samples for the experimental study [70]

As next, the results of our experimental study will be presented along with the extended parametric numerical analysis on reinforcing laminated timber beams with CFRP strips. For the purpose of *experiments*, the beams were strengthened in the compressive zone with reinforced 60-mm-thick concrete slabs, schematically presented in Fig. 4.12. The production of the tested beams was performed in three successive steps [70]:

(a) Production of the glulam beam of the GL34h quality with a constant height of h_t = 250 mm and a width of b_t = 160 mm, drilling of holes for the dowels, gluing of the hydro-insulation and insertion of the steel dowels of diameter d = 16 mm into the timber beam. The dowels were placed in two parallel rows at a distance of 50 mm between the rows, Fig. 4.12.
(b) A concrete slab of a constant thickness of h_c = 60 mm and compressive strength of 30 MPa with a reinforcement S500 placed in the centre of the slab and with a minimum cross section of A_s = 1.39 cm^2/m was produced. The timber beam with steel dowels was simply laid onto the concrete slab.
(c) Finally, the CFRP strips with a thickness of 1.2 mm and a width of 150 mm, constant along the length of the tested beam, were glued to the bottom side of the timber beam, Fig. 4.12.

The values for the CFRP strips of Sika CarboDur-H514 are taken from [86]. According to the schematically presented stress distribution in Fig. 4.4 and proven by the experiments, the failure of the timber beam in tension is finally decisive as the first failure step, which is significant for such reinforcement cases. Figure 4.13 shows steps of one of the specimen's failures where the first evident failure was that of the timber beam, followed by the failure of the CFRP reinforcement and finally

Fig. 4.13 Tensile failure of the timber beam (**a**), failure of the CFRP reinforcement (**b**) and the total failure of the specimen (**c**)

by the total failure of the specimen—that of the concrete slab—which classifies the failure as brittle, i.e. non-ductile failure. The fasteners, i.e. the connection between the concrete slab and the timber beam, were not at risk, according to expectations.

These findings are highly relevant to the designers' decision and their preference for non-ductile bending failure in the tensile area of the timber beam or the ductile—yielding failure of the fasteners.

The experimental analysis was at the same time supported with a wide *numerical approach* presented in Tajnik et al. [69] and based on the theoretical facts (Eq. 4.1) as well as on stress distribution in Fig. 4.4. There were also various parameters checked with the influence on the bending resistance and the bending stiffness. The results of the influence of the beam height (ht) and the dowel spacing on the bending stiffness are graphically presented in Fig. 4.14.

According to Fig. 4.14b, it can be deduced that the effective bending stiffness $(EI)_{ef,sls}$ of a composed section decreases with the increase in the dowel spacing, where the contribution of CFRP is on average 14% higher for the instantaneous bending stiffness and 21% higher for the final bending stiffness. Extensive numerical parametric analyses including variations regarding timber quality, the height of the timber beam and the installation of the fasteners in the connection show that the contribution of the CFRP strips in the form of additional CFRP strengthening results in improving the bending resistance up to 26% and in the bending stiffness up to 18% [69].

Hence, it is obvious that these strengthening concepts have the ability to essentially increase the load-bearing capacity (ULS condition) while not reaching a similar increase range relative to the bending stiffness (SLS condition). The reason for that lies in the fact that CFRP strips have a very high tensile strength which is decisive for the bending resistance increase. On the other hand, given the fact that the modulus of elasticity is not much higher than that of steel, and having in mind that the thickness of the CFRP strip is rather low (1.2 mm), along with respect to Eq. (4.1), the influence on the effective bending stiffness $(EI_y)_{eff}$ of the composite timber–concrete/CLT beam element is not so obvious. In this case, the influence of

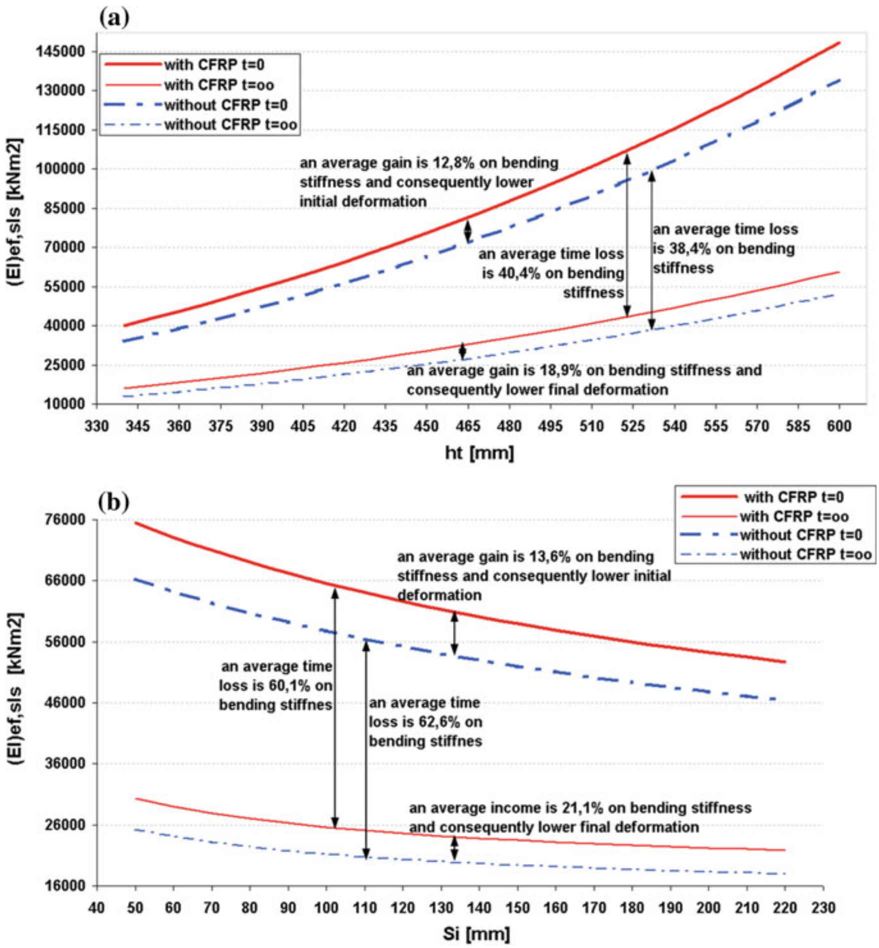


Fig. 4.14 **a** Influence of a variable depth of the timber beam on the bending stiffness and **b** influence of a variable dowel spacing on the bending stiffness [69]

the concrete slab in the floor compressive area is more evident. However, it is important to underline that this type of strengthening with CFRP strips is suitable for composite beams in zones where the bending moment exceeds the ultimate moment of resistance of an unstrengthened beam.

The presented experimental and numerical studies lead to a final conclusion that the composite floor system, consisting of the concrete slab and the timber beam reinforced with CFRP means a highly interesting potential way of increasing the bending resistance of old timber floors in the future. At the same time, this method preserves the original features of the existing buildings.

4.2.1.3 In-Plane Stiffness Floor Strengthening

It is important to stress that besides the previously analysed vertical behaviour of floor structures, the horizontal stiffness of floor structures also proves to be of utmost importance. The horizontal building components should namely behave as stiff horizontal diaphragms able to transfer the horizontal actions of load (wind or earthquake) to the vertical resisting elements (walls) and finally to the basement. Thus, an assumption that the floor and roof elements behave as stiff horizontal elements in their planes is very important for the performed calculation procedures and therefore presents a major adopted boundary condition. The procedure of the horizontal in-plane load transfer is schematically presented in Fig. 4.15.

In cases where timber floors do not behave as rigid horizontal diaphragms (or diaphragms at all), the horizontal load is not equally transferred to the resisting wall elements. Therefore, the walls under horizontal action receive different load impact, and if this load action exceeds their load-bearing capacity, the walls usually fail to have sufficient strength for the forces acting perpendicularly to the wall plane and finally they collapse. As schematically presented in Fig. 4.16, different collapse or overturning modes are possible [87].

However, in the case of old masonry or timber buildings, mostly containing old timber floors, the assumption of rigid floor diaphragms is too optimistic and cannot be adopted at all. Consequently, it is usually needed to propose an in-plane stiffness upgrade of old timber floors. In fact, the eurocodes and many other national codes do not provide any guidance on the strengthening intervention design to be applied to existing masonry buildings damaged by earthquakes, especially when it comes to strengthening of in-plane floor elements. A few codes do in fact propose simplified analytical procedures to determine the in-plane stiffness but in a more general sense, with regard to new timber building floor typologies and not for the process of strengthening old building floors [85].

One of the first documents to propose the in-plane stiffness upgrade of timber floors by means of timber elements was produced by the local authority of

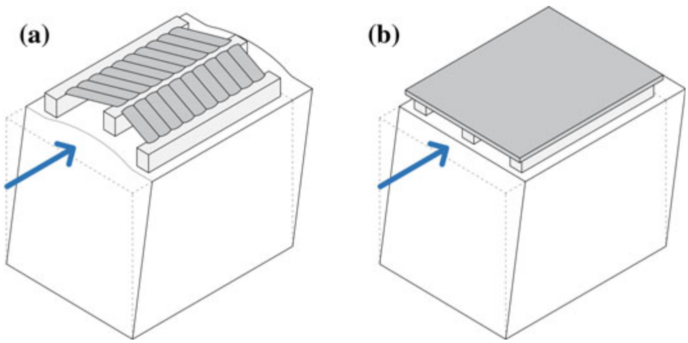


Fig. 4.15 Schematical presentation of a roof (**a**) and floor (**b**) in-plane behaviour as rigid horizontal diaphragms [87]

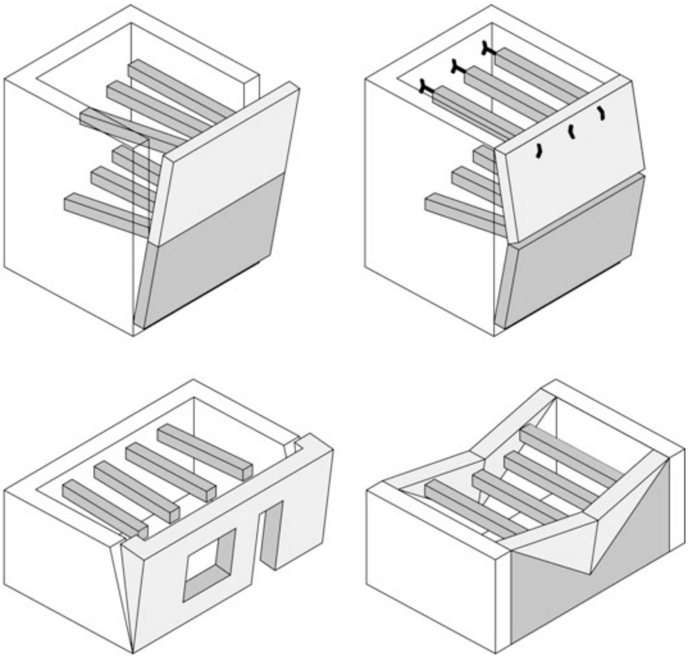


Fig. 4.16 Wall overturning modes due to inadequate stiffness of the floor [87]

Friuli-Venezia Giulia Region, Italy, after the 1976 earthquake [88]. The suggested technique consisted of superposing a second layer of floorboards over the existing one but laid in the orthogonal direction, as schematically also presented in Fig. 4.17b. This alternative strengthening solution, probably the simplest technique from the technological viewpoint, was commonly and widely used in ancient buildings in the earthquake-prone areas of the region [85].

Regarding the previously described and thoroughly analysed facts about out-of-plane stiffness upgrading of old timber floors, similar strategies of strengthening can generally be adapted also to the in-plane behaviour, provided we respect some important modifications. For instance, a local increase of stiffness which may be acceptable in static situations, predominantly for the vertical load, is most often associated with a reduction of ductility which is a fundamental property in seismic design [89]. This type of situation with a simultaneous static stiffness increase and ductility decrease was presented also in our previous study on out-of-plane floor reinforcement with CFRP strips. Recent research programmes have proposed various solutions particularly in view of improving the in-plane behaviour of old timber floors. Besides the addition of a concrete slab (Fig. 4.17e), or that of a timber slab in the cross-wise direction (Fig. 4.17b), the application of a lattice of FRP tapes or metal bands has been examined (Fig. 4.17c) in order to increase the stiffness without excessive material addition [89].

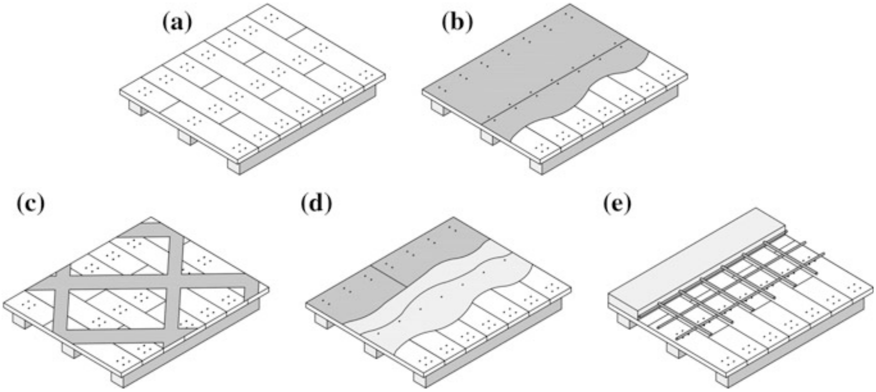


Fig. 4.17 Different timber floor in-plane shear strengthening techniques: **a** existing simple layer of wood planks on the timber beams; **b** second layer of wood planks crossly arranged to the existing one and fixed by means of steel studs; **c** diagonal bracing of the existing wood planks by means of light steel plates or FRP laminate; **d** three layers of plywood panels glued onto the existing wood planks and **e** a stud-connected reinforced concrete slab. Adapted from Piazza et al. [87]

Generally, there are different ways of strengthening upgrade of old timber floors in the horizontal plane. Figure 4.17 is a schematic presentation of some alternative solutions whose basic idea is to obtain a stiff "diagonal horizontal model" which will be able to transfer horizontal loads to the vertical resisting elements, which means that an adequate connection of floor elements to the resisting walls should be performed. The horizontal resisting diagonals can be treated as fictive in cases of boards or concrete slabs strengthening, Fig. 4.17b, d and e, or as real existing elements with inserted diagonal steel or CFRP strips, Fig. 4.17c.

However, it is important to underline that some of these measures are only conditionally useful in practice. One of the least recommendable measures is the replacement of timber floors with reinforced concrete slabs and installing reinforced concrete ties into the masonry, as the higher mass and higher stiffness may produce a negative impact on the building [90]. The problem is the already mentioned connection of the new reinforced concrete elements with the old masonry resisting walls. As Tomaževič [91] claims, it is necessary to ensure monolithic behaviour of the old masonry walls for a successful use of reinforced concrete elements. The same problem is pointed out also in Gubana [85], where the author discusses the in-plane strengthening approach and attributes utmost importance to joining the added floorboards and the joists with walls in cases of adding just a second layer of the floorboards, Fig. 4.15b. Accordingly, a series of full-scale tests to measure experimental in-plane stiffness is described by Valluzzi et al. [92, 93].

4.2.2 *Strengthening of Wall Elements*

Generally, there are different ways of strengthening upgrade of old wall elements with a view to simultaneously increasing the resistance against vertical and horizontal loads. An increase in the vertical load acting on the existing wall elements within the process of building renovation is rare, appearing only if the purpose of the building is changed or when some the existing load-bearing wall elements are partly removed, all of which could subsequently lead to the rest of vertical actions acting on the remaining wall elements.

However, the situation is more problematic in the case of horizontal load actions acting on the renovated building (wind and earthquake). Consequently, it is important to mention that most of the existing old buildings are not dimensioned for seismic actions. Furthermore, if the purpose of the building is changed and the prescribed imposed load consequently increases, the total mass of the building is higher and results in an enlarged inertial seismic force action on the structure. A necessary step worth underlining would then be to improve the horizontal resistance of the whole structure under renovation process which is a common reconstruction process of in-plane strengthening upgrade of floor elements. The aim is to enable the floor elements to transfer horizontal forces to the resisting wall elements which have to undergo a horizontal resisting upgrade. The in-plane strengthening upgrade of floors was already discussed in Sect. 4.2.1; hence, in this stage, we will focus on the racking resistance upgrade of walls.

The strengthening process due to load impact increasing is schematically presented in Fig. 4.18. Similar to the in-plane floor strengthening concepts, already presented in Fig. 4.17, the basic idea is to obtain a stiff "diagonal horizontal model", now placed in the vertical plane, which will be able to transfer the horizontal loads from the floors to the basement. An adequate connection of the strengthened floor elements to the resisting walls should therefore be performed, followed by the process of connecting the strengthened walls to the basement, as presented in Fig. 4.18. Again, these horizontal resisting diagonals can be treated as fictive in cases of board or panel strengthening or as real existing elements with inserted diagonal steel or CFRP strips. In Fig. 4.18, the blue colour marks the existing force stage in the resisting wall element before the renovation process takes place, while the colour of red denotes additional load impact due to the increased horizontal load.

Basically, two types of old load-bearing wall elements have to be strengthened: masonry wall elements and old timber wall elements, especially timber-framed ones. Both types will be briefly discussed in the following section.

4.2.2.1 Strengthening of Masonry Wall Elements

There are many different concepts of seismic strengthening of old masonry wall elements with a view to increasing the existing horizontal resistance, as presented in

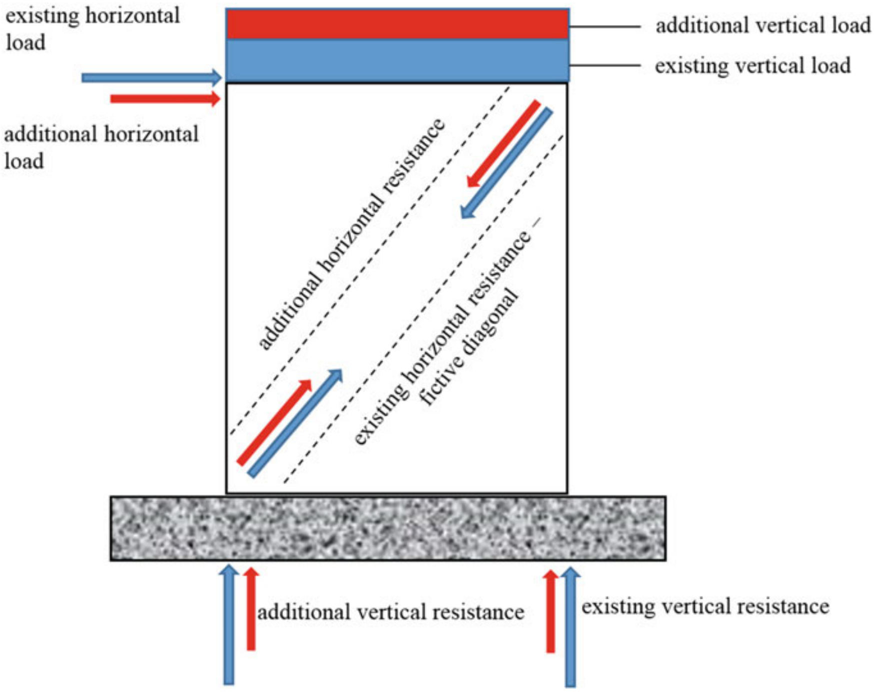


Fig. 4.18 Basic strengthening concept of wall elements

Fig. 4.18. However, the existing scientific literature lacks interdisciplinary studies on earthquake-resistant design, i.e. on various strengthening measures to be taken on masonry wall elements when we wish to remove some of the vertical load-bearing elements or increase the glazing size in the south-oriented façade to achieve better living comfort and higher transparency of the living spaces. Applying strengthening methods to satisfy the above-mentioned aims consequently increases loads on the existing load-bearing wall elements that need to undergo adequate construction-based renovation. Such influences are treated separately, e.g. as a general influence of torsion due to the floor plan asymmetry in the consequent asymmetrical positioning of the load-bearing wall elements, which is often a result of the previously mentioned removal of load-bearing wall elements or installing the non-resisting glass panes [94, 95].

The field of masonry buildings, including both brick- and stone masonry, provides a relatively well-developed area in the sense of modelling seismic response in the existing state [96–98] or when it comes to technological implementation of strengthening measures which need to be applied after the removal of individual load-bearing elements [99, 100]. Brick-masonry wall elements offer multiple possibilities of strengthening:

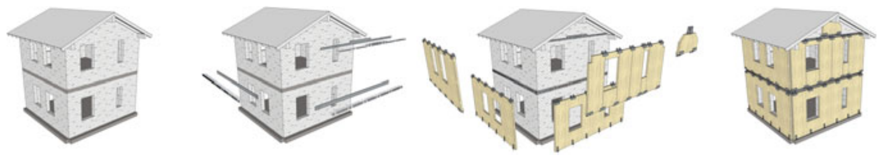


Fig. 4.19 Strengthening concept using CLT plates simply fixed to the existing wall elements [102]

– Replacement of individual walls with new reinforced concrete frames and installation of cross-beams above newly formed openings along with strengthening the existing walls with reinforced concrete cladding or composite stripes.
– The most suitable measure to be taken in stone masonry seems to be systematic injecting of a proper injection mixture type. Moreover, for the purpose of increasing the stiffness, the mentioned procedure usually needs to be applied simultaneously with that of in-plane strengthening of the existing floor elements, which was already analysed in Sect. 4.2.1.
– A most useful recently developed procedure involves external strengthening of the thermal envelope walls with prefabricated CLT façade elements which are easily attached to the existing wall-bearing structure [101, 102]. The latter is a highly practical strengthening system and the only known method of structural strengthening with simultaneous increase in the thermal properties of the renovated external wall element. With an additional CLT panel fixed to the existing wall, according to Fig. 4.18, an additional diagonal racking force can be assured which increases the racking resistance of the refurbished wall element. The process of strengthening is schematically presented in Fig. 4.19. Based on experiments and a numerical study, Šušteršič [102] proved that the racking resistance of such strengthened masonry wall can be increased by even 34%.

4.2.2.2 Strengthening of Timber-Framed Wall Elements

There is a fairly wide range of different concepts of strengthening existing timber-framed walls which mostly function as the main resisting vertical elements in prefabricated frame-panel building. As schematically presented in Fig. 4.18, it is of utmost importance to increase the racking resistance of prefabricated wall elements if the horizontal load impact on the wall element is increased. Timber-framed wall elements are thoroughly presented in Sect. 3.2.3.4 in Žegarac Leskovar and Premrov [103], whose analysis supported by experimental and numerical studies shows that the fibre-plaster boards tend to be "a weaker part" of the presented composite wall system on account of their tensile strength which is essentially lower than the strength of the timber frame. Thus, a problem of cracks appearing in fibre-plaster boards, especially in multi-storey buildings located in seismic or windy areas, may occur. Such inconvenience can also be relevant to the building renovation process if the horizontal load impact due to several previously described reasons increases. Stresses in the timber frame under horizontal load are not usually critical. The same is true of walls sheathed with oriented-strand boards (OSB) as they produce essentially higher horizontal load-bearing capacity, as presented in Žegarac Leskovar and Premrov [103].

Respecting stress distribution due to a horizontal point load action at the top of the wall (Fig. 4.18), there are several possibilities for producers to strengthen panel walls in order to increase the resistance of the tensile board diagonal:

- By using additional fibre boards,
- By reinforcing boards with steel diagonals elements,
- By reinforcing fibre-plaster boards with externally glued CFRP or FRP strips.

(a) *Additional Fibre Boards*

This is the simplest reinforcement solution and thus very popular with producers. Any influence of the added boards strongly depends on the stiffness coefficient of the fasteners (γ) Eq. (4.1) connecting the boards and attaching those to the timber frame. However, in an extended experimental study, Dobrila and Premrov [104] point out that the process of strengthening the horizontal stiffness and the elastic load-bearing capacity prior to the event of any cracks appearing in the boards can result in both being essentially improved, while the final bearing capacity fails to see improvement in the desired range.

Moreover, the ductility even decreases. The results of the experiments are shown in Fig. 4.21, test sample G3*.

(b) *Steel Diagonal Reinforcement*

In the treated composite system of panel walls, the aim is to reinforce fibre-plaster boards. There is no need to reinforce the timber frame as its tensile strength is essentially greater than that of fibre-plaster boards. Inserting steel diagonal elements can be labelled as a “classic” reinforcing method in order to assure the essential increase in the resistance and, especially, in the ductility of the wall elements, which is not achieved when applying additional boards. As already mentioned in reference to similar cases of floor strengthening, it is very important to fix the diagonals to the timber frame. Thereby, only a part of the horizontal force is shifted from the fibre board to the tensile steel diagonal and consequently to the timber frame after the appearance of the first crack in the board.

An example of fixing such reinforced element with diagonals to the timber stud and additionally to the bottom floor element on the erected six-storey prefabricated frame-panel building in Dobrava, Zreče, Pohorje mountain, Slovenia, is presented in Fig. 4.20. The first storey of the four-storey timber part of the building was reinforced within this concept to assure the horizontal stability of the entire building [105]. However, since a special hole has to be made in each timber corner in order to place the diagonals and the boards in the same plane followed by the strips being nail-fastened to the timber elements, this type of reinforcing is technologically rather time-consuming but provides the highest range of ductility. Experimental

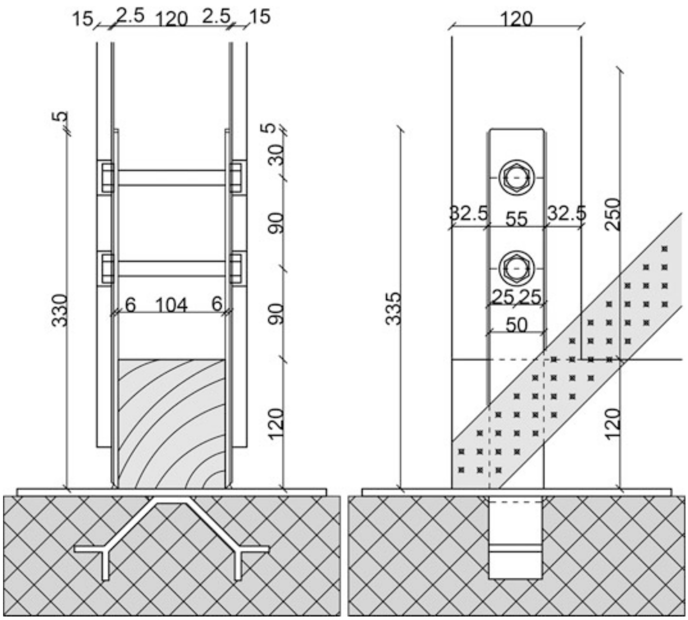


Fig. 4.20 Connection of the steel diagonal elements to the timber frame and to the bottom floor

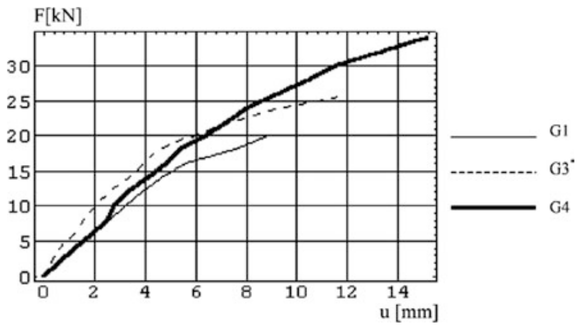


Fig. 4.21 Measured average horizontal displacements at the top of the wall elements [104]

tests [104] Fig. 4.21, test samples G4, proved that the cracks in the reinforced panels are scarcely perceivable and disappear after the action of the short-term load.

The measured values from Fig. 4.21 evidently show that the samples from group G4 (diagonally reinforced panels) demonstrate a less essential increase (by 26.28%) in the force forming the first crack in the fibreboard than the G3* samples (35.71%) with additional boards. However, as predicted, steel diagonal reinforced test samples point to a significant increase in the destruction force (by 77.58%) and the consequent essentially higher ductility.

(c) *CFRP Diagonal Reinforcement*

This is a very similar strengthening approach to that already presented in the case of timber floors. Owing to the time-consuming nature of the previously presented technological concept involving classic steel diagonal strips, we tried to find another, a more practical solution to strengthening the fibre-plaster boards, especially when bigger-sized buildings with the consequently higher number of prefabricated wall elements are concerned. In the case of timber-framed walls with additional fibre-plaster boards, the strengthening concept is seen in the contribution of the composites (CFRP) which take the tensile stresses when the tensile strength of the fibre-plaster boards is exceeded. An extended experimental study performed on timber-framed wall test samples with the same dimensions as in cases (a) and (b) was performed by Premrov et al. [106] and later numerically upgraded by a purposely developed mathematical model using a modified γ-method [107]. In order to analyse also the previously described important influence of the connection between the sheathing boards and the timber frame, three different groups of strengthened test samples were tested:

- The first group (G1) was additionally reinforced with two 300-mm-wide CFRP diagonal strips (one in each FPB) which were glued on the FPB using Sikadur-330 LVP. The strips were additionally glued to the timber frame to ensure the transmission of the force from FPB to the timber frame.
- The second group (G2) was additionally reinforced with two 600-mm-wide CFRP diagonal strips. The strips were glued on FPB and to the timber frame as in G1 to ensure the transmission of the force from FPB to the timber frame.
- The third group (G3) was additionally reinforced with two 300-mm-wide CFRP diagonal strips as in G1, but they were not glued to the timber frame.

Figure 4.22 presents average values of the measured results for all three CFRP strengthened test sample groups as well as for the unstrengthened testing group.

It is evident that the elastic resistance (force forming the first crack) essentially increased for all kinds of CFRP strengthened test samples, but mostly for samples G3, where the CFRP strips were not fixed to the timber frame. The CFRP influence

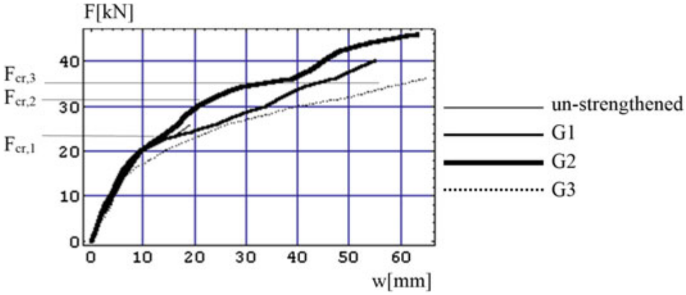


Fig. 4.22 Measured average horizontal displacements at the top of the wall elements for CFRP strengthened test samples [106]

was not so obvious in samples G1 where carbon strips of the same dimensions were additionally glued to the timber frame. When comparing samples G1 and G2, the influence of strengthening definitely depends on the width of the inserted diagonal strips. An interesting observation relevant to all groups of test samples is that the cracks dispersed before they reached the CFRP strips and did not extend to the strip at all.

4.2.3 Structural Upgrade Module

The option of structural renovation with the upgrade module was already shortly discussed from a theoretical point of view in Chap. 3. A presentation from the energy efficiency viewpoint is seen in Figs. 3.12c and 3.17 showing that the main benefit of this renovation approach is to reduce the energy flow through the roof elements of the existing building and simultaneously produce one or more additional storeys which can be constructed in the most optimal way regarding the previously described energy flows and material characteristics of the renovated building.

Structural upgrading may also encompass numerous economical effects, especially in densely populated urban areas. As presented in Fig. 3.18, the added upgrade storey produces additional vertical load impact on the existing structure. Most buildings, particularly those with masonry walls, usually have sufficient structural load reserves to enable one or several storeys to be added [75]. Furthermore, the upgrade structural module also brings about an increase in the horizontal load impact (wind, earthquake) to an even higher degree than it affects vertical loads, Fig. 3.19.

Therefore, in view of a minimal possible increase in the load impact acting upon the existing building a prefabricated timber module with a very low additional mass could present an ideal solution of structural upgrade. Hence, a module constructed in the CLT or timber-panel structural system could be of a special interest. Moreover, due to construction with prefabrication, a quick instalment process substantially reduces the risk of the existing building being exposed to adverse weather conditions [75]. In addition, the installed module constructed in the optimal energy efficiency sense could also be seen as an advantage from the energy efficiency-based viewpoint, which was theoretically described in Sect. 4.1 and, based on our own research projects, thoroughly analysed and discussed in Sect. 4.3.

The analyses of such solutions involving prefabricated timber structural upgrade modules have been already used in practice, as witnessed within the renovation of the Grüntenstrasse residential complex in Augsburg in 2012 [75]. Another highly successful example is renovation of Hotel Terme Čatež, Slovenia, whose reconstruction finished in 2013. The existing four-storey building constructed in a hybrid reinforced concrete frame and masonry wall system (Fig. 4.23) was upgraded by means of installing a two-storey upgrade module in the CLT system, Fig. 4.24 [108], with the total mass of the upgraded building being increased only by 6% and

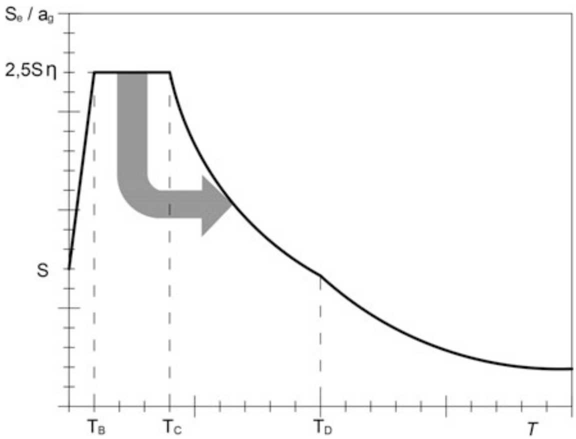
Fig. 4.23 Hotel Terme Čatež prior to structural upgrade [108]

the total seismic force being evenly decreased. This structural phenomenon which can appear in cases of structural upgrades will be further additionally explained in the supported research activities.

However, the analyses of such solutions involving structural upgrade modules have been mainly treated only in scientific studies, and there are currently no subject-related European directives. From the viewpoints of experimental research and numerical parametric analysis, both variants of structural upgrade module, i.e. using either frame-panel wall elements or CLT elements, are thoroughly discussed in Jančar [108], whose study also precisely analyses the impact of the number of storeys of the existing masonry or reinforced concrete building on the seismic behaviour of such upgraded structures. The study also shows cases where a sensible installation of the module results in a minimal increase of seismic loads acting on the existing building, which means a way of minimizing the impact on the

Fig. 4.24 Hotel Terme Čatež during the construction of the two-storey CLT upgrade module [108]

Fig. 4.25 Elastic response spectrum (S_e) decrease depending on the primary period (T) increase [109]



earthquake resistance of upgraded buildings. The reason lies in the fact that the total mass (m) of the upgrade building does not increase in the range as the response spectrum of the structure (S_e or S_d) can evenly decrease. According to Eq. (4.2a) from Eurocode 8 [109], the response spectrum depends on the primary period (T) of the structure, as schematically presented in Fig. 4.25 for the elastic response spectrum:

– For very stiff structures:

$$0 \leq T \leq T_B : \qquad S_e(T) = a_g \cdot S \cdot \left[1 + \frac{T}{T_B} \cdot (\eta \cdot 2.5 - 1)\right] \tag{4.2a}$$

– For stiff structures:

$$T_B \leq T \leq T_C : \quad S_e(T) = a_g \cdot S \cdot \eta \cdot 2.5 \tag{4.2b}$$

– For semi-stiff structures:

$$T_C \leq T \leq T_D : \quad S_e(T) = a_g \cdot S \cdot \eta \cdot 2.5 \cdot \left[\frac{T_C}{T}\right] \tag{4.2c}$$

– For flexible structures:

$$T_D \leq T \leq 4\text{sek} : \quad S_e(T) = a_g \cdot S \cdot \eta \cdot 2.5 \cdot \left[\frac{T_C \cdot T_D}{T^2}\right] \tag{4.2d}$$

The values S, T_B, T_C and T_D depend on the type of the soil foundation, Table 4.3.

As the primary period of the building depends on the height of the structure (H), it increases with the installation of the upgrade module. For example, Eurocode 8 [109] offers a very simple and approximate expression for defining the structural primary period (T_1) in the form of dependence on the structural height (H):

$$T_1 = C_t \cdot H^{3/4} \tag{4.3}$$

where the coefficient C_t depends on the type of the load-bearing structural system. It is evident from Fig. 4.25 that the increase of the primary period (T) may decrease the response spectrum (S_e) if the enlarged primary period (T) of the upgraded structure moves from the "maximal value field" T_B-T_C to the field of T_C-T_D. If we further consider, according to the Eurocode 8 [109], that the resulting seismic base shear force F_b for each horizontal direction was determined by the expression of

$$F_b = S_e(T_1) \cdot m \cdot \lambda \tag{4.4}$$

it can be understood that F_b may evenly decrease in some cases of structural upgrading when the S_e decrease range is higher than the simultaneous mass (m) increase.

Table 4.3 Values of the parameters for response spectrum 1 (Ms > 5.5)

Type of soil	S	T_B (s)	T_C (s)	T_D (s)
A	1.00	0.15	0.4	2.0
B	1.20	0.15	0.5	2.0
C	1.15	0.20	0.6	2.0
D	1.35	0.20	0.8	2.0
E	1.40	0.15	0.5	2.0

Approximate behaviour estimation in the case of extremely lightweight upgrade structures could be based on the research results treating storey spectra [110]. The limitation of the above lies in the assumption of low structural upgrade mass—the results prove to be “accurate” for the structural upgrade mass being lower than or equal to 1% of the existing building’s mass but only approximately accurate for the large structural upgrade mass, with the behaviour estimation accuracy decreasing with the increase in the structural upgrade mass.

According to the presented facts arising from the energy efficiency viewpoint, it is of a high interest to install a timber prefabricated module combined with the suitably oriented installed glazing areas, further called “timber-glass upgrade module”. The module was subject to numerical analysis within the energy demand aspect of building renovation, which is presented in Sect. 4.3. The following renovation measure to be discussed is placement of the prefabricated timber-glass structural upgrade module enabling simple installation onto the existing building, seen in Fig. 4.26. Installation of such modules has several advantages:

– Additional mass of the building is relatively low due to a low mass of the timber upgrade module whose installation is fairly simple and fast on account of prefabricated elements. Timber-framed glass structural system or CLT wall elements can be used, in which case the mass of the module increases.
– Suitably oriented glass areas enable maximum possible contribution of solar heat gains and consequently evidently improve the energy demand for heating.
– Installation of the upgrade module is very fast.

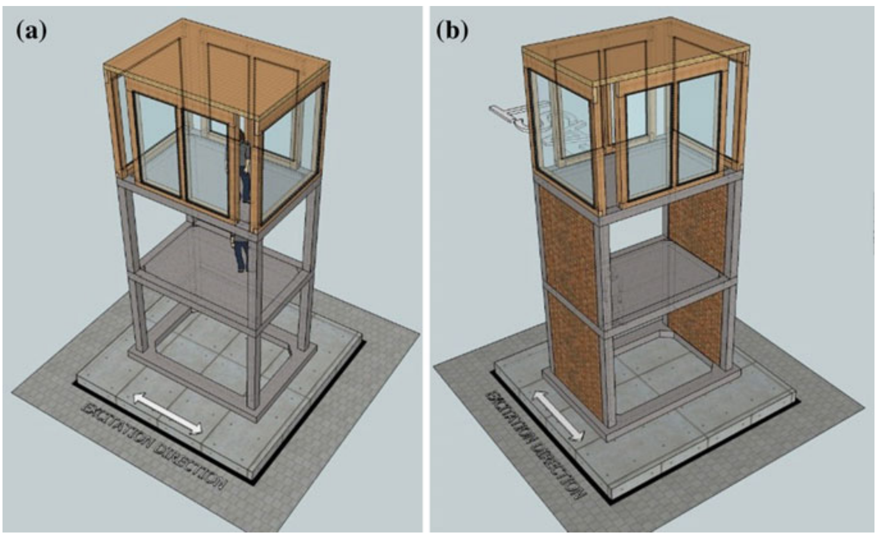


Fig. 4.26 Timber-glass module installed onto the concrete frame (**a**) or masonry (**b**) model building [112]

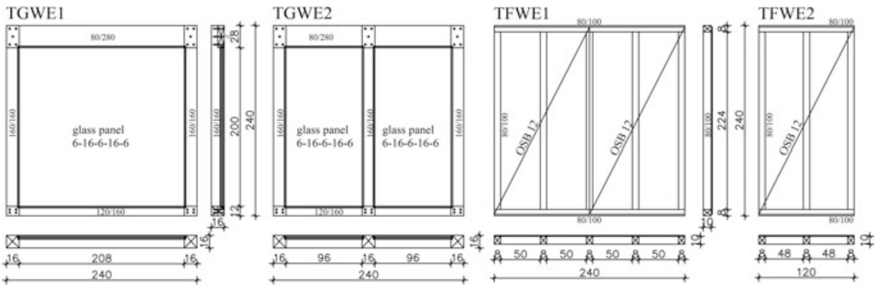


Fig. 4.27 Dimensions of timber-glass and light timber-framed wall elements [111]

However, it should be taken into account that defining the whole structural behaviour of such upgraded buildings is still in its initial stage of process, mostly based only on the performed experimental tests. A huge experimental research on the seismic resistance of single-storey box-house timber-glass models installed onto the concrete frame (Fig. 4.26a) or masonry (Fig. 4.26b) of the existing model building was performed at the IZIIS Institute in Skopje under a common guidance of the University of Maribor, CBD and the Kager company. The upgraded timber-glass box model, schematically presented in Fig. 4.27, consisted of the timber-glass wall elements and the timber-framed wall elements with classic OSB sheathing boards which demonstrated essentially higher racking resistance and stiffness under the monotonic point load than the timber-glass wall elements [111, 112].

The timber-glass wall elements with the same geometrical and material properties were already tested and analysed under the monotonic and the cyclic horizontal point load. Nevertheless, our goal was not limited only to proving the load-bearing capacity of the timber-glass wall elements under a monotonic static and dynamic point load, where the elements are tested in two dimensions only. A further aim was researching the behaviour of the timber-glass wall elements incorporated into a three-dimensional real timber box-house model which was seismically loaded on the shaking table. In this manner, various combinations of one- and two-storey timber-glass model box-house structures were tested by combining different wall set-ups. Single- and two-storey models, five of each, were first placed directly on the shaking table, not as upgrade modules, and subjected to different seismic movement, Fig. 4.28.

Before and after each earthquake simulation, sine sweep test with frequencies in the range of 1–32 Hz and intensity of 0.01 g was applied in order to clearly calculate the vibration period of the structure and to record the response of the building. Diagrams of first frequencies and first periods are shown in Figs. 4.29 and 4.30.

The presented results illustrate that there is only a slight change in the measured first periods before and after excitation observed in all tested models. The latter can prove that there was only a small decrease in the horizontal stiffness of the tested models which can be the first indicator of the deformation range in the structural

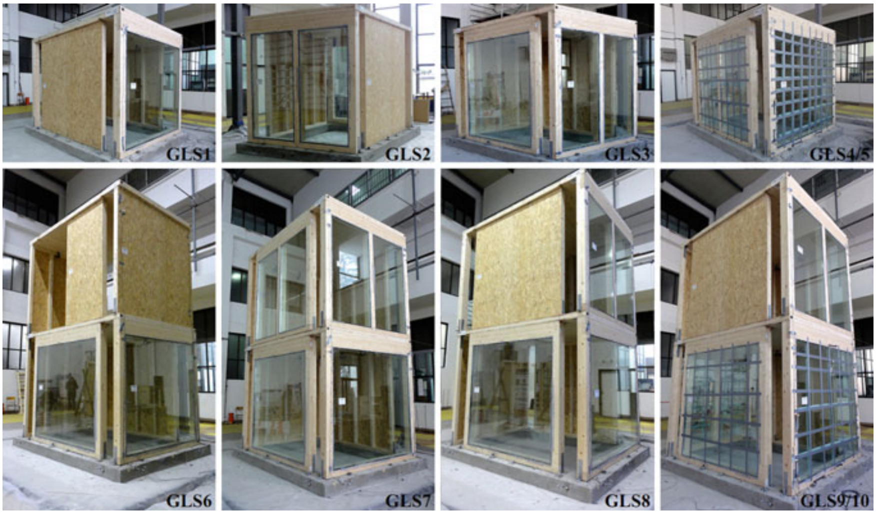
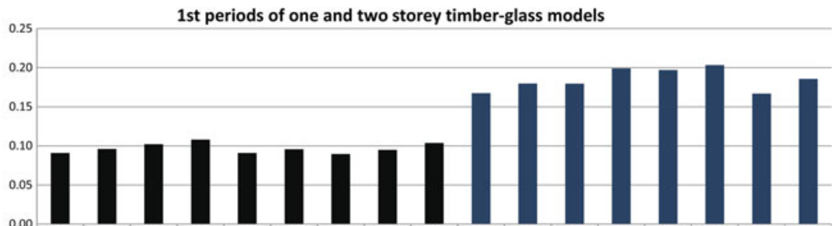
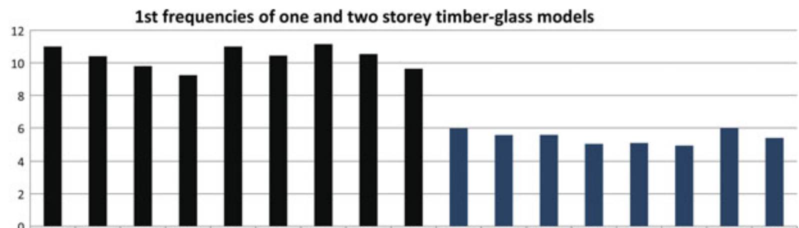


Fig. 4.28 Configuration of one-storey and two-storey test models [111]



	GLS1 before	GLS1 after	GLS2 before	GLS2 after	GLS3 before	GLS3 after	GLS4 before	GLS4 after	GLS5 after	GLS6 before	GLS6 after	GLS7 before	GLS7 after	GLS8 before	GLS8 after	GLS9 before	GLS10 after
1st period [s]	0.09	0.10	0.10	0.11	0.09	0.10	0.09	0.09	0.10	0.17	0.18	0.18	0.20	0.20	0.20	0.17	0.19

Fig. 4.29 Diagram of first periods for each model before and after the earthquake simulation [111]



	GLS1 before	GLS1 after	GLS2 before	GLS2 after	GLS3 before	GLS3 after	GLS4 before	GLS4 after	GLS5 after	GLS6 before	GLS6 after	GLS7 before	GLS7 after	GLS8 before	GLS8 after	GLS9 before	GLS10 after
1st frequency [Hz]	10.99	10.41	9.79	9.25	10.99	10.45	11.15	10.54	9.64	5.97	5.56	5.57	5.02	5.08	4.92	6.00	5.39

Fig. 4.30 Diagram of first frequencies for each model before and after the earthquake simulation [111]

elements and connections not being essentially high. The tested walls demonstrated a desirable rocking type of behaviour without any residual deformations in the adhesive joint, glass panes and the timber frame. An important observation useful for the seismic design of such buildings is a ductile failure mechanism established in the steel hold-downs. It should be noted that a low vertical load on the bracing walls exerted influence on the development of the rocking mechanism. With a higher vertical load, the shear behaviour of the glass panels would be activated, hence increasing the stresses in the shear brackets, the adhesive and the glass.

Considering the given facts we may conclude that the timber-glass box-house models could demonstrate a highly ductile behaviour and resist also under the seismic loads. Thus, this type of structures could definitely be recommended for further experimental and numerical analyses. The presented experimental results are a good starting point for a further parametrical numerical study using a finite element model. The latter will provide a more comprehensive understanding of the influence exerted by different types and dimensions of the glass panes, in addition to that of different types of adhesives and the bonding line conditions. Only such deep parametric analysis can in turn serve to define the most appropriate type of prefabricated timber-glass structural upgrade module to be used in heavy seismic areas. Further conclusions as well as other results of the whole study can be found in Premrov et al. [112].

At the end, it needs to be stressed that the existing literature fails to record compound studies researching the interdisciplinary field of energy efficiency, functional performance and construction-based renovation which is a basic objective/goal of an optimal solution for building renovation. The only study involving multidisciplinary approach to structural and energy efficiency analysis of historical buildings was conducted by the authors Ceroni et al. [113]; however, their research work offers no variants of solution to the problem of building renovation. Related facts from the energy efficiency perspectives of using such upgrade structural timber-glass modules will be therefore analysed in Sect. 4.3.

4.3 Research—Energy Efficiency Renovation

The current research presents a parametrical numerical analysis encompassing partial, deep and comprehensive approaches to building renovation. It is conducted in three stages with the first one concerning the existing building renovation, the second focusing on optimal design of structural upgrade modules and the third concerning application of the timber-glass upgrade module.

4.3.1 Parametrical Study—Renovation of Existing Buildings

The initial renovation of the selected case study buildings, thoroughly presented in Lešnik et al. [114], forms a basis for the following stages since the energy efficiency of the entire hybrid building composed of the renovated existing building extended with the upgrade module is compared to the energy efficiency of the renovated case study building. The following sections contain a description of the selected case study buildings, of their initial renovation and the upgrade modules design, along with results of the parametrical numerical analysis of extending renovated buildings by means of several types of timber-glass upgrade modules, thoroughly presented in [60, 61].

4.3.1.1 Description of the Case Study Buildings

The research is conducted on three case study buildings (multi-family buildings, hereinafter EBs) built in 1950s in the city of Maribor. They were thoughtfully selected according to their building typology (lamella, tower), orientation and erection period, i.e. the time before the first regulations requiring thermal insulation in buildings came into force in 1970. The selected multi-family buildings and their floor plans are presented in Figs. 4.31, 4.32 and 4.33.

The buildings are constructed in the massive structural system with masonry walls and roofs made of precast concrete ribbed slabs (EB A) or concrete brick beams with roof fillers (EB B and EB C). They all have an unheated basement outside the enclosed thermal envelope and an additional service area (EB A and EB C) or skylights (EB B) on the rooftop. Detailed characteristics of the selected EBs, given in Table 4.4, correspond to the original condition of the EBs, disregarding any eventual partial renovations the EBs may have been subjected to in the past.

Dating from the same time period, the selected EBs are built in a similar construction system and have comparable thermal properties of the envelope elements. Apart from their insufficiently insulated thermal envelope, inefficient old windows

Fig. 4.31 Existing case study building—EB A (left) and its floor plan (right) [60]

Fig. 4.32 Existing case study building—EB B (left) and its floor plan (right) [60]

Fig. 4.33 Existing case study building—EB C (left) and its floor plan (right) [60]

without shading devices, the airtightness of the buildings is weak and accounts for approximately n_{50} = 7.0 1/h. The EBs are naturally ventilated.

The selected EBs no longer correspond to the current energy efficiency requirements; therefore, the first interest of this research is to improve the energy efficiency of the EBs. The results of the initial partial and deep renovation are given in the following sections.

4.3.1.2 Renovation Measures

Deep building renovation comprises several renovation measures. In the current research, the influence of renovation measures on the energy efficiency of the EBs is

Table 4.4 Characteristics of the EBs [114]

		EB A	EB B	EB C
a (m) (south- and north-oriented façades)		35.42	17.40	15.40
b (m) (east- and west-oriented façades)		11.10	41.95	18.20
h (m)[a]		18.10	11.70	16.60
A (m^2)[b]		1164.30	2086.03	1047.60
F_s (m^{-1})[c]		0.41	0.35	0.43
NS_{EB} (or NS_{REB})[d]		4	4	5
a/*b*[e]		3.19	0.41	0.85
AGAW[f]	North	26.9%	12.1%	3.8%
	South	51.2%	12.1%	12.0%
	East	13.2%	34.1%	28.6%
	West	13.2%	32.6%	28.6%
Orientation of the longer façade		South–north	East–west	East–west
U (W/(m^2K))	Windows:			
	Frame	2.50	2.50	2.50
	Glass	2.20	2.20	2.20
	g = 0.8			
	External wall	1.45	1.46	1.44
	Roof	1.83	1.99	1.46
	Basement ceiling	1.59	1.46	1.01

[a]Height of the EB
[b]Total net floor area of the EB
[c]Factor of shape, defined as the ratio between the total area of the building thermal envelope and the total heated volume of the building
[d]Height of the EB or REB, expressed in the number of storeys
[e]Aspect ratio, defined as the ratio between the length of the south- and north-oriented and the east- and west-oriented façades
[f]Glazing-to-wall area ratio

initially assessed separately, based on individual renovation measures (hereinafter IRMs). An additional evaluation concerns the influence of combined IRMs taken within several renovation packages.

Individual Renovation Measures

The selected IRMs are mainly targeted at the improvement of the building thermal envelope and aim at the reduction of ventilation heat losses due to air leakages in the building envelope.

This research regards the following IRMs, discussed already in Chap. 3.2:

- IRM A—Replacement of old windows and doors (Sect. 3.2.2),
- IRM B—Improvement of the exterior wall thermal performance (Sect. 3.2.1),
- IRM C—Improvement of the roof thermal performance (Sect. 3.2.1),
- IRM D—Improvement of the basement ceiling thermal performance (Sect. 3.2.1),
- IRM E—Installation of the heat recovery mechanical ventilation system (hereinafter HRV) (Sect. 3.2.4).

Since the energy efficiency of the IRMs depends on the targeted thermal transmittance (U) of the envelope elements, two target levels of the thermal envelope performance were assessed within this research. The first corresponds to current Slovene regulations on energy efficiency (PURES [115]), given in Sects. 3.2.1 and 3.2.2, while the second level correlates to the improved values of the thermal transmittance (U) achieved through the IRMs. The values of the thermal transmittance (U) and other characteristics of the applied IRMs for both target levels of the thermal envelope performance are given in Table 4.5.

For both target levels of the thermal envelope performance, a temporary external shading with the shading factor $z = 0.50$ is taken into account. Improvement of the thermal envelope leads to better airtightness of the building, with the latter gradually improving from the initial $n_{50} = 7.0$ 1/h to the predicted $n_{50} = 2.0$ 1/h.

Packages of Renovation Measures

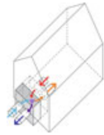
The influence of renovation measures is further assessed by combining different IRMs within partial renovation packages (hereinafter PRPs), based on findings relative to the energy efficiency of the IRMs. Finally, the last part of the current paper contains evaluation regarding the energy efficiency of deep building renovation including all the IRMs combined into two deep renovation packages (hereinafter DRPs) for both target levels of the thermal envelope performance. The composition of PRPs and DRPs of the proposed building renovation are given in Table 4.6.

Based on the number of IRMs involved, the proposed PRPs are divided into two groups combining either two (PRP 2.1 and PRP 2.2) or three IRMs (PRP 3.1 and PRP 3.2). The two proposed DRPs aim at deep building renovation with (DRP 2) or without (DRP 1) the installation of the heat recovery mechanical ventilation system —IRM E.

Software

The study is computed with the Passive House Planning Package (PHPP) [116] which is a certified software designed for low-energy and passive houses planning. It is based on the EN ISO 13790 standard [117] as well as on other European standards.

Table 4.5 Characteristics of the individual renovation measures (IRMs) [114]

Target levels	 IRM A	 IRM B	 IRM C	 IRM D	 IRM E
PURES (Fig. 3.13)	U_{frame} = 0.91 W/(m^{2}K) U_{glass} = 1.30 W/(m^{2}K) g = 0.64	U_{wall} = 0.28 W/(m^{2}K)	U_{roof} = 0.20 W/(m^{2}K)	$U_{basement\ ceiling}$ = 0.35 W/(m^{2}K)	η^a = 85%
Improved thermal performance	U_{frame} = 0.78 W/(m^{2}K) U_{glass} = 0.50 W/(m^{2}K) g = 0.50	U_{wall} = 0.16 W/(m^{2}K)	U_{roof} = 0.16 W/(m^{2}K)	$U_{basement\ ceiling}$ = 0.16 W/(m^{2}K)	η^a = 85%

[a]Heat recovery efficiency

Table 4.6 PRPs and DRPs of the proposed building renovation

	 IRM A	 IRM B	 IRM C	 IRM D	 IRM E
PRP 2.1	X	X			
PRP 2.2		X	X		
PRP 3.1	X	X	X		
PRP 3.2		X	X	X	
DRP 1	X	X	X	X	
DRP 2	X	X	X	X	X

Climate Data

The climate data for Maribor are taken into consideration. The city belongs to the Cfb climate zone according to the Köppen–Geiger climate map [118]. The average annual temperature in Maribor is 10.7 °C with the lowest average temperature of −0.8 °C in January and the highest average temperature of 20.8 °C in July. The average length of the heating period is 187 days. The average annual horizontal solar radiation in Maribor is 1225 kWh/m^2 with the average heating period radiation of 350 kWh/m^2 [119].

4.3.1.3 Results and Discussion

Existing Building Energy Balance

A detailed energy balance calculation of the EBs is crucial for evaluation of the different IRMs, PRPs and DRPs energy efficiency, which is the reason why it is the first subject to assessment. The energy balance of the existing EBs and the corresponding contribution of their different thermal envelope elements to the total transmission heat losses (Q_t) are presented in Figs. 4.34 and 4.35.

As observed from the presented results [114], the energy need for heating (Q_h) in the selected EBs, calculated according to Eq. (3.9a), is evidently stronger than the energy need for cooling (Q_c), calculated according to Eq. (3.10a). The highest energy need for cooling (Q_c) though is observed with EB B due to two skylights installed in the roof. On the contrary, the highest energy need for heating (Q_h) among the selected EBs evidently goes to EB A. The latter derives from high transmission heat losses (Q_t), Eqs. (3.2) and (3.6a), during the heating season.

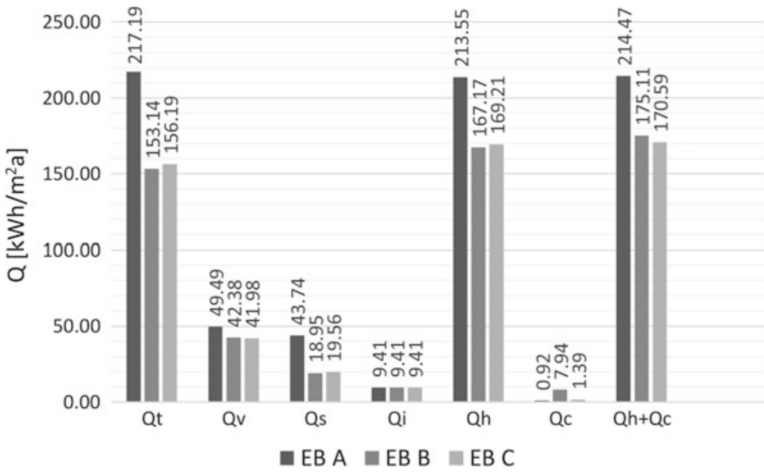


Fig. 4.34 EBs' heat flows and energy balance [114]

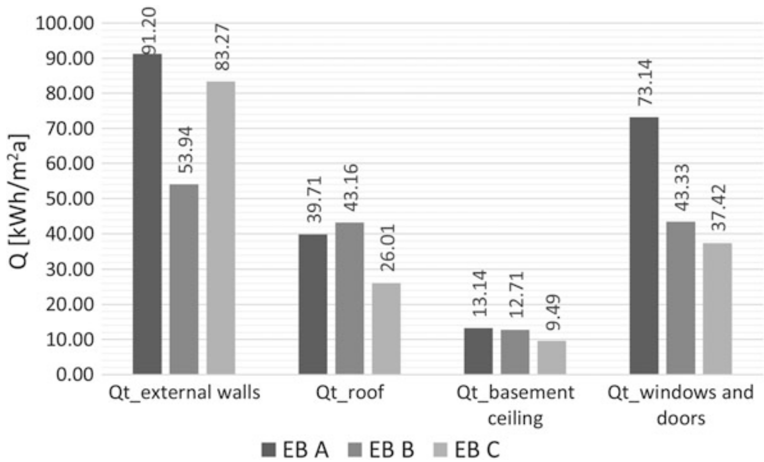


Fig. 4.35 Contribution of different thermal envelope elements of the EBs to the total transmission heat losses (Q_t)

A high AGAW value for the south-oriented façade of EB A ($AGAW_{south}$ = 51.20%, Table 4.4), accounts also for high solar gains (Q_s), calculated according to Eqs. (3.4) and (3.6c), in the heating season, as observed from Fig. 4.34. Despite the amount of glazing in the south-oriented façade, the energy need for cooling (Q_c) in EB A is the lowest among all the EBs, owing to deep balconies extending across the entire building length and providing shading in the cooling season but letting the solar radiation through in the heating period. The lowest total energy need for heating and cooling (Q_h + Q_c) is observed in the case of EB C, which is the consequence of several design characteristics, such as building typology resulting in a small roof and basement ceiling area, lower thermal transmittance (U) of the roof and the basement ceiling combined with low AGAW (Table 4.4), etc.

The transmission heat losses (Q_t) represent the highest share among all energy flows in the EBs energy balance and therefore the strongest influence on the energy need for heating (Q_h) and the total energy need (Q_h + Q_c). They are the lowest in the case of EB B, influenced by the most favourable shape factor (F_s) (Table 4.4 and Eq. 3.12). With regard to relatively comparable thermal transmittance values (U) of the selected EBs' envelope elements (Table 4.4), the divergence in the transmission heat losses (Q_t) originates in different building design characteristics, such as building typology, size and orientation together with the glazing size and orientation. Observation of all the EBs shows that the transmission heat losses through external walls ($Q_{t\_external\ walls}$) and those through windows and doors ($Q_{t\_windows\ and\ doors}$) are the highest, followed by the transmission heat losses through the roof (Q_{t_roof}). Within the total transmission heat losses (Q_t), the losses through the basement ceiling ($Q_{t\_basement\ ceiling}$) are the lowest, which is expected on account of a lower temperature difference between the inside and the outside building thermal envelopes.

The comparison of the EBs energy balance clearly indicates the characteristics of the selected individual EBs which influence the energy efficiency to the highest degree and can serve as the basis for the energy efficiency examination in relation to different building typologies.

Energy Efficiency of Individual Renovation Measures

The resulting savings in the total energy need for heating and cooling ((Q_h + Q_c)$_{SAVING}$) of the selected IRMs applied to the EBs for both target levels of the thermal envelope performance (PURES and the improved thermal transmittance), thoroughly presented in [114], are given in Fig. 4.36.

The savings in the energy need for heating and cooling ((Q_h + Q_c)$_{SAVING}$) in Fig. 4.36 are calculated according to the following Eq. (4.5):

$$(Q_h + Q_c)_{SAVING} = \frac{(Q_h + Q_c)_{EB} - (Q_h + Q_c)_{REB}}{(Q_h + Q_c)_{EB}} \times 100\,(\%) \tag{4.5}$$

where the total energy need for heating and cooling of the renovated building ((Q_h + Q_c)$_{REB}$) is extracted from the total energy need for heating and cooling of the existing building ((Q_h + Q_c)$_{EB}$). The difference is then divided by the total energy need for heating and cooling of the EB ((Q_h + Q_c)$_{EB}$) and multiplied by 100 to get the percentage of savings in the energy need for heating and cooling ((Q_h + Q_c)$_{SAVING}$).

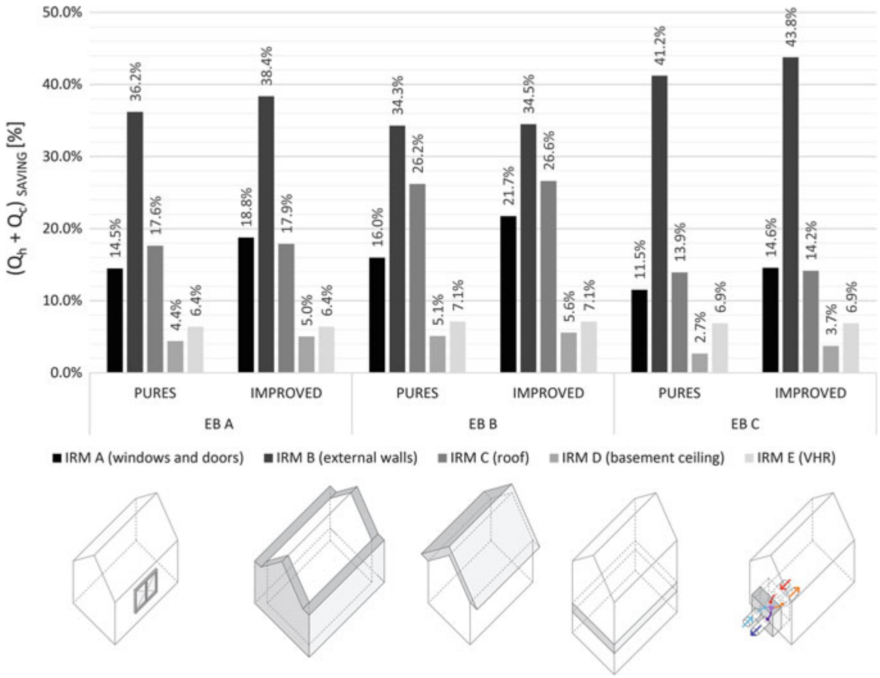


Fig. 4.36 Savings in the total energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$) resulting from the selected IRMs [114]

As evident from the results presented in Fig. 4.36, the savings in the total energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$) for all the EBs are the highest when introducing IRM B. The measure has the weakest influence when applied to EB B, which derives from the envelope area ratio between the external wall and the entire envelope area. On the contrary, the roof areas ratio for EB B is the highest among all of the EBs; therefore, IRM C is the most effective measure when applied to EB B, resulting in approximately 26% of the total energy savings. The strength sequence of the influence IRM A and IRM C have on the EBs is not as obvious as in the case of IRM B. Furthermore, the results suggest a stronger influence of IRM C when targeting the PURES level of the thermal envelope performance while a slightly stronger influence of IRM A relative to EB A and EB C emerges when the improved properties of the thermal envelope are targeted.

The IRM with the lowest influence on the savings in the total energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$) for all the EBs within the target envelope thermal property levels proves to be IRM D (improvement of the basement ceiling thermal properties). However, the results indicate a somewhat stronger influence of IRM E on the savings in the total energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$), although installation of the HRV is usually not affordable from the economic perspective [41] and tends to be difficult to perform in existing populated buildings. Consequently, it is not regularly introduced in real-life renovation projects.

The differences in the total energy savings ($(Q_h + Q_c)_{SAVING}$) occurring between different target levels of the envelope thermal properties (PURES and IMPROVED, Table 4.5) relative to certain IRMs, such as IRM C and IRM D are rather small. On the other hand, incorporating IRM A and IRM B induces more divergence in the predicted total energy savings ($(Q_h + Q_c)_{SAVING}$), which implies a thorough consideration of selecting a target level of the envelope thermal properties as early as in the design stage of building renovation.

According to the above findings and the energy efficiency viewpoint, selecting appropriate IRMs combined into renovation packages calls for consideration of the building typology along with that of the shape factor (F_s) and thereby the building envelope areas ratios in connection with the target level of the envelope thermal performance, which are all vitally important factors.

Energy Efficiency of Renovation Packages

This section deals with partial renovation packages (PRPs) consisting of the IRMs combined in groups of two (PRP 2.1 and PRP 2.2) or three (PRP 3.1 and PRP 3.2), in addition to two deep renovation packages, with (DRP 2) and without (DRP 1) the implementation of IRM E, as presented in Table 4.6. All PRPs and DRPs consist of the IRM combinations based on findings from the previous section, with the purpose of determining the most effective sequence of IRMs in a particular PRP or DRP within the renovation process. The savings in the total energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$), calculated according to Eq. (4.5) and gained by applying the proposed PRPs and DRPs, are given in Figs. 4.37 and 4.38.

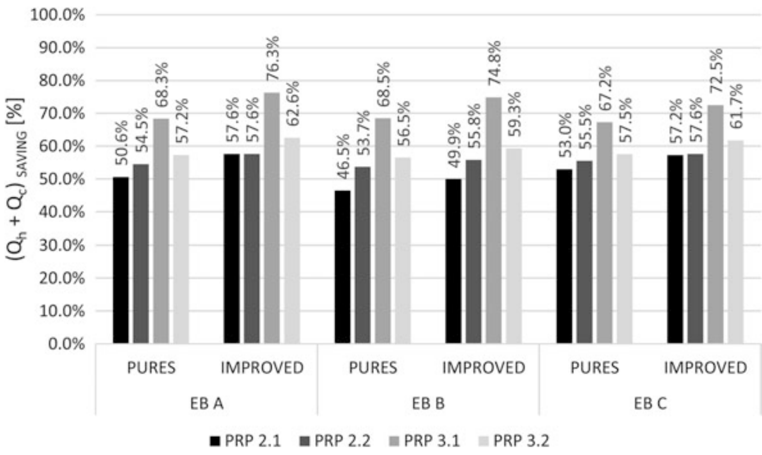


Fig. 4.37 Savings in the total energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$) resulting from the proposed partial renovation packages (PRP)

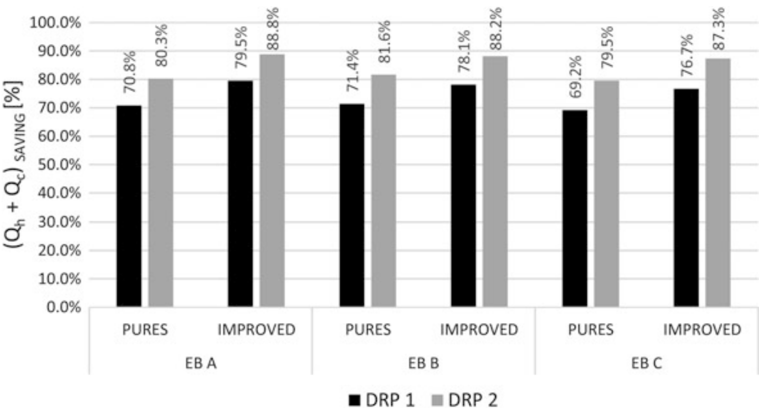


Fig. 4.38 Savings in the total energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$) resulting from the proposed deep renovation packages (DRPs) [114]

The PRPs which combine only two IRMs demonstrate lower total energy savings ($(Q_h + Q_c)_{SAVING}$) acquired with PRP 2.1 which combines IRM A and IRM B and is more common in real-life projects than PRP 2.2, composed of IRM B and IRM C. On the other hand, observation of the three IRMs shows that the implementation of PRP 3.1 results in the highest total energy savings ($(Q_h + Q_c)_{SAVING}$) among all of the proposed PRPs, ranging from 67.2% for the PURES level of the envelope thermal properties in EB C to 76.3% for the improved values of the envelope thermal properties in EB A. PRP 3.2, combining IRM B, IRM C and IRM D, results in significantly lower total energy savings ($(Q_h + Q_c)_{SAVING}$), which is expected due to a weaker influence of IRM D if compared to that of IRM A, implemented in PRP 3.1.

Consequently, if considering only the energy efficiency of PRPs, PRP 3.1 would be the most recommendable package. However, regardless of the above finding, the implementation of IRM A and IRM D is vitally important for reaching high IEQ within all of the EBs storeys. The latter speaks in favour of implementation of various renovation measures within deep building renovation packages (DRPs), whose results are presented in Fig. 4.38 [114].

As expected, DRP 2 incorporating all of the IRMs generates higher total energy savings ($(Q_h + Q_c)_{SAVING}$) than those gained by DRP 1 or by the previously discussed IRMs and PRPs. The savings are the highest when targeting the improved values of thermal performance, accounting for 88.8% when applied to EB A. Yet, targeting the PURES values of the envelope thermal performance leads to an average of only 7.9% lower energy savings. Nevertheless, up to 79.5% of the total energy savings ($(Q_h + Q_c)_{SAVING}$) are achieved without the implementation of IRM E (DRP 1). Regarding a difficult and economically unfeasible implementation of IRM E, DRP 1 is found to be more applicable to real-life projects.

We can conclude that the individual renovation measures demonstrate significant influences on the energy efficiency of the REBs with regard to their different typology, orientation and the selected level of the envelope thermal performance. Nevertheless, applying deep renovation packages to different existing buildings results in comparable total energy savings ($(Q_h + Q_c)_{SAVING}$). Moreover, the findings support the importance of deep building renovation and prove its advantages over partial renovation.

4.3.2 *Parametrical Study—Development of the Timber-Glass Upgrade Module*

4.3.2.1 Design Parameters of the Timber-Glass Upgrade Module

For further parametric analysis of the extent to which the upgrade module influences the energy efficiency of the entire hybrid building (REB + *M*) different module types were developed within [60]. An attempt at a systematic analysis was made with timber-glass upgrade modules designed according to several variable parameters. The latter served as guidelines in designing different types of timber-glass upgrade modules to suit most of the typical existing buildings geometries whose construction period matches approximately that of the case study buildings. The modules are constructed in the timber frame-panel system. Basic design parameters of the eight basic upgrade module types covering the entire rooftop area of the REBs are presented in Fig. 4.39.

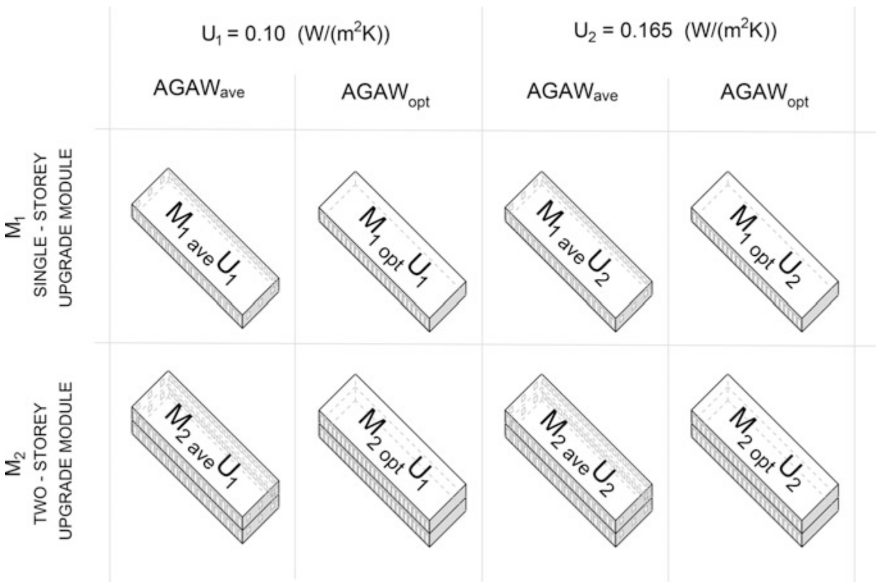


Fig. 4.39 Module types with regard to their main variable parameters

Table 4.7 Geometric characteristics of the upgrade modules

Module type		h (m)	A (m^2)				$AGAW_{ave}$ (%)[a]		
			REB A	REB B	REB C		REB A	REB B	REB C
M_1	U_1	3.13	318.22	605.38	212.08	North:	25.00	5.00	15.00
	U_2	3.00				South:	40.00	10.00	50.00
M_2	U_1	6.03	636.44	1210.77	424.16	East:	10.00	40.00	25.00
	U_2	5.91				West:	10.00	40.00	25.00

[a]Average glazing-to-wall area ratio

Owing to their limited load-bearing capacity, the existing buildings can be mostly upgraded with single or two-storey lightweight structures, as explained in Sect. 3.2.5. The thermal transmittance value U_1 was selected as one of the lowest values of thermal transmittance, with the value U_2 being selected as the average value of thermal transmittance usually used in contemporary timber-framed construction. Upgrade modules are applied onto the roof of the REBs and are therefore designed without a floor slab. It is assumed that there is no heat transfer between the REB and the upgrade module, as schematically presented in Fig. 3.17. The windows used for all upgrade module types have a thermal transmittance value of the frame U_{frame} = 0.78 W/(m^2K), with that of glass being U_{glass} = 0.50 W/(m^2K) and with the coefficient of permeability of the total solar energy amounting to g = 0.50. Other geometrical characteristics of the upgrade modules dependent on the REB and the module type are listed in Table 4.7.

The last parameter considered in the upgrade module design is the glazing size described as the average glazing-to-wall area ratio (AGAW) (Eq. 3.14). As one can notice from many real-life projects, glazing in buildings can be placed and sized in countless possibilities. However, for buildings of similar typology, construction system and construction time period, the average amount of glazing can be estimated. In this manner, the average glazing size ($AGAW_{ave}$) with windows installed in all cardinal façades of upgrade modules was defined according to the original window distribution of the EBs and contemporary buildings of the same size and orientation. The estimated values of $AGAW_{ave}$ are given in Table 4.7.

4.3.2.2 Design Parameters of the Optimal Timber-Glass Upgrade Modules

With the aim of designing "optimal upgrade modules", the optimal glazing sizes ($AGAW_{opt}$) [103], which correspond to the minimum annual energy need for heating and cooling ($Q_h + Q_c$), were calculated using the same approach as in Špegelj et al. [59].

South Orientation

In most cases, the optimal glazing-to-wall area ratio ($AGAW_{opt}$) can be determined only for the south-oriented façades [59, 103] due to a favourable ratio between the transmission heat losses (Q_t) (Eqs. (3.2) and (3.6a)) and the solar heat gains (Q_s) (Eqs. (3.4) and (3.6c)). For the purpose of the current research and with a view to a possibility of wider use, optimal glazing-to-wall area ratios ($AGAW_{opt}$) for different footprint areas (A_m), aspect ratios (a/b) and upgrade modules of different heights and thermal transmittance values (U) were designed to suit a variety of different existing building typologies. Within the parametric analysis, the modules' footprint areas of A_m = 100 m^2, A_m = 200 m^2, A_m = 400 m^2, A_m = 600 m^2 and the aspects ratios from a/b = 0.14 up to a/b = 7 were considered. The obtained $AGAW_{opt}$ for the south-oriented façades is given in Figs. 4.40, 4.41, 4.42 and 4.43.

As evident from the presented results, the $AGAW_{opt}$ for all four module types decreases with the increase of the aspect ratio (a/b). Additionally, substantial differences in the $AGAW_{opt}$ appear among upgrade modules of different footprint areas (A_m) of the same type and aspect ratio (a/b). The $AGAW_{opt}$ for all module types is the highest for larger footprint areas (A_m), in our case for A_m = 600 m^2. A comparison of different module types having the same aspect ratio (a/b) and footprint area (A_m) demonstrates that less energy-efficient modules, such as M_1 U_2 and M_2 U_2, require a higher $AGAW_{opt}$ than the most efficient ones.

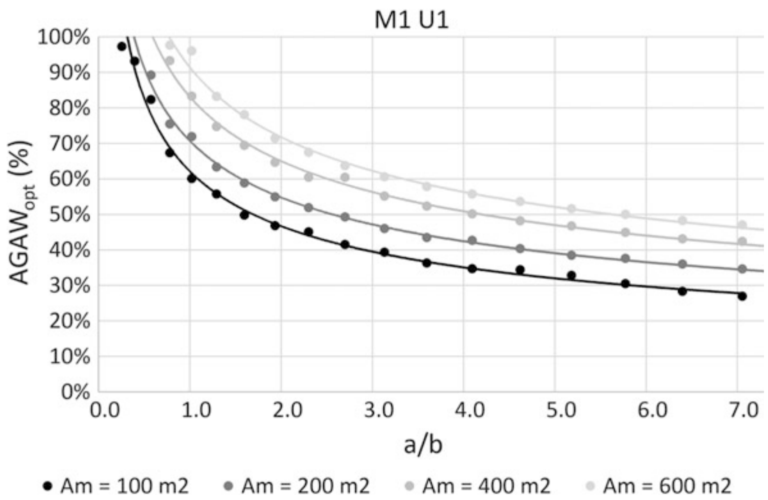


Fig. 4.40 Optimal glazing-to-wall area ratio ($AGAW_{opt}$) for the south-oriented façades of single-storey (M_1) upgrade modules with thermal transmittance U_1

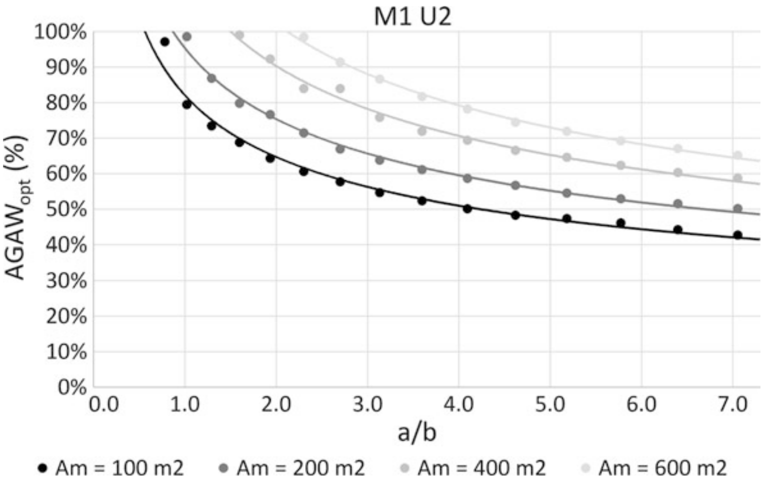


Fig. 4.41 Optimal glazing-to-wall area ratio ($AGAW_{opt}$) for the south-oriented façades of single-storey (M_1) upgrade modules with thermal transmittance U_2

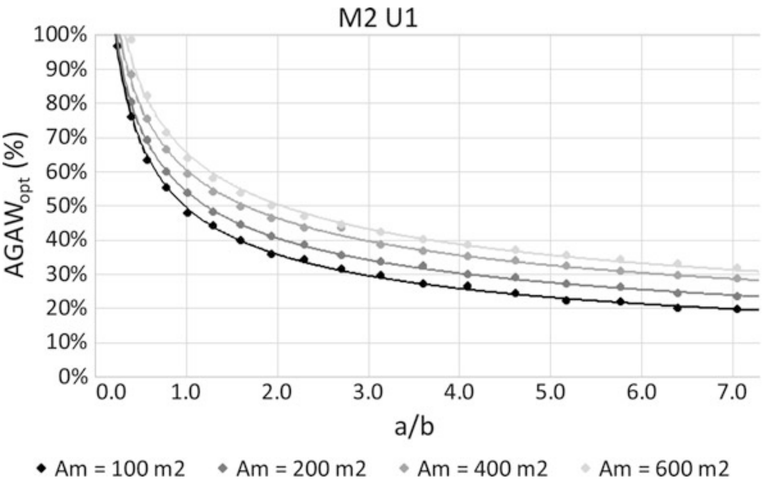


Fig. 4.42 Optimal glazing-to-wall area ratio ($AGAW_{opt}$) for the south-oriented façades of two-storey (M_2) upgrade modules with thermal transmittance U_1 [61]

East–West Orientation

However, $AGAW_{opt}$ for the south-oriented façades is the highest for upgrade modules of $a/b < 1$. Furthermore, we estimate that the AGAW surpassing 70–80% is not achievable in real buildings due to a difference in the external and the available internal surfaces of the façades. As a consequence, the optimal glazing

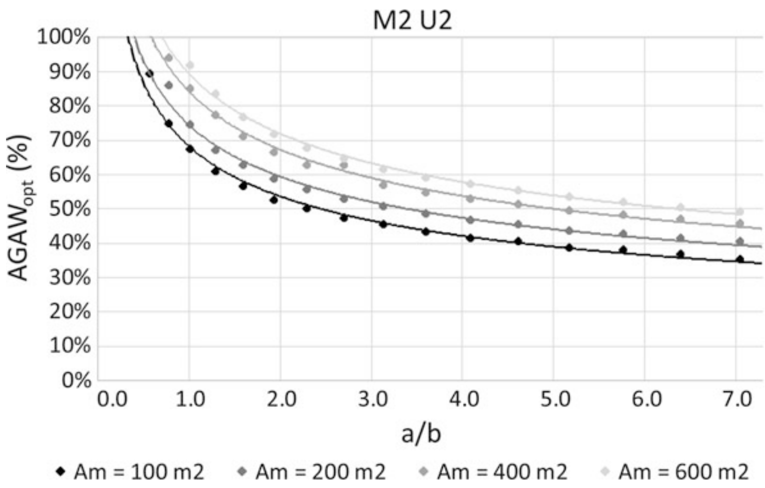


Fig. 4.43 Optimal glazing-to-wall area ratio ($AGAW_{opt}$) for the south-oriented façades of two-storey (M_2) upgrade modules with thermal transmittance U_2 [61]

sizes ($AGAW_{opt}$) cannot be determined for all aspects ratios (*a*/*b*). To enable optimal design of upgrade modules with low aspects ratios ($a/b < 1$) and predominantly east- and west-oriented windows, we took into account also the possibility of $AGAW_{opt}$ for the east- and west-oriented façades. Since the received solar radiation on the east- or west-oriented façades is presumed to be of a comparable extent and as two-sided orientation of grazed surfaces is recommendable for achieving high indoor environment quality (IEQ), the calculated $AGAW_{opt}$ for east- and west-oriented façades, presented in Figs. 4.44 and 4.45, is equally distributed on both façades. Thus, AGAW = 50% indicates that the $AGAW_{east}$ = 50% and the $AGAW_{west}$ = 50%.

The optimal glazing-to-wall area ratio ($AGAW_{opt}$) for east- and west-oriented façades can be determined only for M_1 U_2 and M_2 U_2 modules which are the least energy-efficient ones. The results from Figs. 4.44 and 4.45 reveal a possibility for achieving the $AGAW_{opt}$ only for upgrade modules of high aspect ratios (*a*/*b*) where the areas of east- and west-oriented façades are small if compared to those facing south or north. Moreover, the $AGAW_{opt}$ are rather small, especially for M_2 U_2 modules where only modules of smaller footprint areas (A_m = 200 m^2) and the approximately aspect ratio of $a/b > 5$ surpass the $AGAW_{opt}$ = 10%, which points to the uselessness of applying the results to real-life projects. What is more, the $AGAW_{opt}$ decreases with the increase of the footprint area (A_m), which is in contrast with the findings obtained for the south-oriented glazing. The design of optimal glazing sizes ($AGAW_{opt}$) on east- and west-oriented façades in such upgrade module geometry is therefore not recommendable, since it does not contribute to meeting high indoor comfort requirements in terms of daylighting and visual connection with the surrounding.

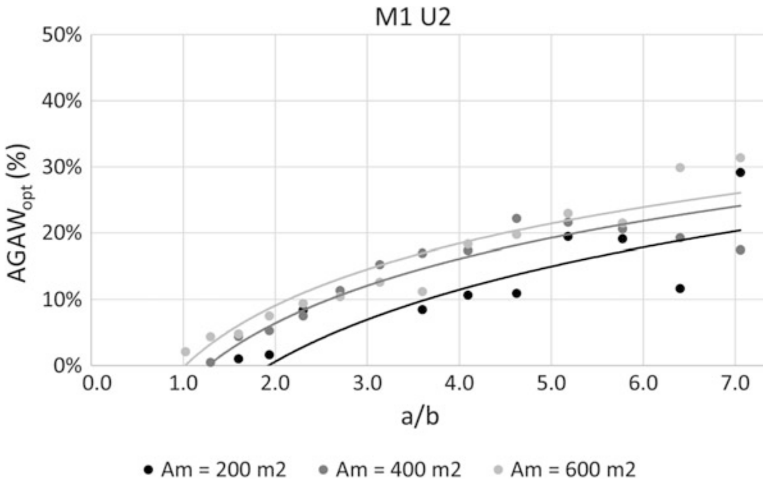


Fig. 4.44 Optimal glazing-to-wall area ratio ($AGAW_{opt}$) for the east- and west-oriented façades of single-storey (M_1) upgrade modules with thermal transmittance U_2

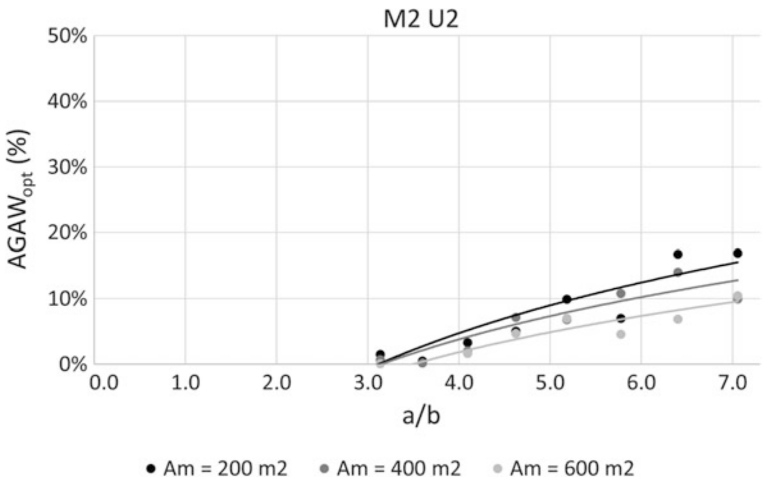


Fig. 4.45 Optimal glazing-to-wall area ratio ($AGAW_{opt}$) for the east- and west-oriented façades of two-storey (M_2) upgrade modules with thermal transmittance U_2

The obtained $AGAW_{opt}$ values for both, south- or east- and west-oriented façades, of various module types can serve architects or designers as a tool and a basic guideline in their efforts to predict the optimal glazing size for the corresponding EB type with regard to its size and orientation.

Defined Optimal Glazing Sizes for the Developed Upgrade Module Types

The values of $AGAW_{opt}$ for south-oriented façades corresponding to different upgrade modules and REBs relevant to this research are presented in Table 4.8.

Due to a low aspect ratio of EB B which is oriented predominantly towards east and west (a/b = 0.41), the $AGAW_{opt}$ cannot be determined on either the south or the east- and west-oriented façades. The same applies to REB C M_1 U_2 module type, as evident from Figs. 4.41, 4.44 and 4.45. Therefore, all $AGAW_{opt}$ given in Table 4.8 and applied in the following research concerns only the glazing placed in the south-oriented façades.

4.3.3 *Parametrical Study—Application of the Timber-Glass Upgrade Module*

The third part of this research discusses the effectiveness of installing upgrade modules onto the REBs. Moreover, since the number of existing building storeys varies from one case to another, the aim of the study is to explore to which extent the application of the upgrade module influences the energy need of the entire hybrid building (REB + M) with regard to the renovated building height (NS_{REB}—Table 4.4). In view of the above, the influence of upgrade modules covering the entire rooftop area of the REBs is evaluated [60], with an additional assessment of certain variations relative to upgrade modules covering only a part of the REBs rooftop areas, which was thoroughly presented in [61].

4.3.3.1 Energy Need of Simplified Existing and Renovated Buildings

As already explained in Sect. 4.3.1, some of the selected EBs were originally designed with supplementary service areas on rooftops which have to be removed in order to make extension with upgrade modules feasible. The energy efficiency of the simplified REBs without rooftop areas is thus considered in the evaluation of the effectiveness of this renovation measure—REB extension with a timber-glass upgrade module, as also discussed in Sect. 3.2.5. The main energy flows of the

Table 4.8 $AGAW_{opt}$ for different upgrade module types and different REBs

Module type		$AGAW_{opt}$ (%)[a]		
		REB A	REB B	REB C
M_1	U_1	52.39	/	79.01
	U_2	72.39	/	/
M_2	U_1	37.41	/	60.79
	U_2	55.42	/	85.79

[a]Optimal glazing-to-wall area ratio

Table 4.9 Energy need for heating (Q_h) and cooling (Q_c) of the simplified EBs and REBs [60]

	Q_h (kWh/(m^{2}a))		Q_c (kWh/(m^{2}a))		$Q_h + Q_c$ (kWh/(m^{2}a))		$(Q_h + Q_c)_{SAVING}$ (%)
	EB	REB	EB	REB	EB	REB	
A	199.76	21.64	1.15	0.40	200.91	22.04	89.0
B	160.60	19.43	0.63	0.78	161.24	20.21	87.5
C	166.74	20.06	1.26	1.16	168.00	21.22	87.4

simplified EBs and REBs, subject to all IRMs (IRM A–IRM E) corresponding to the level of the improved thermal performance (Table 4.5), according to [60] are given in Table 4.9.

As evident from the presented results, the total energy need for heating and cooling ($Q_h + Q_c$) of EB A surpasses that of EB B and EB C. If compared to the results of the original EBs renovation including rooftop areas conducted in the first part of the research (Sect. 4.3.1.1, Fig. 4.34), the most obvious divergence emerges in the energy need for cooling (Q_c) of EB B. Due to skylight in the original building, the energy need for cooling (Q_c) is the highest, whereas the calculated value for the simplified EB B (Table 4.9) proves to be the lowest among the values relative to the selected EBs. Owing to much lower energy need for cooling (Q_c), the simplified EB B demonstrates the lowest total energy need for heating and cooling ($Q_h + Q_c$) among the selected EBs. When comparing final energy savings in the energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$) of the original EBs (Fig. 4.38—DRP 2) with those of the simplified EBs, no major difference appears. Applying IRM A–IRM E to the simplified EBs results in up to 89% savings. The results listed above refer to the original buildings of different heights, with respect to the NS_{REB} listed in Table 4.4.

4.3.3.2 The Influence of the Renovated Building Height

The usefulness of the presented results is limited to the height of the EBs which can vary among the buildings of the same building type. The following point of interest therefore is to explore the influence of different building heights, expressed in the number of storeys (NS_{REB}) prior to application of timber-glass upgrade modules, exerted on the energy need for heating and cooling ($Q_h + Q_c$), as presented in Fig. 4.46.

A decrease in the energy need for heating and cooling ($Q_h + Q_c$) is evident from the results relative to increasing the number of storeys (NS_{REB}). The differences between the REBs are rather small, which offers a possibility to parametrically predict the expected energy standard of any REB, if the buildings undergo the same renovation pattern.

REB B demonstrates the lowest energy need for heating and cooling ($Q_h + Q_c$), as evident from Fig. 4.46. It is interesting to note that REB C, despite its smallest

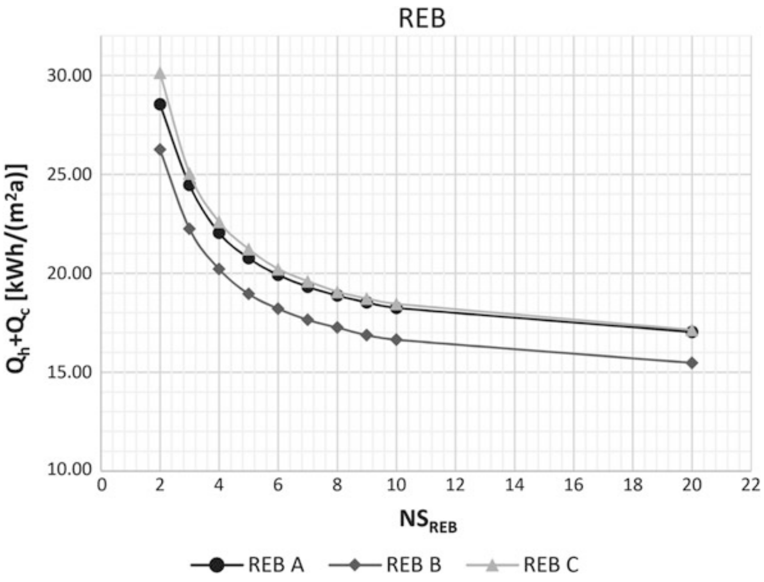


Fig. 4.46 Energy need for heating and cooling (Q_h + Q_c) for different NS_{REB} [60]

net floor area of a single storey along with the east- and westward orientation of the longer side, provides comparable results to those of REB A. This finding derives mainly from the characteristics of REB A and REB C, with reference to a high F_s ratio (Table 4.4), resulting in high transmission heat losses (Q_t).

4.3.3.3 Attic Extension with the Energy-Efficient Structural Upgrade Module Covering the Entire Rooftop Area

In addition to our previously stated findings proving a positive impact of a higher number of storeys (NS_{REB}) on the reduction in the energy need for heating and cooling (Q_h + Q_c) [60], our further interest goes to determining the influence of the upgrade module and cases where the impact of the module on the reduction in the energy need for heating and cooling (Q_h + Q_c) surpasses that of a higher number of storeys (NS_{REB}).

The energy need for heating and cooling (Q_h + Q_c) of the REBs extended with each of the corresponding module types is presented in Fig. 4.47 in order to verify the impact that modules exert on the energy need when increasing the NS_{REB} in comparison to the energy need for heating and cooling (Q_h + Q_c) of the REBs prior to taking the extension measure.

A reduction in the energy need for heating and cooling (Q_h + Q_c) of the hybrid buildings (REBs + *M*) in comparison with the energy need for heating and cooling (Q_h + Q_c) of the REBs prior to application of the upgrade module is evident from

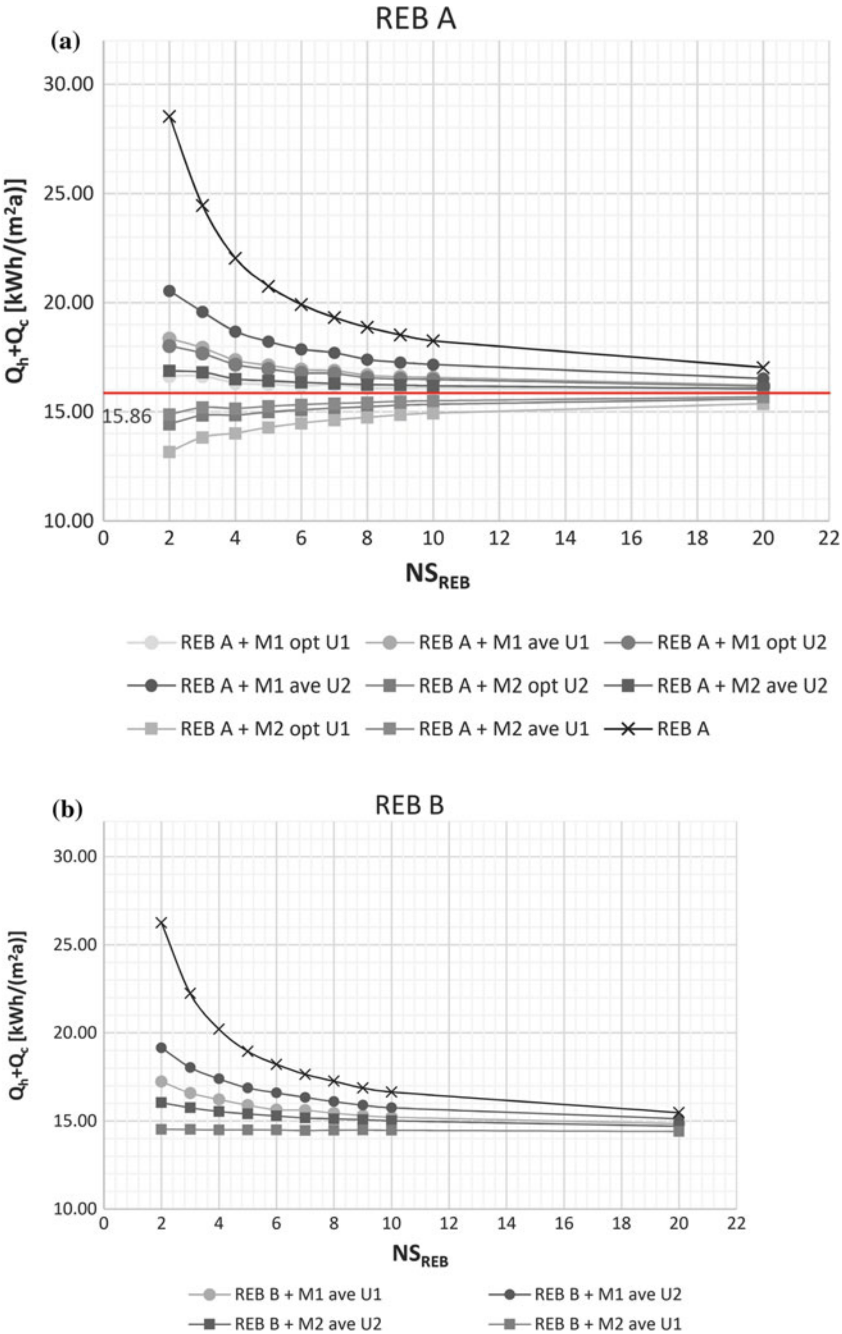


Fig. 4.47 Energy need for heating and cooling (Q_h + Q_c) for different heights of the REBs **a** REB A, **b** REB B and **c** REB C and the hybrid buildings (REBs + *M*) [60]

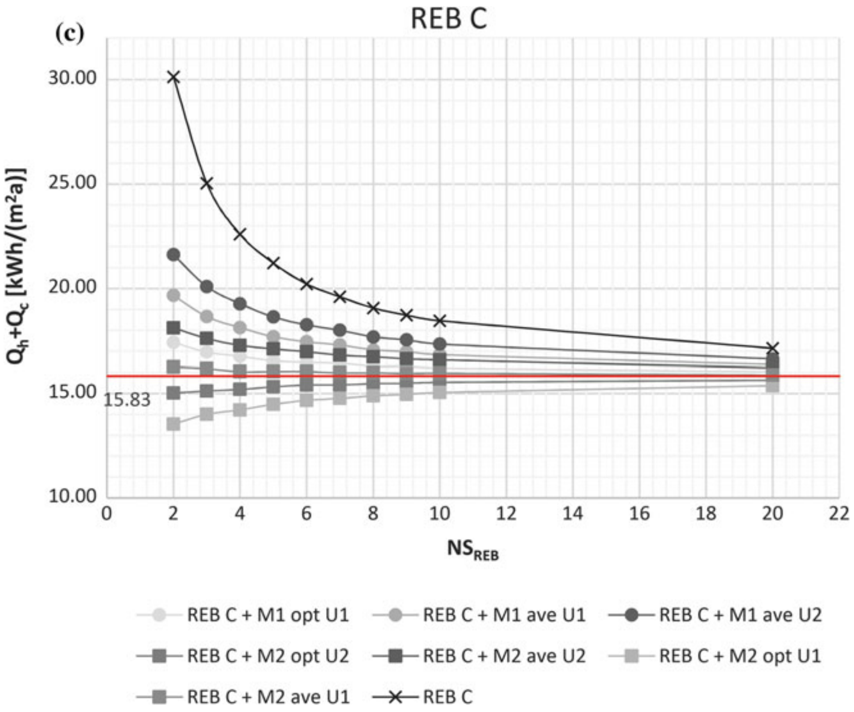


Fig. 4.47 (continued)

Fig. 4.47. A further observation points to considerable differences which appear among different module types in reference to lower heights (NS_{REB} = 2) and tend to decrease with the increasing number of storeys until becoming almost negligible, at heights of NS_{REB} = 10. The latter finding demonstrates the strongest influence of all upgrade module types on the reduction in the energy need for heating and cooling ($Q_h + Q_c$) of the hybrid buildings (REBs + M) when applied to buildings of lower heights, from NS_{REB} = 2 to NS_{REB} = 6.

It is furthermore shown that installing the best among the single-storey modules $M_{1\ \mathrm{opt}}\ U_1$ leads to reaching a better energy standard of the hybrid building (REB + M) than in the case of extension by means of the least effective two-storey module type $M_{2\ \mathrm{ave}}\ U_2$.

Moreover, the so-called influence line between the influence exerted by the upgrade module and that of increasing the number of storeys (NS_{REB}) (Sect. 4.3.3.2) can be defined as the borderline between the increase and decrease in the energy need for heating and cooling ($Q_h + Q_c$) of certain upgrade module types, when increasing the number of storeys (NS_{REB}), as seen from Fig. 4.47. The area below the influence line shows the prevailing upgrade module impact, with the area above this line demonstrating a stronger impact of a higher number of storeys (NS_{REB}). Module types exerting the prevailing influence of upgrade modules are predominantly two-storey modules with the optimal glazing sizes ($M_{2\ opt}\ U_1$, $M_{2\ opt}\ U_2$). However, the influence line cannot be defined for all the REBs, such as in the case of REB B, where the influence of increasing the number of storeys (NS_{REB}) always surpasses that of the influence exerted by the upgrade module.

We can conclude that the use of construction systems with lower thermal transmittance (U) combined with the most optimal glazing size is recommendable if the energy efficiency is the only aspect taken into account. However, with respect to other viewpoints, such as good visual connection with the surroundings and proper daylighting, the average module types would be more suitable for real-life building extensions.

Impacts of the Design Parameters of the Timber-Glass Upgrade Module

The influence strength of different parameters on the savings in the energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$) of the hybrid buildings (REBs + M) is partially seen in Fig. 4.47. In the extension of the REBs, the strongest influence thus generally proves to be the height of the module, with the application of two-storey modules (M_2) showing the highest degree of impact, which is an expected result in view of two-storey module sizes in comparison to those of single-storey modules (M_1).

For the purpose of easier estimation of the influence sequence relative to the glazing size (AGAW) and the thermal transmittance (U) impacts, Fig. 4.48 shows savings in the energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$) of the selected hybrid building (REB A + M) which was selected by reason of being the only hybrid building that allows for the design of all module types.

The savings in the energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$) are calculated according to the following Eq. (4.6):

$$(Q_h + Q_c)_{SAVING} = \frac{(Q_h + Q_c)_{REB} - (Q_h + Q_c)_{REB+M}}{(Q_h + Q_c)_{REB}} \times 100\,(\%) \tag{4.6}$$

where the total energy need for heating and cooling of the entire hybrid building ($(Q_h + Q_c)_{REB+M}$) is extracted from the total energy need for heating and cooling of the REB ($(Q_h + Q_c)_{REB}$). The difference is then divided by the total energy need for heating and cooling of REB ($(Q_h + Q_c)_{REB}$) to get the percentage of savings in the energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$).

The highest savings in the energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$) (Eq. 4.6) evident from Fig. 4.48 are achieved with the optimal module types of lower thermal transmittance ($M_{1\ opt}\ U_1$ and $M_{2\ opt}\ U_1$). On the contrary, the lowest savings result from applying the average module types with higher thermal transmittance values ($M_{1\ ave}\ U_2$ and $M_{2\ ave}\ U_2$). Lesser influence of modules with the average glazing size ($AGAW_{ave}$) is expected on account of the glazing installed also in the north-oriented façade where there is no possibility for solar gains (Q_s) but only for heat losses due to the transmission heat losses (Q_t).

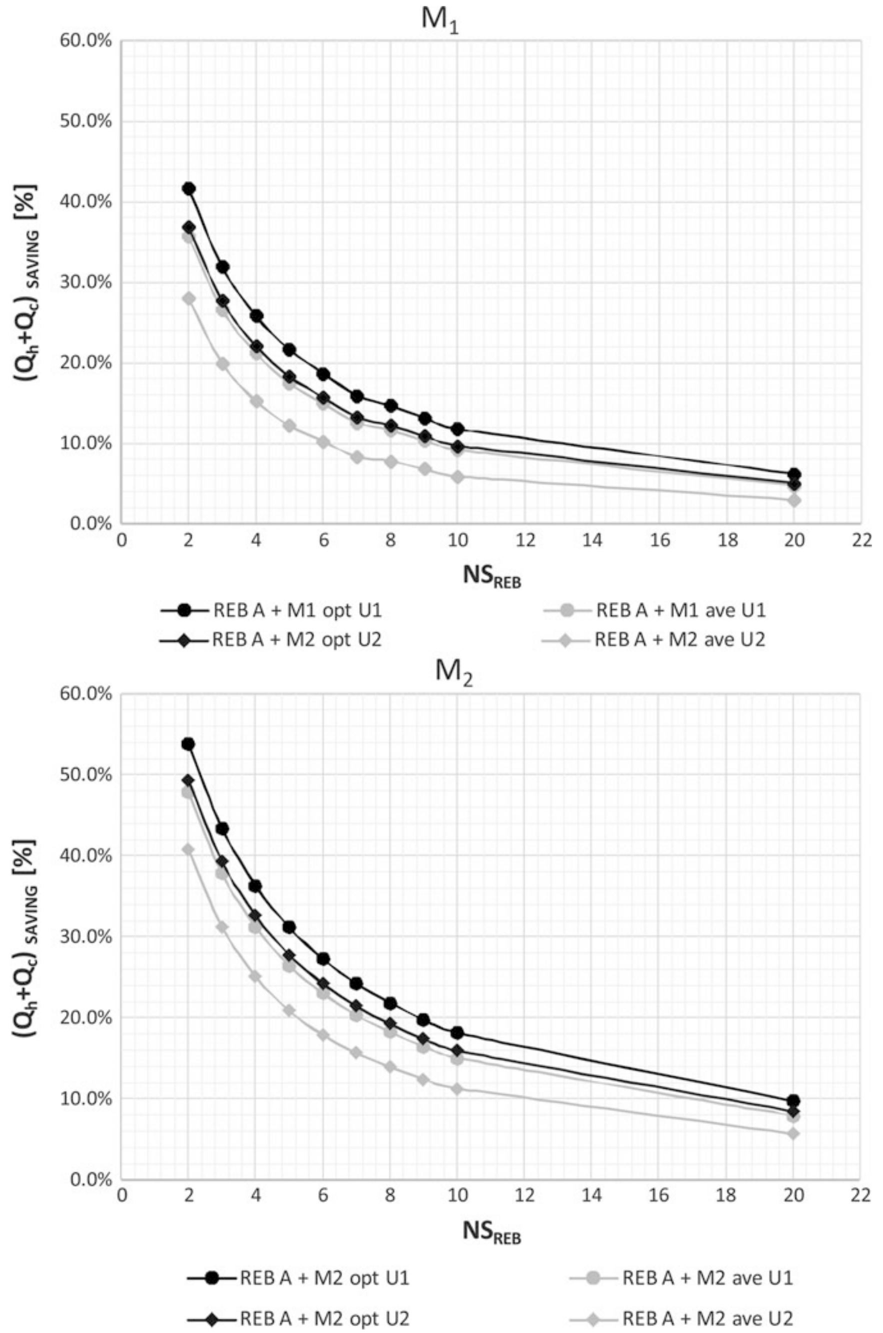


Fig. 4.48 Energy savings (%) for the extension of REB A with different types of single-storey (M_1—above) and two-storey (M_2—below) upgrade modules for different $NS_{REB\ A}$ [60]

The difference in the savings of the total energy need ($(Q_h + Q_c)_{SAVING}$) between the average module ($AGAW_{ave}$) of lower thermal transmittance and the optimal module ($AGAW_{opt}$) of higher thermal transmittance for both single-storey modules (M_1) and two-storey modules (M_2) is relatively low.

The latter results suggest the order of influence strength, indicating the strongest influence of the module height. Furthermore, the glazing size (AGAW) proves to have a slightly stronger influence on the decrease in the energy need for heating and cooling ($Q_h + Q_c$) than the impact of the thermal transmittance (U) of the module's envelope.

Impact of the Existing Multi-family Building Typology

The four charts in Fig. 4.49 represent energy savings arising from extending different REBs by means of upgrade modules combining their heights (M_1, M_2) with both thermal transmittance values (U_1, U_2). Our interest goes to savings in the total energy need ($(Q_h + Q_c)_{SAVING}$) (Eq. 4.6) resulting from the extension of REB A, B and C, with regard to their different building typology (lamella, tower).

The extension of the REBs with different module types shows a difference in the savings relative to the energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$) between modules having the optimal ($AGAW_{opt}$) or the average glazing size ($AGAW_{ave}$), although their function lines behave in a similar way.

Installing the most influential optimal module $M_{2\ opt}\ U_1$ leads to the highest savings in the energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$) when applied to REB C which proves to be the least energy-efficient REB in Sects. 4.3.3.1 and 4.3.3.2. The savings in the energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$) are comparable to those defined in the extension of REB A with the same optimal upgrade module type. On the other hand, when applying the average module types, the highest savings in the energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$) are achieved when extending REB A with the $M_{2\ ave}\ U_1$ type. The savings in the energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$) are comparable to those seen in REB B and C. Applying the same module types therefore leads to similar savings in the energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$), regardless of the REB.

To summarize, types of buildings resembling those of REB A and REB C, with aspect ratios larger than approximately $a/b = 0.85$, can benefit from taking the extension renovation measure the most, provided that the energy efficiency is the only considered aspect. Nevertheless, as the energy efficiency is not the only criterion in a building renovation process, all other buildings are in fact also suitable for the implementation of the building extension renovation measure.

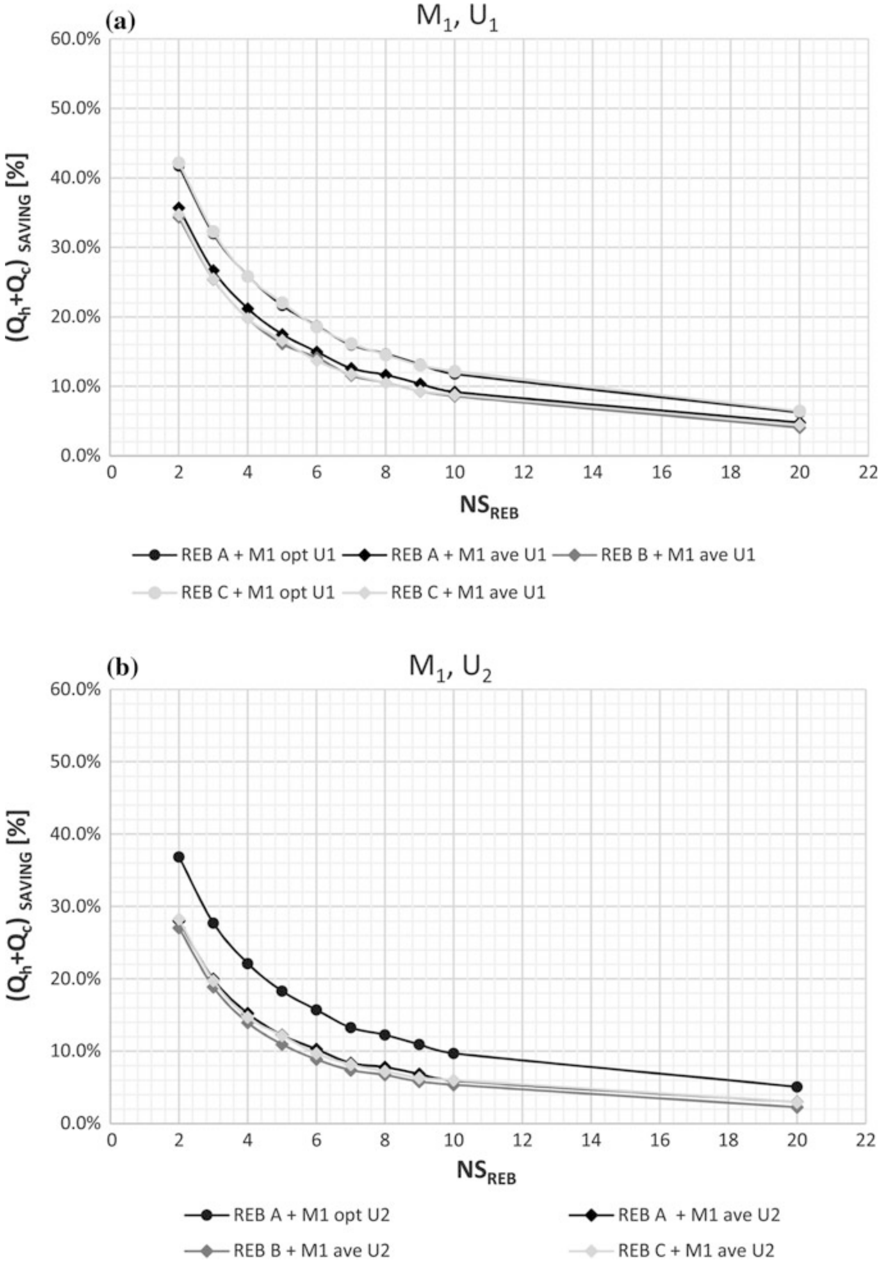


Fig. 4.49 Energy savings (%) resulting from the extension with different types of upgrade modules for different NS_{REB} [60]

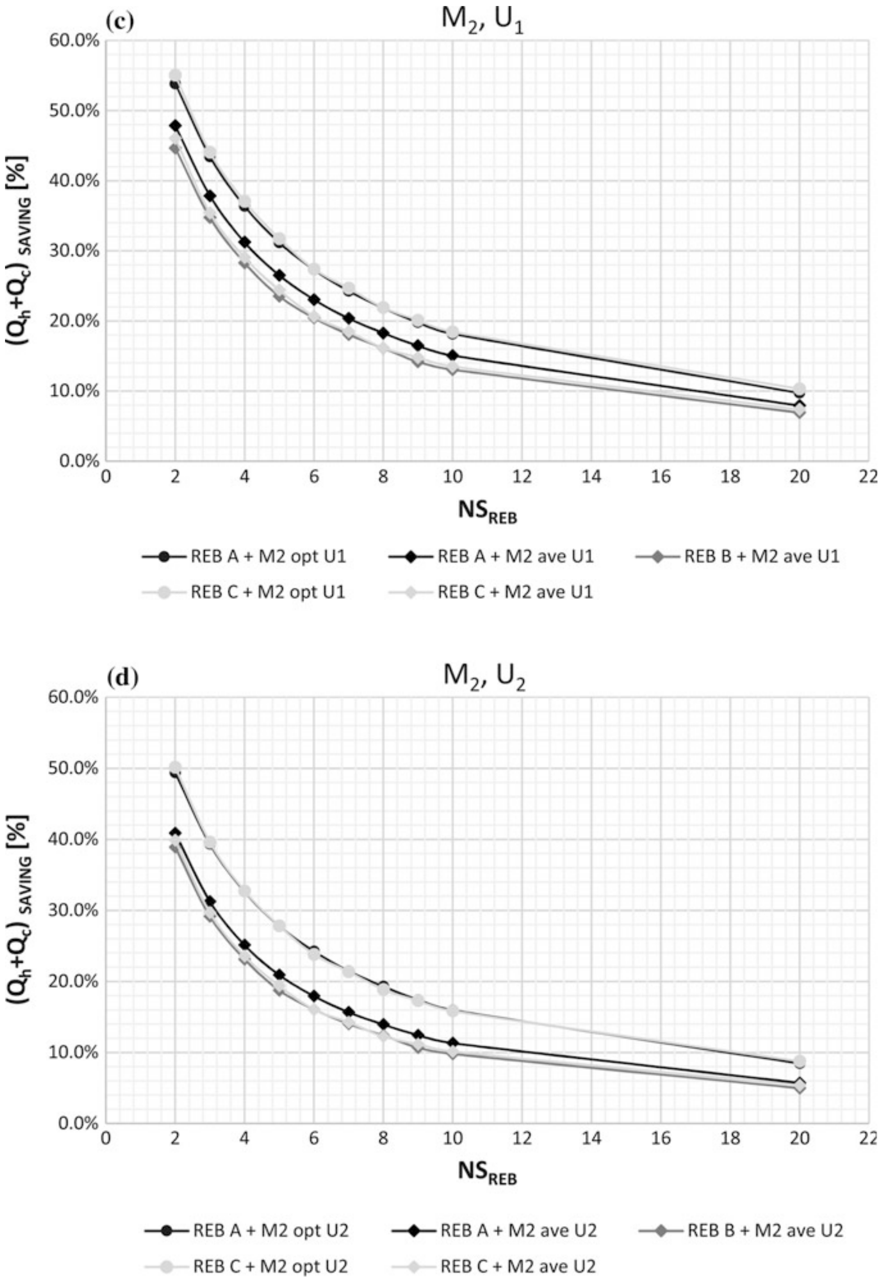


Fig. 4.49 (continued)

Building Extension with the Average Module Types

Figure 4.50 demonstrates a comparison between average savings in the energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$) (Eq. 4.6), averaging the results of REB A, B and C extended with the most ($M_{2\ ave}\ U_1$) and the least ($M_{1\ ave}\ U_2$) influential among upgrade modules with the average glazing size ($AGAW_{ave}$).

The following comparison aims at illustrating the fact that in spite of a higher impact of the optimal module types, a choice for building extension with the average module types can be beneficial. Appropriately selected upgrade modules to be applied to different types of buildings whose height ranges from $NS_{REB} = 3$ to $NS_{REB} = 6$, which is the most frequently occurring building height in Slovenia, can thus save the energy needed for heating and cooling ($(Q_h + Q_c)_{SAVING}$) in the amount from 36.0 to 9.6%, as evident in Fig. 4.50.

Design Guidelines

Relatively small differences between the influences modules of the same type exert on the energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$) (Eq. 4.6) of the

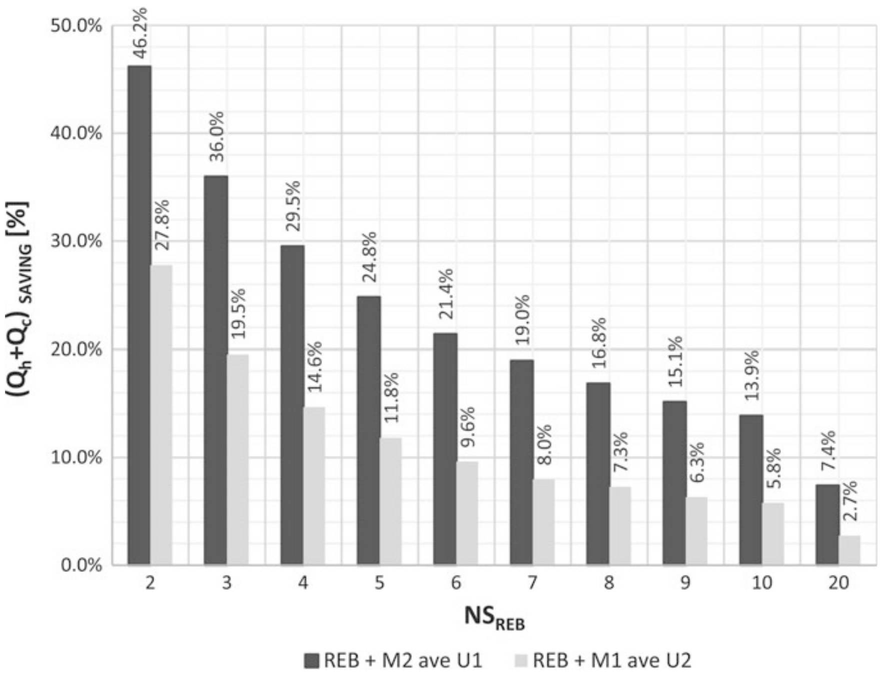


Fig. 4.50 Comparison of the average savings in the energy need for heating and cooling (%), averaging the results of REB A, B and C upgraded with the modules with the average glazing size ($AGAW_{ave}$) exerting the lowest and the highest influences at different NS_{REB} [60]

hybrid building (REB + M) allow for the possibility of estimating the amount of savings for the extensions of different REBs. The average values of the savings in the energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$) are therefore summarized, as seen in Fig. 4.51, where each module type data encompass average values of the savings in the energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$), defined as the average of the values for hybrid buildings (REB A + M, REB B + M and REB C + M).

Such approach serves for preliminary estimation of the savings in the energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$) (Eq. 4.6) based on the number of storeys (NS_{REB}) and the upgrade module type. It can be used to estimate the expected savings in the energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$), normed to a m^2 of the hybrid building's (REB + M) floor plan area, depending on the number of storeys of the renovated building (NS_{REB}) and the upgrade module types covering the entire rooftop area of the REB, provided that the building undergoes a renovation process within the same scope of standards as set by the current study.

4.3.3.4 Attic Extension with the Energy-Efficient Structural Upgrade Module Partially Covering the Rooftop Area

The upgrade modules in the above-presented research cover the entire area of the EBs rooftops. Nevertheless, there are countless design options for upgrade modules which do not necessarily cover the entire EB rooftop. Therefore, the aim of this section is to explore to which extent the application of the timber-glass upgrade modules influences the energy need for heating and cooling ($Q_h + Q_c$) of the REBs when modules cover only a part of the rooftop area in comparison to the total rooftop area coverage, which was thoroughly presented also in [61].

The study is based on the findings of the above-presented research [60] and is limited to the selected case study building—REB A, described in Sect. 4.3.1.1. REB A was selected since it is the only case study building among the selected REBs suitable for design of all upgrade module types. Furthermore, only the impact of the most effective two-storey upgrade modules (M_2) is assessed for the theoretical heights of the REB up to $NS_{REB} = 6$ which proved (in the previous study, Sect. 4.3.3.3, [60]) to be the most suitable height for the extension renovation measure. The stated NS_{REB} is also one of the most commonly occurring heights of typical Slovenian multi-family residential buildings.

Design Parameters of Timber-Glass Upgrade Modules Partially Covering the Rooftop Area

In addition to design parameters, discussed already in Sects. 4.3.2.1 and 4.3.2.2, a new parameter—the rooftop coverage ratio (hereinafter RCR)—describing the relation between the entire rooftop area and the footprint area of the module (A_m)

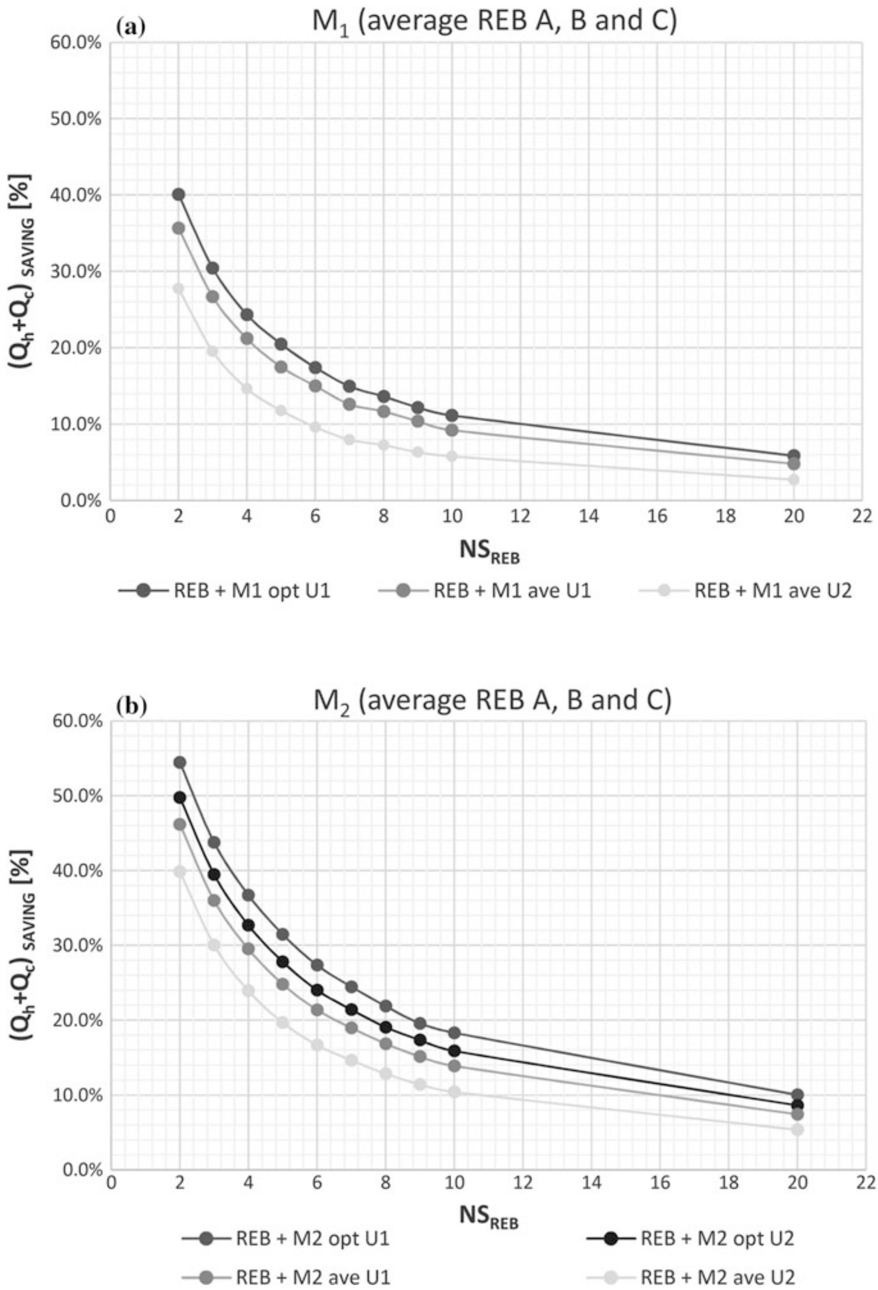


Fig. 4.51 Energy savings (%) for the extension with different types of single-storey (M_1) (**a**) and two-storey (M_2) (**b**) upgrade modules for different NS_{REB} (average values defined for hybrid buildings (REB A + M, REB B + M and REB C + M)) [60]

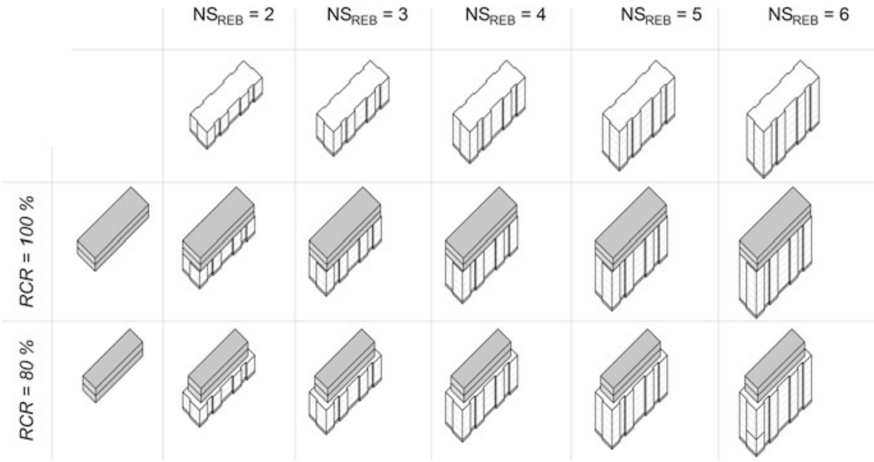


Fig. 4.52 Building extension variations in regard to different RCRs for different NS_{REB} and volume ratios [61]

was defined to evaluate the influence of modules covering only a part of the rooftop area. To illustrate the idea, upgrade modules covering two different shares RCR = 80% and RCR = 100% for different NS_{REB} are presented in Fig. 4.52. Additionally, the values of RCR ranging from 50 to 100% are used later in the research.

Comparison of the Influence Exerted by the Rooftop Coverage Ratio

Firstly, a comparison of the influence the attic extension with different upgrade module types of RCR = 100% and RCR = 80% exerts on the energy need for heating and cooling ($Q_h + Q_c$) is evaluated and presented in Fig. 4.53. The value of RCR = 80% was selected in view of our estimation of the mentioned value, as presenting the average relation between the inside and the outside living areas of contemporary multi-family buildings.

Figure 4.53 demonstrates a reduction in the energy need for heating and cooling ($Q_h + Q_c$) of the hybrid building (REB + M) in comparison to the energy need for heating and cooling ($Q_h + Q_c$) of the REB prior to the extension measure for both module types, those of RCR = 100% and RCR = 80%. Although the reduction in the case of module types of RCR = 100% is more significant, the divergence between modules of the same type but a different RCR is relatively small. The later speaks in favour of upgrading the REB with upgrade modules even if the coverage involves only a part of the REB rooftop area.

Similar to building extension with upgrade modules covering the entire rooftop area (Sect. 4.3.3.3, [60]), modules of partial coverage also allow for the definition of the influence line which distinguishes the influence of the extension measure

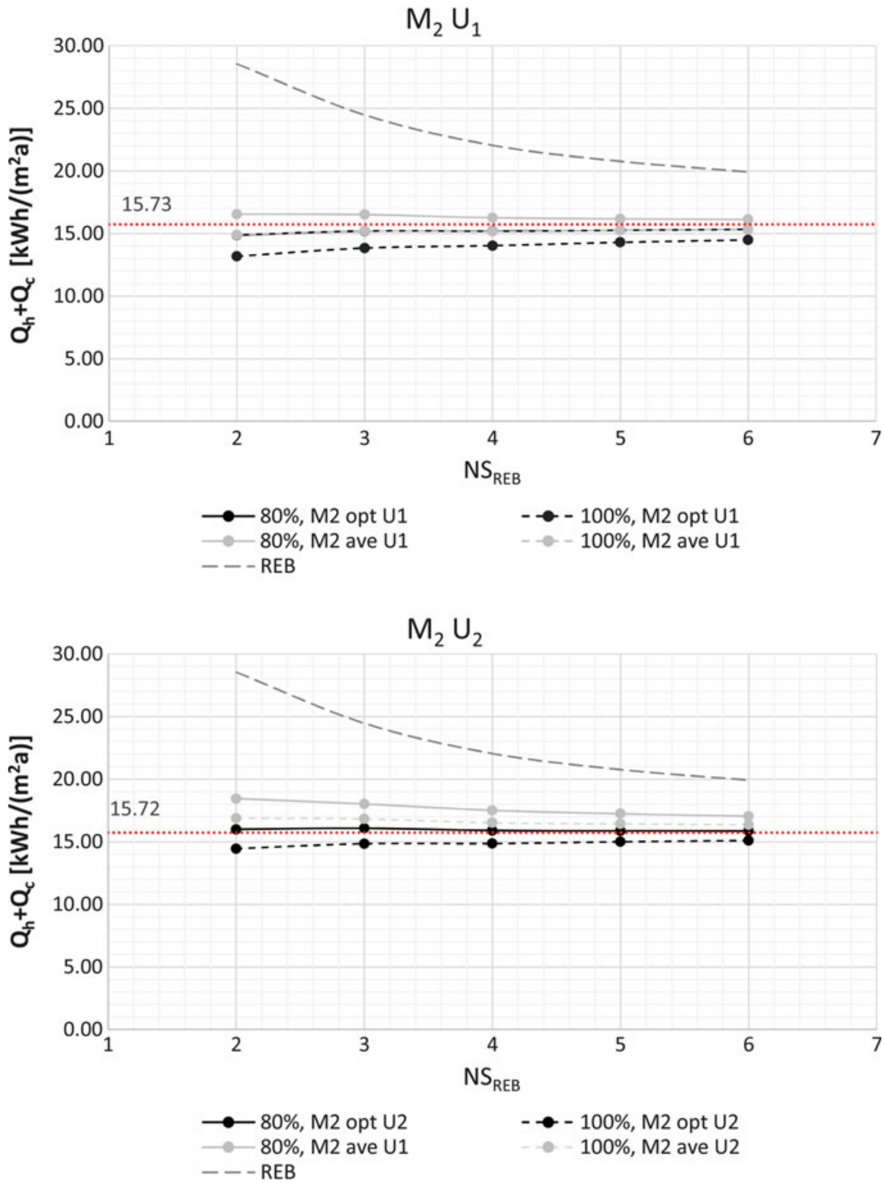


Fig. 4.53 Energy need for heating and cooling ($Q_h + Q_c$) resulting from the extension with different types of two-storey (M_2) upgrade modules (U_1, U_2) [61]

from that of the increasing number of storeys (NS_{REB}). Nevertheless, among the upgrade module types of RCR = 80%, only the most influential module $M_{2\ opt}\ U_1$ surpasses the prevailing influence of the increasing number of storeys (NS_{REB}) [61].

The most influential parameter evident from Fig. 4.53 proves to be the rooftop coverage ratio (RCR), followed by the glazing-to-wall area ratio (AGAW) in the second place and thermal transmittance of modules envelope elements (U) in the last. A comparison of the presented results points to a higher impact of the selected glazing size (AGAW) for module types partially covering the REB rooftop area (e.g. RCR = 80%) in comparison to those covering the entire REB rooftop area (RCR = 100%). Moreover, a less significant influence of the RCR when upgrading with module types of lower thermal transmittance of the thermal envelope (U_1) is noticed.

An obvious advantage of upgrade modules covering the entire rooftop area of the REBs, as seen from a purely energy efficiency viewpoint, is diminished when taking into account also other aspects of living comfort, including outside living areas, such as balconies and terraces. Since a possible design of upgrade modules varies in RCR, we analysed the impact of building extension for the decreased RCR, from RCR = 100% down to RCR = 50%. Figure 4.54 shows the influence of the changing RCR on the energy need for heating and cooling ($Q_h + Q_c$) and the total energy savings ($(Q_h + Q_c)_{SAVING}$) when extending REB A of different theoretical NS_{REB} with different two-storey module types.

As evident from Fig. 4.54, the energy need for heating and cooling ($Q_h + Q_c$) for all NS_{REB} values decreases almost linearly with the increase of the RCR. The steepest decrease for the most energy-efficient $M_{2\ opt}\ U_1$ type and the most gradual decrease for the $M_{2\ ave}\ U_2$ type can be noticed, suggesting a higher impact of the RCR for the most energy-efficient upgrade module types. Moreover, the NS_{REB} proves to be most influential at a lower RCR, with the impact of RCR being weaker for taller buildings. The influences of the RCR and NS_{REB} achieve balance/equalize at some point, which emerges in the area from approximately RCR = 75% up to approximately RCR = 90%. This feature cannot be defined for $M_{2\ ave}\ U_2$, where the NS_{REB} always surpasses that of the RCR.

On the contrary, Fig. 4.54 points out that the total energy savings ($(Q_h + Q_c)_{SAVING}$) increase with the increase of the RCR and the decrease of the NS_{REB}, where higher energy savings due to the increased RCR result from the increased upgrade module's influence. The highest total energy savings ($(Q_h + Q_c)_{SAVING}$) go to the $M_{2\ opt}\ U_1$ type with a higher RCR and a lower NS_{REB}, as expected according to our previous findings in Sect. 4.3.3.3.

The presented results can assist professionals in their estimation of the corresponding energy savings relative to the extension renovation measure based on the selected existing building height, desired RCR and module type. The results are also beneficial to the process of defining appropriate upgrade module design parameters in order to achieve a desired energy standard of renovated buildings.

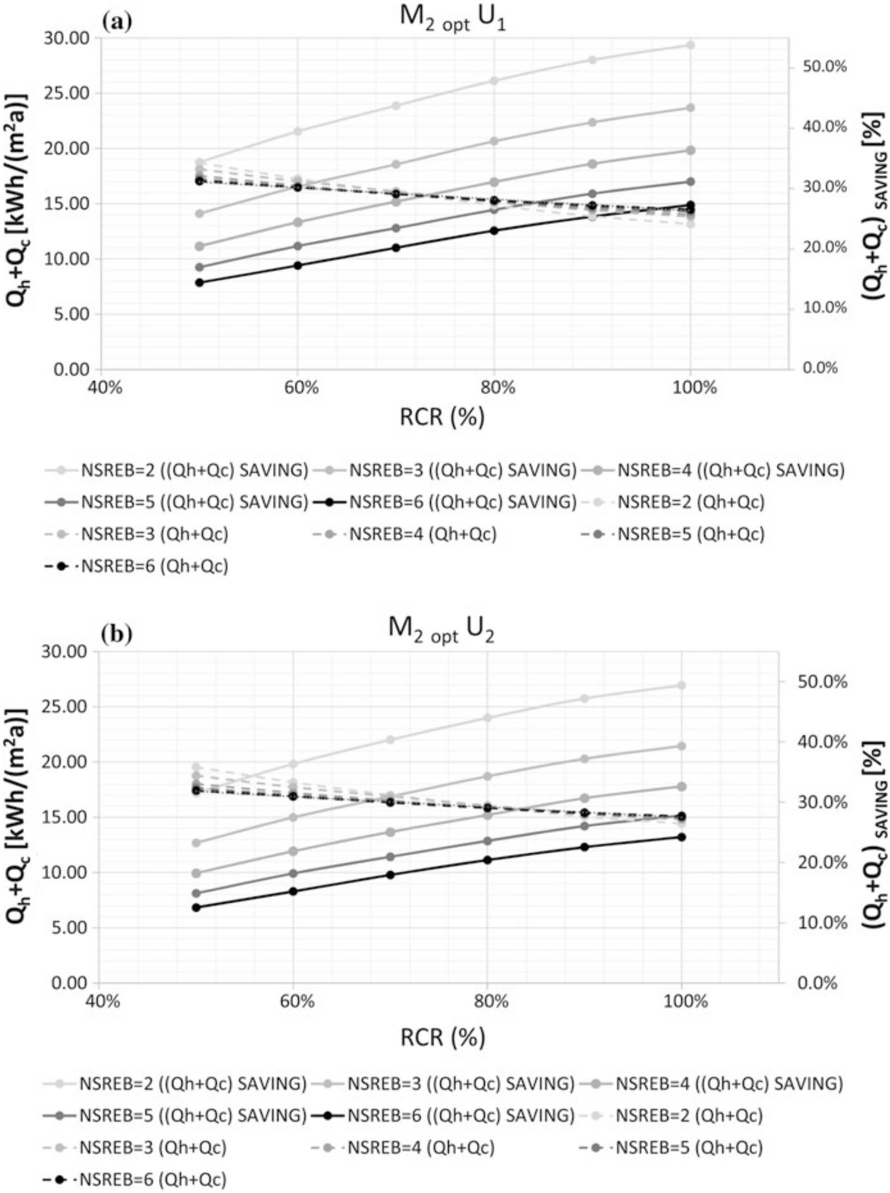
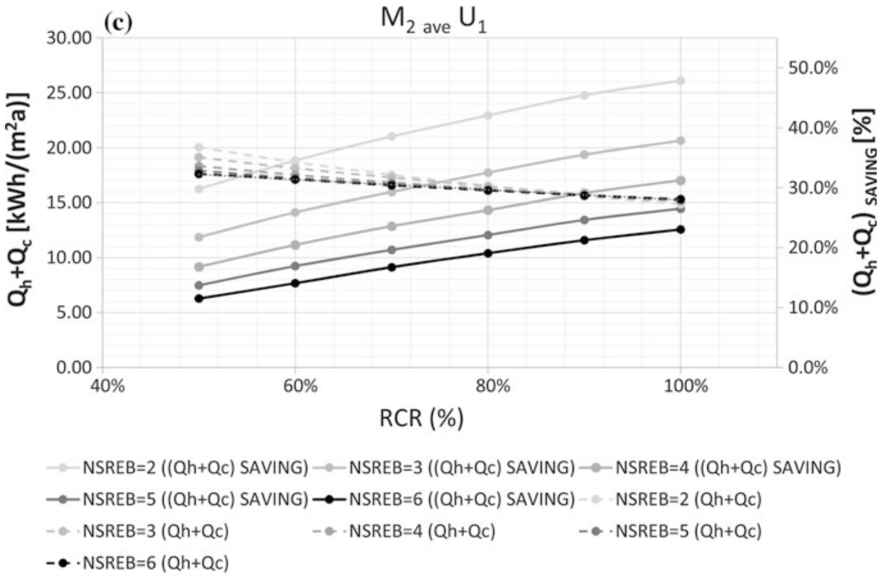


Fig. 4.54 Energy need for heating and cooling ($Q_h + Q_c$) and the total energy savings ($(Q_h + Q_c)_{SAVING}$) resulting from the extension of different NS_{REB} with different RCR and two-storey (M_2) module types



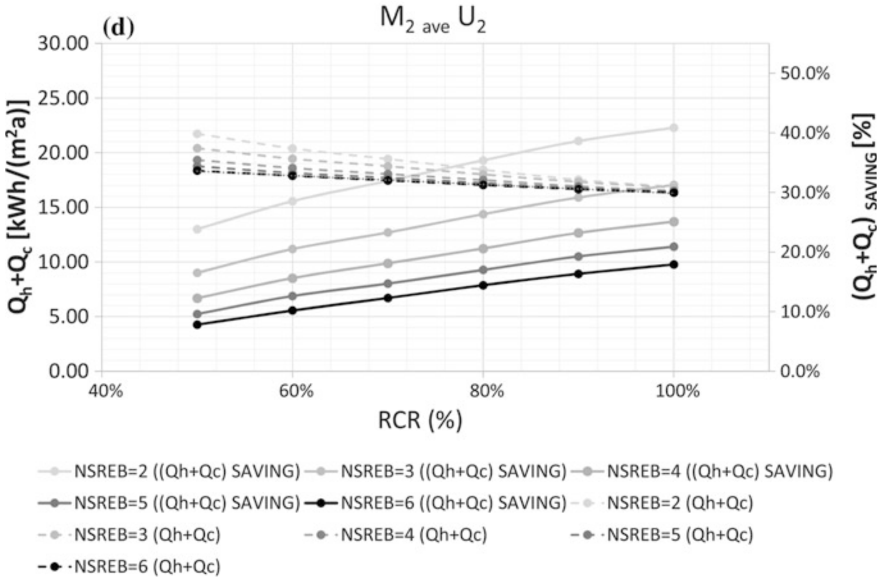


Fig. 4.54 (continued)

Although the results prove that building extension by means of installing two-storey modules with a higher rooftop coverage ratio (RCR = 100%), lower thermal transmittance (U_1) and the optimal glazing size ($AGAW_{opt}$) is the most energy-efficient, taking into consideration also other aspects supports the usefulness of other versatile upgrade module design possibilities for extending the REBs with upgrade modules.

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