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Vesna Žegarac Leskovar
Miroslav Premrov

Integrative Approach to Comprehensive Building Renovations

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Chapter 1
Introduction

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1.1 Why Researching the Topic of Building Renovation?

Factors to consider in the decision to renovate buildings arise from various causes. In most cases, the building state does not correspond to the current or future requirements of its users. Decisive reasons calling for the renovation are excessive energy consumption or inadequate fire or structural safety, indoor air quality thermal and visual comfort. Additionally, also the weaknesses related to unsuitable building functionality or to various economic or social issues can generate efforts aimed at building renovation. Considering various building deficiencies, it is crucial to be aware of the influence the building quality has on its users and broader society.

Built environment is a focal point of human socio-economic activities and represents one of the biggest European and worldwide economy sectors as seen from the economic perspective, which creates its inseparable connection to socio-economic influence and general development of the society. A predominant part of our daytime being spent inside buildings makes living comfort vital to the well-being and work effectiveness of its users. The quality of the building is assessed by a set of various parameters with the most general ones being its functionality, static stability and safety along with multiple criteria related to the indoor environment quality (IEQ). While the trends in new build design and construction focus on achieving high energy efficiency, excellent environmental performance in addition to flexible design and architecturally conceived unique building geometry, the current situation regarding the existing housing stock, at least within the scope concerning energy efficiency, is completely different.

Buildings in Europe date from different periods with specific building strategies and regulations typical of the time. A substantial proportion of the existing European housing stock, consisting of 75% of residential surfaces and approximately 25% of non-residential buildings, is more than 50-years old. Almost 40% of residential housing stock was built prior to 1960 with a share of 50% dating from

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the period before 1970 [1–3], when building regulations mandating thermal properties of building envelopes and seismic safety standards were rather loose and inadequate. The most substantial increase of the new build, i.e. 45% of the existing stock [4], was seen in the period from 1961 to 1990. The fact that most European countries' national building regulations mandating thermal properties of building envelopes were introduced after 1970 leads to the assumption that 50% of the housing stock lacks proper thermal protection [5]. Only when the Energy Performance of Buildings Directive 2002 [6] serving as a base to stricter national regulations came into force, significant efforts to increase the energy efficiency in the operational phase of the building were put forth and became even more pronounced after the implementation of the EPBD recast in 2010 [7]. The listed data referring to the age of buildings are in accordance with the situation in the field of energy use within which buildings in Europe account for approximately 40% of the final energy consumption, with the largest share being spent on heating, and are responsible for greenhouse gas emissions in an almost equal proportion. Renovation of older housing stock built before the introduction of stricter national directives on the energy performance of buildings thus represents an enormous potential to improve their energy efficiency and achieve the subsequent reduction of the final energy consumption and greenhouse gas emissions. Furthermore, the focus of building renovation should also be laid on the improvement of the indoor environment quality factors which can be indicated by the indoor air quality along with thermal, acoustic and visual comfort. Unfortunately, as often seen in practice, especially in cases where buildings underwent only a partial renovation process, almost no attention was paid to IEQ while in many instances even a worsening of the air quality was detected after the implementation of specific renovation measures. Another case of a common error committed in the process of energy-efficient renovation is seen in focusing solely on the optimal energy efficiency, occasionally also on the functional performance, while neglecting the seismic safety of buildings. Numerous instances of buildings collapse due to recent catastrophic earthquakes worldwide call for the need to take a serious approach when designing and renovating earthquake-resistant buildings. Unfortunately, the issue of seismic safety of renovated buildings is regulated only by Eurocode 8 [8], whose provisions do not cover a variety of possible design concepts of building renovations. Moreover, there are no guidelines nor is there an interdisciplinary approach which would consider a parallel energy performance, indoor environment quality and construction-based renovation which is the only sensible path leading to comprehensive renovation of buildings. The existing building regulations, therefore, fail to define specific approaches to systematic consideration of the efficiency and feasibility of various measures to be taken when renovating existing buildings. Additionally, it is also important to note that renovation within the context of historic buildings presents even a more demanding challenge since it comes with many of the earlier mentioned quality problems while trying to retain the building original character and design concept.

In addition, a strong argument supporting the need to develop systematic guidelines for comprehensive building renovation encompassing functional

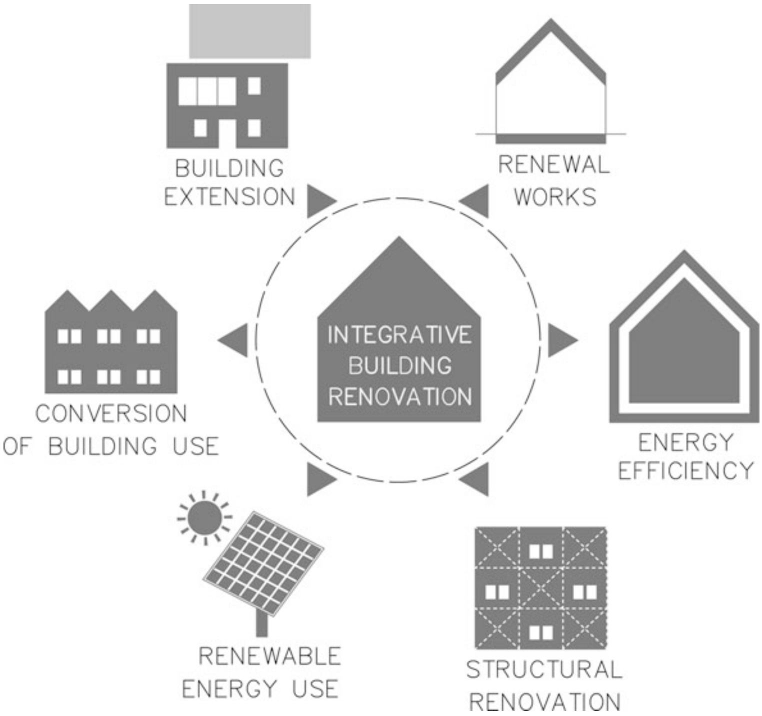

Fig. 1.1 A scheme of comprehensive building renovation

performance, energy efficiency as well as construction-based renovation (Fig. 1.1) is also seen in a relatively low percentage of the new build representing only 1% of the total housing stock in the period from 2005 to 2010 [4]. According to the literature sources [9] relevant to the 2005 situation in industrialized western countries, the number of existing buildings needing to be taken care of was even higher than the number of buildings that needed to be built. Regarding the need for the new build, a lack of available surfaces, both residential and non-residential can be identified in large central, northern and western European cities. Due to a shortage of free construction positions in city centres, renovation by vertical extension of existing buildings in view of increasing the surface proportion would be a sensible option, which represents a further level of functional and energy performance renovation.

As the text above opens a long list of energy performance, IEQ, construction-related and functional problems, the aim of the construction sector should, therefore, be to find solutions through an interdisciplinary approach using the knowledge, research results and experiences from various disciplines.

1.2 Definition of the Term "Renovation"

The existing literature indicates that a general use of terminology associated with improvement of the building quality is rather inconsistent and unclear among experts and researchers from different regional or international environments. There is a mixture of most commonly used terms referring to the processes of building improvement, such as renovation, retrofit, upgrade, refurbishment, etc. Owing to the lack of unified and clearly defined terminology, the term "renovation" will be used in this book. According to Collins dictionary [10], the term "renovation" refers to the process of repair, improvement and returning something to a good condition. Consequently, in the construction industry renovation refers to the process of improving or modernizing an old, damaged or defective building. Renovation, therefore, leads to improvement which displays better physical conditions, enhanced functional performance or even a changed use of a building.

1.3 The Content of the Book

The current book has been written in order to present various priorities of renovation processes in addition to emphasizing the importance of interdisciplinary and integrative approach when considering the issue of building renovation.

The book consists of four chapters. This chapter is an introduction to the issue of building renovation identifying the need to renovate buildings and defining the terminology used. Chapter 2 presents an overview of various renovation approaches according to their scope, intensity and priorities. A brief explanation of particular approaches is based on examples taken from practice. The first part of Chap. 3 contains theoretical backgrounds considering energy flows in buildings with subsequent analysis of the climate data and building geometry parameters that influence building behaviour. Moreover, a development of a special approach to defining an effective building thermal transmittance coefficient implementable in the newly built or renovation design process is presented. The second part of Chap. 3 offers a theoretical and systematic description of separate energy efficiency renovation steps forming a good theoretical base to be used for more complex analyses of renovation measures and their combinations presented in Chap. 4. The last chapter, Chap. 4, contains an overview of existing scientific literature on building renovation. As previously mentioned, the second part of the chapter presents the authors' own research on the energy efficiency renovation.

The general aim of the current book is to expose various approaches to renovation of existing buildings and to combine practical experience with existing research findings in order to disseminate knowledge and raise awareness on the importance of integrative and interdisciplinary solutions, which can lead to multiple benefits and enable provision of best possible living conditions for the current and future generations.

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Chapter 2
Classification of Renovation Approaches

Vesna Žegarac Leskovar and Miroslav Premrov

2.1 Renovation Measures and Their Impact on the Building Quality

Multiple cases of building renovations conducted across Europe exhibit a great variety in renovation concepts specific for their priorities. Various decision factors precondition the selection of the most adequate renovation approach. Primarily, the decisions are based on a detailed analysis of an existing building, of its urban and social context, its physical state and function, taking into account a consequent degree and type of hazard in the case a building would not undergo any interventions. Furthermore, the concept of renovation process depends also on the stakeholders' interests, availability of economic resources, accessibility of building materials and construction techniques, current building legislation, etc., whereby all these factors may vary between different countries and even local environments. Apart from technical and economic influential factors, some social aspects specific to certain societies, such as the general perception of building and indoor environment quality, may also affect renovation decisions.

Taking into account a diversity of possible renovation solutions, this chapter aims to define, describe and differentiate between most typical renovation approaches with the classification based on the main targets as well as priorities of the renovation process.

Before presenting the classification of renovation approaches, it is necessary to specify basic renovation measures and their contributions to the rise in the building quality. It is a well-known fact that within its lifespan each building has to undergo regular preventive maintenance cycles and in some cases also the emergency maintenance, in order to maintain its original quality, value and function. Maintenance works are related to general repairs of the building fabric and building service systems. In the context of the whole building life cycle, these works can prologue the building use phase. Carrying out repeated maintenance cycles is beneficial until the point at which a building fails to satisfy the occupiers' demands

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[1]. Even if buildings are regularly maintained, certain circumstances that provoke a need for more significant changes in their original or current state will eventually appear. In such cases, maintenance is no longer an adequate process and the treatment of buildings has to be upgraded to the level of building renovation.

Renovation refers to the execution of measures aiming at improvement of the building physical condition and it is functional performance. In cases of partial renovation, the range of performed measures is quite limited and results mainly in partial improvement of the building's physical condition. Contrariwise, increasing the set of improvement measures leads to a more thorough outcome affecting both, the current physical state and functional performance of the building. The relation between renovation measures and the effects of their implementation on the building physical condition and functional performance improvement is shown in Table 2.1.

Table 2.1 Renovation measures and their effect on the building physical condition and functional performance

Groups of measures	Measures improving the building physical condition	Consequent effect on the building functional performance
Renewal of the building thermal envelope	Retrofit of the building thermal envelope performance (non-transparent)	Reduction of the energy need for heating and cooling, improvement of thermal comfort and airtightness
	Replacement of the existing windows with the energy-efficient ones	Reduction of the energy need for heating and cooling, improvement of thermal comfort, acoustic comfort, visual comfort and airtightness
	Application of solar control strategies (shading elements, devices or systems, solar coatings)	Reduction of the energy use for cooling, improvement of thermal and visual comfort
	Enlargement of glazing areas	Reduction of the energy use for heating, improvement of thermal and visual comfort
	Green roofs, green façades	Reduction of the energy use for heating and cooling, improvement of thermal comfort
Renewal of the building components	Addition of structural elements	Structural reinforcement, seismic reinforcement, noise reduction, new spatial arrangement
	Removal of structural elements	New spatial arrangement
	Installation of fire-resistant materials	Improvement of fire safety
	Replacement of hazardous building materials	Reduction of health risk
	Replacement of damaged building materials	Reduction of health and safety risk, provision of better living conditions
	Addition of insulation materials or/and structural elements	Improvement of thermal and acoustic comfort

(continued)

Table 2.1 (continued)

Groups of measures	Measures improving the building physical condition	Consequent effect on the building functional performance
Renewal or addition of active technical systems	Retrofit or replacement of the heating system (space heating, water heating)	More efficient use of the primary energy, improvement of thermal comfort
	Retrofit, replacement or initial installation of the ventilation system	Improvement of air quality, reduction of ventilation losses
	Retrofit, replacement or initial installation of the cooling system	Improvement of thermal comfort
	Replacement of the existing with energy-efficient lighting	Decrease in the electric energy use, improvement of visual comfort
	Installation of PV panels	Energy generation
Building extension	Addition of building volumes (upgrade modules, balconies, loggias, other horizontal extensions)	Acquisition of new usable floor area, increase of the building energy efficiency
Addition of alternative ecosystems	Rainwater collection and use	Decrease of potable water consumption
Accessibility	Addition of ramps, inclined surfaces, elevators	Enabling barrier-free communications

As shown in Table 2.1, renovation measures aimed at improving the building physical condition have a direct influence on the improvement of building functional performance. Individual measures are joined into groups according to the area of their application. Many of the above-stated interventions are not only beneficial for their technical and measurable consequences. The effects of their application can be correlated to different aspects of sustainability. For example, retrofit of the building thermal envelope has a positive impact on the reduction of the energy use for heating, which is associated with the environmental and economic perspectives. Additionally, it raises the building market value, which is correlated to the economic aspect of sustainability. Simultaneously, the same measure allows for the improvement of indoor thermal comfort influencing the occupants' well-being, which directly correlates to the social aspect of sustainability. Furthermore, interventions raising the building's aesthetics, enabling better flexibility or a new use of space result in the improvement of the building architectural significance, which is again connected to sociocultural perspectives of sustainable development. Thus, the effects of individual renovation measures are often multi-layered and the overall benefit of the renovation process is expected to be dependent on the scope of all conducted measures.

2.2 Approaches to Building Renovation According to the Intensity and Scope of Interventions

The scope of renovation, i.e. the quantity of renovation measures defines how this process is going to affect the building quality. Accordingly, three main categories of renovation, i.e. partial, deep and comprehensive, can be distinguished (Table 2.2). In the context of sustainability, the building quality indicators can be further correlated to the main aspects of sustainable design.

Partial renovation represents a process where just one or few measures focusing on a relatively narrow target area are taken. For example, in the case prioritizing partial improvement of the building energy efficiency, only single measures, like window replacement or thermal façade installation or roof insulation, are conducted. A consequence of such partial renovation is a relatively low decrease in the energy need [2]. For a substantial decrease in the energy need, a deep renovation is unavoidable, where also the measures improving the building active technical systems are taken in addition to a complete set of measures improving the properties of the building thermal envelope. Besides, the energy savings which have a major effect on lowering environmental burdens and building maintenance costs, such a deep renovation process induces the rise of indoor thermal comfort quality and the users' satisfaction—the factors belonging to the social aspect of sustainability. The terms "partial" and "deep" are commonly correlated to one target area, for example partial renovation of the building envelope or deep energy efficiency renovation. The highest level of building improvement according to the intensity and scope of interventions and in relation to the context of sustainability can be achieved by a comprehensive renovation aiming at improving multiple criterions of the building quality and their associated sustainability aspects. Comprehensive renovation can be, therefore, treated as an integrative sustainable solution. Although it is possible to detect the use of terminology like "comprehensive energy-efficient renovation" or "comprehensive functional renovation" by authors of the existing literature, in our book the concept of comprehensiveness corresponds to renovation

Table 2.2 Types of renovation approaches according to the intensity and scope of interventions

Intensity and scope of renovation	Partial	Deep	Comprehensive
	One or few renovation measures	Set of requisite renovation measures	All requisite renovation measures
Achievement	Partial improvement of the building physical condition and functional performance	Thorough improvement of the building physical condition and functional performance	Improvement of the building quality from technical, functional, environmental, social and economic perspectives
Level of overall efficiency	Low	High	Excellent

processes displaying interdisciplinary solutions not focusing solely to one goal. A comprehensive renovation approach is a process considering the building weaknesses and potential enhancements in a highly holistic manner. The problem solving tends to integrate several viewpoints linked to different expert disciplines. Many questions related to building safety, structural and seismic stability, indoor environment quality associated with thermal, acoustic, visual comfort and health aspects, usefulness, its adaptability to the needs of the current user, accessibility for persons with disabilities, aesthetic appearance, economic issues, etc., are considered within the process of comprehensive building renovation. Accordingly, positive outcomes are expected within multiple criteria of sustainability. Environmental benefits of buildings having undergone a comprehensive renovation process are seen in lowering environmental burdens, i.e. emissions to air, water and landfill, and in a decrease in the energy consumption, all of which is, however, related to the phase of the building use stage. Within the social sphere, the outcomes followed by comprehensive renovation involve preservation of the building design qualities and sociocultural values [1], health and well-being aspects. Furthermore, initial building design concepts can even see improvement compared to the original state of design and adapt to the current needs of our modern society, to technical requirements and current building regulations. Next to environmental and social advantages, economic benefits such as lowering maintenance costs, increasing the asset value, avoiding void periods, extending the building life cycle, can also be achieved by a comprehensive renovation approach [1]. Additionally, it is highly sensible to extend the consideration of optimal renovation solutions throughout the whole building life cycle and not only within the phase of building use.

Regarding the importance of a multidisciplinary approach renovation of buildings should be projected with the intention to attain a high degree of comprehensiveness. The required level of comprehensiveness needed to attain a radical improvement of the building quality depends on specific requirements of each individual case. Numerous examples of building renovations conducted in practice still lack a comprehensive approach. The causes can be mainly found in limited financial resources, while unfortunately in many cases the reason is also deficiency in holistic knowledge investors and decision-makers have of the benefits of such renovation approaches. In this context, the aim of the current book is to expose various approaches to recovery of existing buildings in order to disseminate knowledge and raise awareness of the potential socio-economic and environmental contribution.

2.3 Approaches to Building Renovation According to the Main Priorities

As already mentioned in the previous section, most buildings have a useful lifespan with regular maintenance cycles required to upkeep their original state, function and performance. In the course of time, the buildings can become obsolete and consequently inadequate for its original use. Langston et al. [3] identify different causes of obsolescence; from physical, over economic, functional, technological and social to legal obsolescence. Over time, buildings can experience natural decay which leads to physical obsolescence; economic obsolescence is recognized when buildings fail to meet the cost efficiency criteria in regard to the investors' interests; functional obsolescence occurs where the current state of the building no longer corresponds to its original purpose; technological obsolescence appears where the building or its components no longer technologically achieve the performance of contemporary solutions; social obsolescence is encountered where the building no longer meets behavioural trends or needs of the building users; and legal obsolescence arises where the building no longer satisfies a variety of current building rules and regulations. Besides the above-stated types of obsolescence, the building can be inadequate for further use due to damages caused by fire, earthquake or toxic pollutants. The above-stated types of building obsolescence and causes of building inadequacy are responsible for the determination of respective priorities in particular building renovation processes focusing on improvement of the building properties, performance or function. In this context, types of renovation approaches can be distinguished according to their absolute improvement priority (Table 2.3).

Table 2.3 Types of renovation approaches according to main priorities

Approaches	Priorities
Minor renewal	Replacement of deteriorated building components or technical systems
Renovation within the context of historic buildings	Preservation Rehabilitation Restoration Reconstruction
Renovation targeting improvement of the building state and performance	Energy efficiency Structural resistance Indoor environment quality Fire safety
Functional renovation	Building biology Retention of use Building extension Conversion of use

2.3.1 Minor Renewal Works

Even if regularly maintained, the building components or services may become subject to deterioration, damage or inadequate performance. Minor renewal works are necessary in such cases to retrofit the state of defection, which is usually conducted without any design plan. Minor renewal is actually not treated as a design approach but an urgent reaction to specific building malfunction.

2.3.2 Approaches Within the Context of the Treatment of Historic Buildings

Historical buildings may have a unique heritage value which is crucial in terms of remaining the evidence from the past and transferring cultural identity to further generations [4]. These buildings should, therefore, be treated by suitable conservation approaches prolonging their lifespan and retaining their intrinsic heritage, historical and cultural value. The treatment of historical buildings addresses many challenges like sociocultural, economic and technical, while the regulatory challenges are predominately very restrictive in many cases and limit the selection of renovation measures. Although not addressed in the second part of this book, basic approaches to treatment of historic buildings are briefly presented in this section.

2.3.2.1 Preservation

According to standards for the treatment of historic properties with guidelines for preserving, rehabilitating, restoring and reconstructing historic buildings [5], preservation is defined as *“the act or process of applying measures necessary to sustain the existing form, integrity, and materials of an historic property”*. It is required in the preservation process to retain the building’s historic form and the highest possible amount of fabric focusing on the protection of the property, while any new additions, such as extensive replacement and new construction, are being out of the scope of this treatment. Although very limited in the scope of renovation measures, it is still possible to carefully conduct some minor new interventions necessary to enable the building operation according to its use.

2.3.2.2 Rehabilitation

The rehabilitation process acknowledges alteration of a historic building to meet continuing or new uses while retaining the building’s historic character, its cultural and architectural values [5]. The alteration works like repairs, new additions or replacements of extensively deteriorated, damaged, or missing features may be

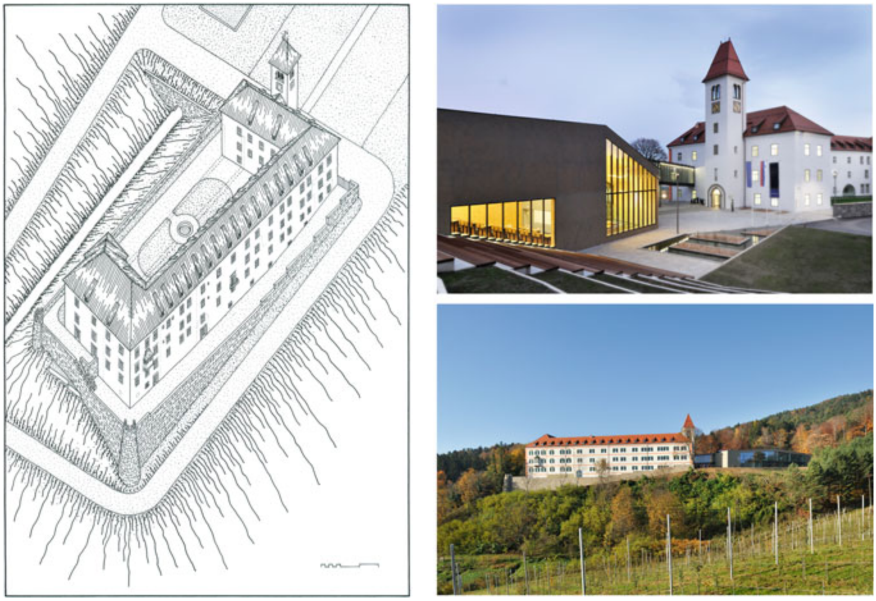

Fig. 2.1 Drawing of the Hompoš Castle denoting its state around 1950—left (drawing by Igor Sapač [6]); The university building consisting of the rehabilitated castle and the new building extension—right up and right below (photos by Miran Kambič)

used, whereby only limited changes to distinctive building materials, spaces, and spatial relationships are accredited. Despite alterations, the essential form and integrity of the historic building should remain unimpaired, while an efficient contemporary use of the property is enabled.

An extensive rehabilitation of a historical castle complex with a new building addition has been carried out on one of the oldest preserved castles in Slovenia, the Hompoš castle (Fig. 2.1).

The castle that served several purposes in the history lost a lot of its authentic, historical, artistic and architectural motives owing to numerous historical reconstructions. Besides its original use, it functioned as a health resort, a sanatorium and also as a psychiatric hospital. Due to diverse past interventions, the style-related diversity of the building structure could be detected from the presentations of the façade treatment, details and materials. In the 2007–2008 period, the castle underwent a process of a major rehabilitation with the transformation into a university institution and it serves today as the Faculty of Agriculture and Life Sciences of the University of Maribor [6]. The rehabilitation project was fairly complex and a subject to cooperation of multiple specialists of various disciplines ranging from archaeology, preservation, architecture, structural engineering to history, all of whom devoted their efforts to preservation of the authentic historical building structure, artistic details and elements while creating new revitalized facilities fully adapted to the demands of new users. The main architectural contribution was developed by an interdisciplinary group of architects, consisting of a specialist for conservation, Eva Sapač, a specialist for the castle architecture, Igor Sapač and the architect David Mišič; with a new building extension designed by David Mišič from the Styria Arhitektura office. The rehabilitation process significantly increased the cultural and historical significance of the castle and additionally influenced the cultivation of the environment which now gained the role of an educational and research area. As stated in [6], this case firmly shows that the cultural heritage is not a burden but an opportunity.

Another representative renovation case implemented on historical buildings is the rehabilitation of the neoclassical corner palace in the centre of Maribor, built in 1914 for the needs of the state bank. The original building representing one of the main architectural contributions of the early twentieth century in the town of Maribor was designed by architects Fritz Friedriger and Max Czeike. Up to the end of the twentieth century, the building served a most diverse line of users with occasional periods of the building being vacant. In 2016, the building experienced a major renovation and was rehabilitated for the needs of the Faculty of Civil Engineering, Transportation Engineering and Architecture, University of Maribor (Fig. 2.2).

The architects responsible for the renovation, Janko Zadravec and Uroš Lobnik, planned a transformation and spatial reorganization of the existing building with a view to preserving as much of the historical structure as possible without major

Fig. 2.2 Interior and façade views of the renovated city palace; today the University of Maribor facility (photos by Virginia Vrecl)

interventions to the original and historically protected architectural elements, while ensuring the highest quality in regard to usability of the premises for the educational, scientific and artistic activity. Emphasizing the importance of reusing the existing empty building the renovated palace also acts as a liveable classroom to students of the Faculty of Civil Engineering, Transportation Engineering and Architecture, University of Maribor, experiencing education in the innovative manner through activities being held in classrooms, communication areas redesigned to be used as social activity nodes, work and experimental rooms, exhibition places, etc. With thoughtful interventions, the palace succeeded to preserve the character of an individually identifiable representative urban building with socially important public content. An additional contribution of the project is seen in the increased cultural–historical value of the building, while at the same time an important step forward was made in the context of a sustainable revitalization of the city centre.

2.3.2.3 Restoration

In standards for the treatment of historic properties with the guidelines for preserving, rehabilitating, restoring and reconstructing historic buildings [5], restoration is defined as a process of accurate depiction of the form, features, and character of a building as it appeared at a particular period of time through the removal of features from other periods in its history and reconstruction of the missing features from the restoration period. According to Grimmer and Weeks [5], the goal of the restoration process is to make a building appear as it did at a particular and most significant time in its history, rather than maintaining and preserving a building as it has evolved over time. Detecting a building state of development over particular historical periods is, therefore, basic to the process of building restoration (Fig. 2.3). As opposed to other treatments of historical buildings, the scope of work in restoration can include removal of features from other periods. A limited upgrading of active technical systems and taking other necessary measures in order to make the building functional are allowed within a restoration project.

2.3.2.4 Reconstruction

According to Grimmer and Weeks [5], reconstruction is defined as *"the act or process of depicting, by means of new construction, the form, features, and detailing of a non-surviving site, landscape, building, structure, or object for the purpose of replicating its appearance at a specific period of time and in its historic location"*. Since the original structures no longer exist, the reconstructed buildings are generally rebuilt with new materials [8].

Reconstruction is based on a comprehensive process where the data on the original building are acquired from available documentation, such as old design drawings, illustrations and photographs. Furthermore, the collected information

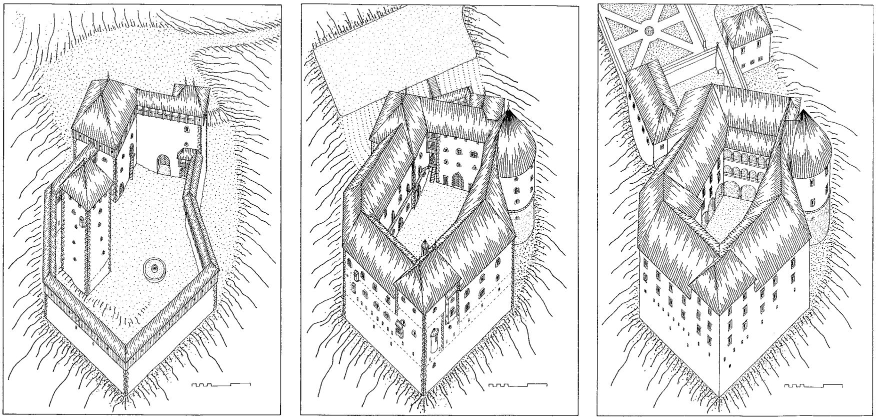

Fig. 2.3 Drawings presenting historical development of the Rajhenburg castle in Slovenia: twelfth century—left, sixteenth century—middle, eighteenth century—right [7] (drawings by Igor Sapač)

needs to undergo data processing aimed at generation of comprehensive and detailed documentation on the original building. However, the availability of historical documentation tends to be of a varying nature, since the existing sources may be rather inhomogeneous in level of detail, scale and complexity. Discussions on whether the quantity or quality of available information is sufficient and adequate for the reconstruction to reach a desired degree are often subject to heated debate. Fortunately, there is a wide variety of photogrammetric techniques available, enabling provision of adequate and complex information about the original buildings based on the historical images [9].

An instance of the reconstruction of a partly existent structure is that of the Mirna castle representing one of the oldest castle architectures in Slovenia dating from the eleventh century (Fig. 2.4).

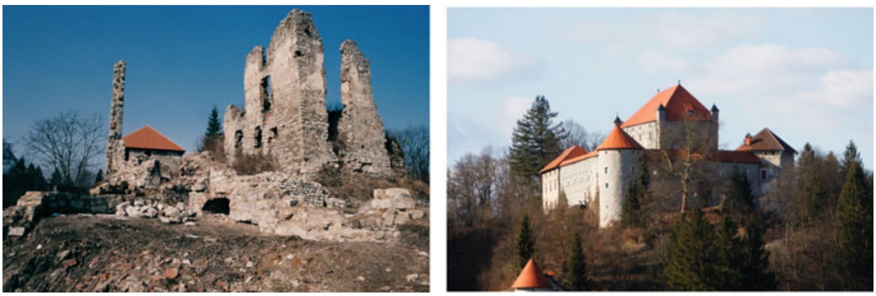

Fig. 2.4 Reconstruction of the Mirna castle, Slovenia: state prior to reconstruction in 1990—left, reconstructed state—right [10] (photos by Igor Sapač)

The castle was damaged in an arson attack in the Second World War (WW2). The ruins were subject to several blasting operations in the post-war period until being totally demolished by 1961. Partial renovation of the castle started in 1962 with major reconstruction works finished in 2006. It is the only example of castle architecture in Slovenia being ruined in and after WW2 that has undergone total reconstruction, successfully implemented mainly on account of the preserved and reliable historical documentation. The reconstruction succeeded in restoring the original form with a partial use of modern materials clearly pointing at restoration interventions [10].

2.3.3 Renovation Approaches Targeting Particular Improvement of the Building State and Performance

In regard to the cause of obsolescence or decay, renovation can be focused on specific goals prioritizing certain improvements of the building state or performance. In the last two decades, a large share of conducted renovations has been oriented towards the improvement of the building energy efficiency. The energy efficiency renovation still presents one of the main challenges for the EU building stock. Residential and public buildings in Europe have been undergoing an intensive trend in the field of energy-efficient renovation recently, which is to largely imposed by the Energy Performance of Buildings Directive [11]. With the aim to significantly reduce the energy consumption of the existing buildings, EU countries provide various financial instruments subsidizing energy efficiency renovation. On the other hand, there is still a lack of control over the adequacy of implementation regarding such renovations. Unfortunately, the financial subsidies are mainly preconditioned by the indication of energy saving due to renovation, while a complex control of the indoor environment quality improvement is not a matter of financial incentives. For example, although the energy need for heating was reduced, the indoor air quality can even exacerbate if ventilation strategy has not been reconsidered when replacing the existing windows. The latter is especially important since the existing buildings can contain building materials with toxic solutions that can affect the users' health. Another important issue inducing a need for building renovation is safety. The design knowledge on building performance in earthquakes, fires and other extreme events was still nascent in the periods when many of the existing building were planned. The broadening of knowledge led to stricter regulative demands in building design in order to attain fire resistance, seismic resistance, resistance to extreme winds and other extreme weather events. The issue of building safety conditions is unfortunately getting far less attention as the energy efficiency, although it might be even more important to the building occupants. Accordingly, the comprehensive renovation process should be planned to pursue more objectives at the time in order to affect the overall enhancement of building quality.

2.3.3.1 Energy Efficiency Renovation

In terms of energy use, the basic aim of energy-efficient renovation is to reduce the energy consumption for building operation. The structure of energy use in buildings consists of the energy need for space heating, space cooling, domestic water heating, lighting, electricity for operation of active technical systems—HVAC systems and household appliances. As an additional objective, the integration of energy generation systems based on solar and wind energy also fits in the context of energy-efficient renovation. Although emphasizing primarily the energy problem, which is related to economical and environmental aspects, the next important benefit of such renovation should be placed within the social perspective of sustainability. In terms of indoor climate quality, the basic aim is to improve air quality, thermal comfort and visual comfort which all affect the users' health and well-being. Consideration of improving the indoor environment quality indicators is often very superficial in practice, especially in cases where the energy-efficient renovation is just partial. For example, if only the replacement of old windows with energy-efficient ones along with additional insulation of external walls is conducted without taking care of appropriate ventilation and reduction of thermal bridges, the air comfort quality drastically decreases, while also some other instances of damages, like mould on building fabric due to an increased surface condensation appear. It follows that energy-efficient renovation is not adequate if carried out with partial measures only. For the overall effect in the building quality improvement, the comprehensive energy-efficient renovation is the only acceptable option.

A detailed theoretical description of the energy-efficient renovation approach is given in Chap. 3, while the current section only addresses its main challenges. In this context, the comprehensive energy-efficient renovation consists of three groups of measures (Table 2.4):

- Measures affecting the energy flow between the building and its surroundings (for a detailed explanation on energy flows see Sect. 3.1.1) with the consequent IEQ improvement potential,
- Measures affecting the improvement of the energy use efficiency and the integration of renewable energy use,
- Measures for the integration of electrical energy generation systems.

The first group of measures presented in Table 2.4 unifies a variety of interventions taken on the building envelope, such as additional insulation of the roof, external walls and bottom plate with an adequate treatment of thermal bridges, replacement of windows or even addition of new transparent surfaces, etc. In everyday practice of comprehensive energy efficiency renovation projects, the scope of interventions is wide and not limited to separate measures, as in the case of partial renovations, or to one group of measures only. As an example, the renovation of the 906 Sabadell school building (Fig. 2.5) dating from 1959 shows improvements of the building energy and functional performance on account of the following interventions; building extension has generated a new south façade in

Table 2.4 Groups of measures specific for energy-efficient renovation

Groups	Individual measures
First group: Optimization of the energy flows between the building and its surroundings	Improvement of the thermal performance of a non-transparent thermal envelope (additional insulating, elimination of thermal bridges, integration of green roofs or/and façades)
	Replacement of the existing with the energy-efficient windows, airtight installation
	Use of solar control systems (shading devices, other shading strategies)
	Enlargement (or reduction) of glazing (transparent envelope) areas
	Improvement of air tightness
	Installation (or retrofit) of the energy-efficient ventilation system—heat recovery ventilation system (HRV)[a]
	Building extension: Addition of the building volumes (upgrades modules, closed loggias or balconies, other horizontal extensions)[b]
Second group: Improvement of the energy use efficiency and integration of renewable energy use	Retrofit of the heating system (space heating, water heating)—replacement of the existing with the energy-efficient heating system using renewable energy sources (heat pumps, solar panels)
	Installation (or retrofit) of the energy-efficient ventilation system—heat recovery ventilation system (HRV)[a]
	Retrofit or initial installation of the energy-efficient cooling system
	Replacement of the existing with the energy-efficient lighting
3rd group: Energy generation	Installation of the photovoltaic (PV) system
	Installation of wind turbines or vibro-wind systems

[a]Integration of the heat recovery ventilation system influences both, the reduction of energy flows between the building and its surrounding (the reduction of ventilation heat losses) and also the improvement of the efficient use of energy

[b]Although the building extension belongs predominately to the group of measures affecting the building function, it simultaneously reduces the energy losses through the building envelope

combination with some other individual measures. Prior to the renovation, the old south-facing façade was exposed to high solar radiation causing indoor thermal discomfort in the classrooms in warm periods of the year.

A combination of measures affecting the optimization of energy flows between the building and its surroundings (see Table 2.4, 1st group of measures) has been carried out resulting in the new south façade composed with the intermediate 50 cm

Fig. 2.5 A new south façade enables multiple functions next to the energy performance improvement (photo by Adrià Goula, drawing by HARQUITECTES)

wide permanently ventilated air chamber, new energy-efficient windows and integrated solar control of fixed metal and perforated slat blinds. The ventilated air layer acts as a thermal buffer zone and enables the installation of exterior window shelves, while the metal slat blinds not only reduce the solar radiation gains but also offer the protection against ball impacts of school playgrounds. As seen, the overall outcome of the conducted measures is versatile. Besides the reduction of energy flows, enabled natural ventilation and the already mentioned functional advances, some other benefits such as the enhancement of indoor climate conditions and embellishment of the building aesthetic appearance can be detected in this renovation case [12].

The second group of energy-efficient renovation measures is targeting the improvement of efficient energy use and integration of renewable energy use. These measures are related to retrofitting or new addition of systems for heating, cooling and ventilation. The common name for these systems is active building technical systems or, as usually found in literature, also the HVAC systems. Currently, there are various modern technologies available for the purpose of space and water heating, such as different types of heat pumps, solar collectors and hybrid systems, using primarily the energy of the air, water, ground and sun. The selection of appropriate HVAC system depends on the locally available renewable energy sources, the local energy supply system and energy mix and also on the climate conditions. For example, air-source heat pumps are appropriate merely for climates with moderate heating and cooling needs as they are less efficient in cold climates due to a relatively low average air temperature in the heating season. Next to conditioning, the ventilation presents an influential factor defining building energy consumption and indoor thermal comfort and air quality. Numerous existing buildings are only naturally ventilated or are in some cases equipped with energy inefficient mechanical ventilation. Retrofit in terms of installation of local or central heat recovery ventilation system leads to multiple benefits. It influences the reduction of ventilation heat losses, exploits the energy from the indoor air to heat up the incoming external air, increases the indoor thermal comfort, reduces the possibility of formation of mould and the concentration of health hazardous substances in air, etc. The second group (Table 2.4) unifies the measures for the replacement of old inefficient active technical systems consuming non-renewable energy sources with highly efficient modern systems using predominately the renewable energy.

In order to reduce the dependency on local energy supply, the rising trend of energy-efficient renovation projects is installation of systems for electrical energy generation (see Table 2.4, third group of measures). The most common solution is the installation of photovoltaic (PV) system generating renewable electricity by converting energy from the solar radiation. Along with other components required to properly conduct, control, convert, distribute, and store the energy produced by the system, the most exposed components from the architectural viewpoint are the PV panels. They are usually integrated onto the building roofs, façades and also in windows and shading elements, whereby their optimal orientation and size depend on the location and electrical load requirements. Another solution for the generation of electricity is found in exploitation of the wind energy; however, there are still many discussions treating the questions on the feasibility and safety of mounting wind turbines or vibro-wind systems onto buildings.

The overall effect of the energy-efficient renovation depends on the scope of renovation measures conducted and can account up to 90% [2], however, only in the cases involving comprehensive energy-efficient renovation consisting of interventions from all three groups (Table 2.4).

2.3.3.2 Structural Renovation

The load-bearing capacity and stability of existing buildings are affected by their original structural design, increase of loads (live loads, heavy snowfalls, wind intensity, vibrations, etc.), long-term material degradation, damages and deterioration of structure caused by fire, extreme weather conditions or earthquakes. Furthermore, structural modifications such as elimination of walls or columns, addition of new volumes, slab openings, etc., implemented due to the change of spatial organization or use can affect the vertical and lateral strengths of the building. Due to the above-stated reasons, many of the existing buildings do not meet the load-bearing requirements determined by the current building codes [13]. On the other hand, even buildings with no distinctive state of deterioration may face the progressively stricter regulations as a binding obligation to improve the quality and safety conditions. The latter is particularly relevant to broader knowledge in the

Fig. 2.6 Prior to seismic retrofit the structural system of the Hildebrand Hall lacked shear-resisting elements. The architects Anshen and Allen and structural engineers Forell/Elsesser decided for the strategy of seismic strengthening through the use of unbounded braces made of steel and concrete in combination with additional shear walls [14] (photographs by Forell/Elsesser)

field of seismic safety and the subsequent updating of seismic design codes, which points towards the need for seismic strengthening of the existing buildings not meeting the lateral strength requirements relevant to particular seismically active zones.

An exemplary case of comprehensive seismic renovation programme was undertaken in the campus of the University of California, Berkley. Consequently, the campus has become a museum of advanced seismic renovation strategies employed at the end of 1990s and beginning of the new century [14].

The selection of methods for structural renovation of buildings depends on the level of structural safety risk. Various measures of structural improvement can be distinguished, from minor interventions, like repair of deteriorated concrete, wooden structures or components subject to fire damage, to complex strengthening implemented on the level of building elements (foundations, slabs, walls, beams, columns, structural connections) or on the level of complete structural system (Fig. 2.6).

2.3.3.3 Improvement of IEQ Parameters Influencing Users' Health and Well-being

A predominant part of our daytime being spent inside buildings makes the indoor environment quality (IEQ) vital to well-being, health and productivity of its users. Consideration of IEQ through thermal, visual, acoustic comfort and indoor air quality factors is gaining a vital attention in new built design as in building renovation processes. The driving forces responsible for the quality of building indoor environment can be psychological, social, physical and contextual [15]. The comprehensiveness of the IEQ improvement, therefore, largely depends on the scope of renovation interventions. The building industry even recognizes a field of

Table 2.5 Building biology parameters affecting public health. Adapted from [15, 16]

	Parameters affecting public health
Biological loads	Mould
	Fungi and bacteria growth
	Allergens
Chemical loads (air pollutants)	Volatile organic compounds or VOCs (formaldehyde, benzene, etc.)
	Pesticides (biocides and fungicides)
	Toxic pigments, fire retardants
	Carbon oxides (CO and CO_2)
	Asbestos
Physical loads	Low- and high-frequency electric and magnetic fields and electromagnetic radiation (among these also radon radiation, electrosmog, etc.)
	Acoustic comfort parameters
	Visual comfort parameters
	Thermal comfort parameters

building science investigating the influence of indoor environment quality and its irritants on the health of the occupants. According to El Khouli et al. [16], building biology studies holistic interrelation between humans and their living environment. The main building biology strategies affecting public health aim at the reduction and control of harmful biological, chemical and physical loads [16] caused predominately by building materials, electromagnetic fields, other radiation sources, pure ventilation and inadequate design (Table 2.5).

These strategies should be thoughtfully implemented within the building renovation processes to a highest possible extent in order to prevent the existence of factors responsible for the so-called “sick building syndrome”, i.e. a state of the indoor environment presenting a high health risk and its consequent ill-health effects such as allergies, headaches, respiratory problems, tiredness, nausea, infections, asthma, liver, kidney or central nervous system damage, cancer and other damages to skin, eyes and hearing. In practice, this means removing the contaminated materials and replacing them with those having no or at least an acceptable content of substances of very high concern (SVHCs). An additional measure to be taken is prevention of emissions caused by some integrated materials that cannot be replaced, e.g. by sealing the cracks or covering them with other materials. Furthermore, it is equally important to reduce harmful physical loads, enable adequate ventilation and improve design conditions having harmful effects on the occupants’ health and well-being.

2.3.4 Renovation Approaches Concerning the Building Use

In the cases where the building becomes inadequate in terms of its original purpose, several renovation approaches are convenient in order to improve its usability and functionality. The following sections describe three main renovation approaches affecting the enhancement of the building use and function.

2.3.4.1 Functional Renovation—Rehabilitation with Retention of the Building Use

Lifestyle habits and the consequent demands of the modern society are subject to a process of constant evolution. Over a specific time period and if retained in their original design, the existing living and working environments can become obsolete, unsuitable for the users and therefore redundant. Not entirely fulfilling the needs of their living population, these buildings require rehabilitation where the original use of the building is retained or adapted to new purposes. In the case of retention of the use, such functional renovation approach demands rearrangement and reorganization of the building design with the measures carried predominately within the existing building shell.

Another important issue tackling the functional design of existing buildings is the necessity to adapt them to users with permanent or temporary disabilities. Modernization of currently non-accessible into the so-called inclusive environments enables equal conditions to all building users regardless of the age, gender or disability. Modernization into inclusive environments shall be applied predominately to areas expected to serve the needs of persons with disabilities with respect to their employment, residential stay or the use of public areas and facilities [17].

An example of functional renovation with the retention of the building original use was implemented on the centre for education and rehabilitation of physically handicapped children and adolescents (CIRIUS) in the town of Kamnik, Slovenia. The school complex was originally planned in the spirit of the modernist open design by a Slovenian architect Jože Ušenik, in the early 1960s. After almost 30 years of existence, the centre no longer satisfied the spatial needs to enable all daily activities and it, therefore, had to undergo a process of major renovation with extension which has been implemented in three phases in the period from 1998 to 2008. The extensive renovation designed under cooperation of architects Miha Dešman, Katarina Pirkmajer Dešman, Matej Vozlič and Vesna Vozlič Košir aimed at retaining the original building design which was gradually upgraded and enlarged through vertical and horizontal building extensions. Through the renovation process, the school complex gained new spaces like an enlarged central hall, two gyms, a swimming pool, a therapy wing, an enlarged classroom wing, a new kitchen with an Internet café, health facilities and a library, whereby all the facilities along with the exterior demonstrate inclusive environments design. The renovated complex exhibits a spirit of a small-scale city with corridors and halls acting as streets and

Fig. 2.7 Renovated Centre for education and rehabilitation of physically handicapped children and adolescents CIRIUS in Kamnik, Slovenia (photos by Miran Kambič)

squares, connected with exterior ambient. The interior architecture is vibrant and colourful, allowing children with mobility disability to enjoy as much freedom as possible as they live, work and play [18] (Fig. 2.7).

It can be concluded that even if the building retains its original use, the necessity to modernize the building functional capacity is of vital importance for the well-being and productivity of its users.

2.3.4.2 Functional Renovation—Building Extension

Many large European cities are nowadays facing a new development stage offering new professional and personal opportunities, which influences the growing trend of population and simultaneously the growing demand for new usable surfaces, both residential and non-residential. Due to a shortage of free construction positions in city centres, renovation aimed at increasing the usable building surface proportion is seen as a sensible option of increasing urban density, which represents a further level of functional and energy performance renovation along with the necessary consideration of structural demands. The building extension can be carried out by means of vertical structural upgrade or the so-called attic extension and horizontal volumes addition, while also the closure of existing balconies and loggias with the thermal envelope presents an intervention of increasing the building usable floor area.

In the context of the constantly increasing urban density, vertical building extension proves to be a highly favourable as well as recently often applied solution in common practice and thus represents an ever more emerging phenomenon of building renovation. Vertical extensions are mainly conducted as attic extensions of one building only, while more complex cases also occur with the extension being implemented on the larger urban scale.

An example of vertical upgrading of one building only is seen in the project of Didden Village designed by MVRDV architects, implemented by means of additional storey installation on top of an existing monumental house and atelier. The upgrade volumes are arranged as separate houses distributed in a way that a series of plazas, streets and alleys appear as a mini-village on top of the building (Fig. 2.8). The implemented extension exhibits numerous benefits. Firstly, it exploits the urban roof-scape for the creation of new living and working spaces, while from the aspect of energy efficiency the upgraded volumes act as additional insulation of the existing roof surplus collectors of heat transmitted through the glazing surfaces [19].

The benefits are far more distinctive if the intervention of vertical building extension is carried out on the urban level. An example of the latter is demonstrated with a project Treehouses Bebelallee, realized in Hamburg by blauraum architects (Fig. 2.9) whose task was to densify a residential district dating from the 1950s.

Renovation of the existing building volumes through addition of a new façade with an external layer of insulation and brickwork cladding was performed with the aim of retaining the building's original character, while a new development is exhibited in the addition of rooftop volumes constructed in timber prefabricated lightweight structural system. The advantages of upgrading with a prefabricated lightweight construction are found in relatively low loads of additional stories, in quick construction periods and minimal noise or disturbance for residents of the existing units, in comparison with a massive construction. The Treehouses Bebelallee project is an example of urban densification featuring the extension of the existing housing by 47 new units configured as the maisonette apartments with roof terraces and loggias. The façades of the upper stories are cladded by wooden cedar shingles emphasizing the lightweight character of the new construction, while resembling the surrounding trees in their materiality, wherefrom the name of the project is Treehouses. In terms of configuration and dimensions, the new apartments were designed to be family-friendly and attractive to younger tenants. The project also entailed updating of the energy infrastructure. In general, the planning measures pursued the objective of doubling the estate's overall usable area while at the same time halving CO_2 emissions caused by the building operation [20].

In the context of building renovation, vertical building extensions offer a great potential for creating additional usable space while taking the advantage of the existing infrastructure. However, a necessary step to precede the planning of attic

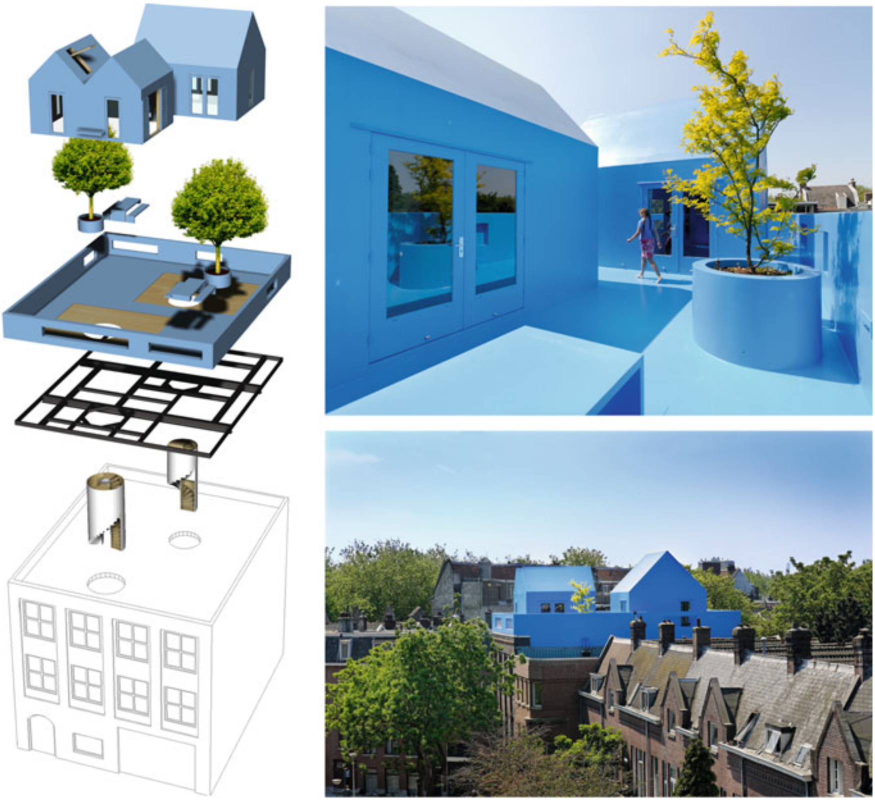

Fig. 2.8 Rooftop extension Didden Village fulfils a need for additional space and creates the conglomerate of building volumes and open space with the views on the city of Rotterdam (photograph and drawing by MVRDV)

extension is to check the building's capacity to support the load of additional stories. An additional profit of vertical extensions is that of providing the possibility of covering the costs of the retrofit of the existing building volumes through offering the upper upgraded stories to the real estate market.

2.3.4.3 Functional Renovation—Conversion of the Building Use

Over the building life cycle, a primarily designed building use can be converted to suit new conditions. The use phase duration of buildings within their life cycle is limited and depends on various factors such as the type and quality of construction, the quality of maintenance, climate conditions, extreme events causing possible damages to buildings, etc. With proper maintenance, much of the existing building stock can be in use for over 100 years—a period affected by ongoing economic and

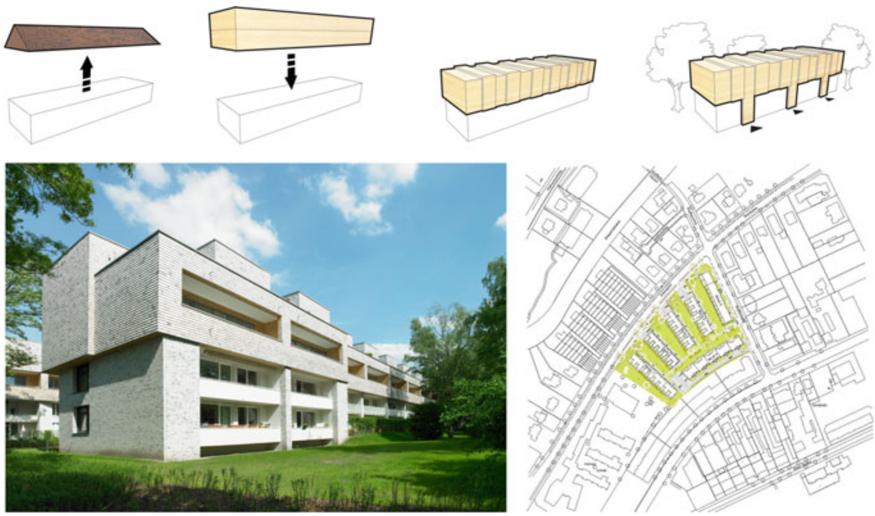

Fig. 2.9 Urban densification of a residential district located at the edge of the Hamburg city by means of vertical building extension (photograph by Martin Lukas Kim, drawings by blauraum)

social changes influencing the perception of the building use. The latter calls for a need to prolong the building service life and raise the building value through different approaches with one of the most suitable being building rehabilitation involving the change of use or the so-called adaptive reuse [21], i.e. an approach to building renovation which transforms the existing building and adapts its use to new purposes. The need to be adapted to a new use appears among different building types and categories. In the context of historical buildings that can no longer function within their original use, proposing a new function is inevitable in order to preserve their cultural significance [4]. A significantly high potential for adaptive reuse is seen in industrial buildings and industrial areas where the shifts in economy and technology make the buildings become obsolete with the consequent failure to serve their primary function.

A relatively unconventional but interesting example of adaptive reuse is the transformation of the Jægersborg Water Tower into a building of mixed-use. The original water tower located in the northern suburbs of Copenhagen designed by the architect Edvard Thomsen as a 45 m tall concrete building was completed in 1955. The initial design phase idea was to build apartments on lower floors, which was not realized for the fear of a possible sound discomfort in apartments caused by the water from the container. Instead, the floors under the red water tank were used for warehouses, municipal archives and an after-school activity centre. In 2004, Dorte Mandrup Architects won the competition of converting the Jægersborg Water Tower into a building hosting a youth centre and student residences.

The renovation approach throughout the conversion process (Fig. 2.10) involved strengthening and maintaining the tower topped with a 3 m tall wind vane, a local

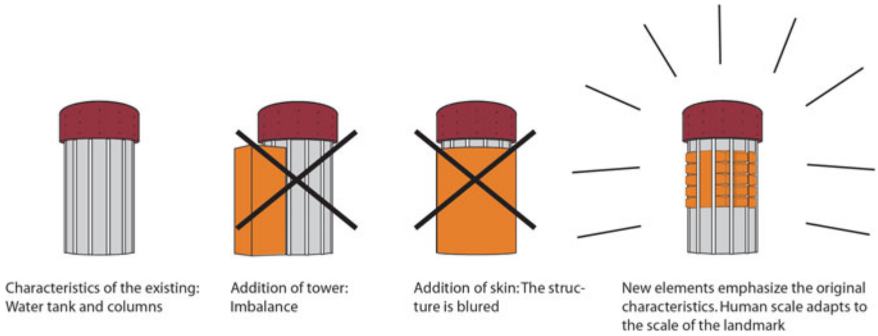

Fig. 2.10 In the conversion process the architects succeeded in retaining the building's original character (drawing by Dorte Mandrup)

Fig. 2.11 Jægersborg Water Tower prior to (left) and after (right) the conversion (photograph by Dorte Mandrup and Jens Markus Lindhe respectively)

landmark, by retaining the characteristic large-scale columns and the tank. An adapted mixed-use building consists of the leisure youth centre located on the first three floors, a youth housing located on five consecutive floors ranging from the fourth to the eighth and the original red water tank at the top of the tower, holding 2000 cubic metres of water.

The pictures of the Jægersborg Water Tower prior to and after the transformation process (Fig. 2.11) show that the initial architectural identity has been preserved.

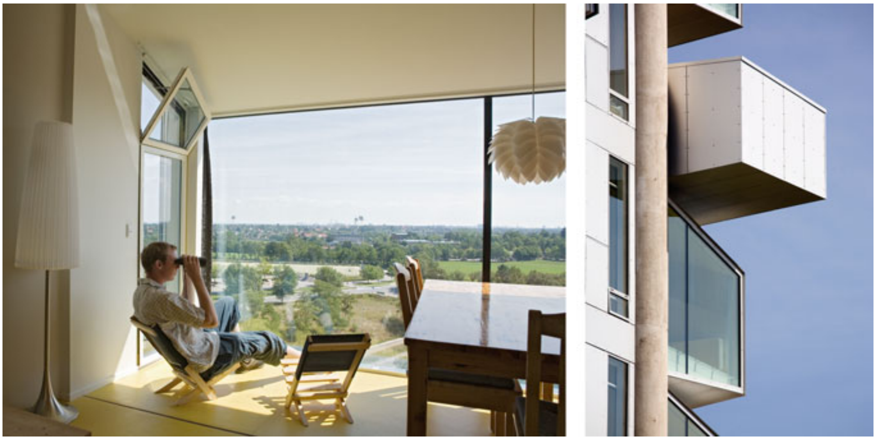

Fig. 2.12 Along with unimpeded views the added crystal-like bay windows enlarge the usable floor area and emphasize the refreshed aesthetics as also the added function of the renovated building (photographs by Torben Eskerod)

Regarding the living units, the intent of architects was to create student apartments with the emphasis laid on the quality, daylighting and the optimal use of space in addition to a view worthy of a penthouse apartment. In this context, they added a new layer of the protruding bay windows to the core of the existing structure accentuating the building's new function while bringing a sufficient amount of daylight into the apartments and offering unobstructed views of the surrounding landscape (Fig. 2.12).

The Jægersborg Water Tower indicates how even a building with a specific design not fully suitable for residential purposes can be successfully converted to a new function. One of the crucial contributions of such adaptive reuse is seen in the prolongation of the building use phase and adaptation of its function to the relevant needs of the society [22].

Within the framework of sustainability, the conversion of the building use presents an attractive alternative to the process of demolition and new construction [23], predominately on account of lower waste burdens and lower material and transport costs relative to renovation [21]. On the other hand, the adaptive reuse may be linked to a number of risks especially in the cases where the building's poor condition affected by technical defects, hazardous materials, unstable structures and inadequate fire protection increases the uncertainty associated with the scope of urgent renovation measures. Thus, in many instances the process of transformation requires major architectural, structural and technical interventions tending not only to suffice the new function and the associated building code requirements but above all to preserve and enhance the original character and architectural value of existing buildings [24].

2.4 Conclusion

As seen from the presented approaches to renovation, the necessity to preserve and improve the existing building stock is of vital interest to the modern society aiming at creating user-friendly, sustainable and all-inclusive built environments.

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Chapter 3
Renovation Process Methodology

Miroslav Premrov and Vesna Žegarac Leskovar

3.1 Basis of Energy Flows in Buildings

With a view to obtaining adequate conclusions from the energy-efficient renovation steps in Sect. 3.2, the current section briefly explains the basis of energy flows in buildings. Presentation of adequate explanation based on the obtained numerical results from our previous studies and theoretical correlations therefore needs to be preceded by the overview of basic theoretical facts regarding energy flows in buildings. Planning and designing energy-efficient buildings is a complex process whose definition could be understood as a three-level one.

The first—*basic design level* comprises an optimal selection of the building components, i.e. the structural design concept, the thermal envelope composition, construction details, the type of glazing and other materials, with respect to the location, climate data and a suitable orientation.

The following level is that of *passive design strategies* which allow for heating with solar gains, cooling with natural ventilation, using thermal mass for energy storage where renewable energy sources are exploited with no need for electricity.

Only the third, i.e. the last level involves design concepts of the *building's active technical systems* using renewable sources of energy with the necessary recourse to electrical energy. The current study is limited to the first two levels.

3.1.1 Energy Demand for Heating and Cooling

Energy efficiency of buildings according to EN ISO 13790 [1] calls for consideration of the energy demand for heating (Q_H) and cooling (Q_C). To determine both components, the building can be considered as a thermal system with a series of heat flows, inputs and outputs, Szokolay [2]. The energy balance of the building therefore generally consists of four basic heat flows:

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https://doi.org/10.1007/978-3-030-11476-3_3

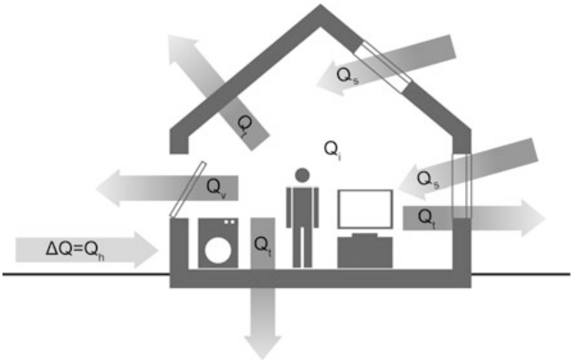

Fig. 3.1 Scheme of energy flows in a building, typical of the cold period scenario, [30]

- transmission heat losses (Q_T),
- ventilation heat losses (Q_V),
- internal heat gains (Q_I),
- solar heat gains (Q_S),

schematically presented in Fig. 3.1 and given in the form of Eq. (3.1a):

$$Q_T + Q_V + Q_I + Q_S \approx \Delta Q \approx Q_H \quad \text{for the heating season} \tag{3.1a}$$

$$Q_T + Q_V + Q_I + Q_S \approx \Delta Q \approx Q_C \quad \text{for the cooling season} \tag{3.1b}$$

With the quasi-stationary method, highly usable for controlling **only** the annual energy behaviour, the *transmissions heat losses* (Q_T) during the annual heating/cooling periods are calculated for every building element of the heat-exchanging envelope, in the form of:

$$Q_T = \sum A_i \cdot U_i \cdot f_T \cdot G_T \text{ (kWh/annually)} \tag{3.2}$$

where A_i is the building envelope area (m^2) of the ith envelope element, U_i (W/m^2 K) is its corresponding building thermal transmittance coefficient, f_T is the reduction factor for the reduced temperature difference and G_t (K h) is the temperature difference time integral (heating degree hours) taken from the climate data for the considered location regarding the whole heating/cooling period. The total transmission heat losses (Q_T) can be finally calculated as a sum of partial transmission losses ($Q_{T,i}$) through the walls, roof, basement and windows. As the U-values of windows are usually the highest in comparison with the other building envelope elements, maximal transmissions losses are mainly obtained through the window areas.

The quasi-stationary *ventilation heat losses* (Q_V) caused by air exchange between the building and its surroundings (air infiltration, natural ventilation, mechanical ventilation, air leakage through the building envelope) are calculated in the form of:

$$Q_V = V \cdot n_v \cdot c \cdot \Delta T_1 \cdot H_t \cdot 0.024 \text{ (kWh/a)} \quad (3.3a)$$

where V is the interior building heated volume (m^3), n_v is the air exchange ratio (h^{-1}), c is the air thermal capacity (0.33 W h/m^3 K), ΔT_1 (K) is the temperature difference between inside and outside of the building and H_t (days) is the duration of the heating/cooling period which is taken from the climate data for the considered location. The air exchange ratio is calculated as a sum of mechanical ventilation ($n_{v,mech}$) and infiltration ($n_{v,inf}$), in the form of:

$$n_v = (1 - \eta_{hr}) \cdot n_{v,mech} + n_{v,inf} = (1 - \eta_{hr}) \cdot n_{v,mech} + n_{50} \cdot e \quad (3.3b)$$

where η_{hr} is the recuperation efficiency (usually at about 0.75 for heating and 0 for cooling), $n_{v,mech}$ is 0.3 h^{-1} for heating and 0.5 h^{-1} for cooling, n_{50} is the air exchange at the pressure test (usually 0.6 h^{-1}) and e is the coefficient of the wind protection (usually 0.07).

The quasi-stationary *solar heat gains* (Q_S) caused by solar radiation through transparent building envelope elements are calculated using:

$$Q_S = r \cdot g \cdot A_w \cdot G_s \text{ (kWh/a)} \quad (3.4)$$

where r is the reduction factor taking into account the frame-to-window-area ratio, shading, dirt on the glazing and the tilted incidence angle of radiation through the glazing, g is the degree of solar energy transmitted through the glazing normal to the irradiated surface, A_w (m^2) is the window area (rough opening) and G_s (W h/m^2) is the total radiation during the heating period.

The quasi-stationary *internal heat gains* (Q_I) generated inside the building by occupants, lighting and household appliances, are therefore prescribed with EN ISO 13790 (2008) according to the purpose of the building, in the form of:

$$Q_I = q_i \cdot A_{TFA} \cdot H_t \cdot 0.024 \text{ (kWh/a)} \quad (3.5)$$

where A_{TFA} (m^2) is the building usable floor area, H_t (days/annually) is the duration of the heating/cooling period taken from the climate data. The basic internal energy load q_i (W/m^2) depends on the building purpose (2.1 W/m^2 for residential buildings, 2.8 W/m^2 for public buildings, 3.5 W/m^2 for commercial buildings, 4.1 W/m^2 for hotels).

The calculated values for all energy flows in Eqs. (3.2)–(3.5) are usually presented per a square metre of the total occupied/usable floor area (A_{TFA}), in the forms of:

$$Q_t = \frac{Q_T}{A_{TFA}} \left(\text{kWh/m}^2\text{ a}\right) \quad (3.6a)$$

$$Q_v = \frac{Q_V}{A_{TFA}} \left(\text{kWh/m}^2\text{ a}\right) \quad (3.6b)$$

$$Q_s = \frac{Q_S}{A_{TFA}} \ \left(\text{kWh/m}^2\,\text{a}\right) \tag{3.6c}$$

$$Q_i = \frac{Q_I}{A_{TFA}} \ \left(\text{kWh/m}^2\,\text{a}\right) \tag{3.6d}$$

On the basis of different temperatures of the building and its surroundings, we can distinguish between two opposite heat flow scenarios:

- The heating period in cold periods of the year when the average outdoor temperature is generally lower than the prescribed or chosen indoor temperature. The heating season begins when the external air temperature measured at 9 p.m. is lower than or equal to 12 °C for three days in a row.
- The cooling period in warm periods of the year when the average outdoor temperature is generally higher than the prescribed or chosen indoor temperature.

In the *heating period,* the sum of all heat flows in the building is usually negative, which is mainly due to the energy output caused by transmission and ventilation heat losses. In such cases (Eq. 3.1a), the ΔQ results in the amount of energy required for heating (Q_h) in order to reach a desired indoor temperature of approximately 20 °C. In this case, the energy losses (Q_l) in buildings, according to EN ISO 13790 [1], consist of a sum of the transmission heat losses (Q_t) and ventilation heat losses (Q_v), in the form of:

$$Q_l = Q_t + Q_v \tag{3.7}$$

The heat gains (Q_g) in buildings in the heating period are a sum of solar heat gains caused by solar radiation (Q_s) and internal heat gains generated inside the building (Q_i), in the form of:

$$Q_g = Q_s + Q_i \tag{3.8}$$

The amount of energy required for heating (Q_h) equals the difference between the sums total of heat losses (Q_l) and heat gains (Q_g) of the building, where the heat gains are, according to EN ISO 13790 [1], multiplied with the utilization factor η_G, in the form of:

$$Q_h = Q_l - \eta_G \cdot Q_g \tag{3.9a}$$

$$\eta_G = \frac{1 - \left(\frac{Q_G}{Q_L}\right)^5}{1 - \left(\frac{Q_G}{Q_L}\right)^6} \tag{3.9b}$$

The utilization factor η_G represents, in an approximate manner, the part of energy gains which cannot be accumulated in the building due to a low thermal capacity and thus predominantly depends on the type of the load-bearing structural system. In Passive House Planning Package programme (PHPP) [3], it is recommended to take a value for the specific capacity of 60 W h/K per m^2 of the usable area for structural systems with low thermal mass (timber buildings) and a value of 200 W h/K for massive structural systems (concrete, brick or stone buildings). It is important to point out that the described method is a quasi-stationary method which is used for controlling only the annual energy behaviour, and it is not able to control peak case scenarios, especially during the hottest midday period in the summer time. PHPP computation values concerning the annual needed energy for heating and cooling of buildings show a minimal deviation from the actual, measured ones, as seen in the already conducted relevant studies, Leskovar and Premrov [4], Badescu et al. [5] and Premrov et al. [6].

The opposite is the *warm period scenario* (cooling period), i.e. that of the summer period in the majority of European areas, when the peak daily outdoor temperature may be higher than the prescribed or chosen maximal indoor temperature in a particular part of the day. In this case, the sum of all heat flows in the building has a positive value, mainly due to solar heat gains. The case-related ΔQ from Eq. (3.1b) shows the amount of heat that has to be extracted from the building for cooling (Q_c) to prevent overheating, in order to reach a desired indoor temperature which should not exceed 25 °C. It is given in the opposite expression of Eq. (3.9a):

$$Q_c = Q_g - \eta_L \cdot Q_l \tag{3.10a}$$

$$Q_l = Q_t + Q_v \tag{3.10b}$$

$$Q_g = Q_s + Q_i \tag{3.10b}$$

The only change according to the equations for the heating scenario, Eqs. (3.1a)–(3.8), is shown for the utilization factor η_L which is expressed in the form of:

$$\eta_L = \frac{1 - \gamma_c^{-2.77}}{1 - \gamma_c^{-3.77}} \tag{3.11a}$$

$$\gamma_c = \frac{Q_G}{Q_L} \tag{3.11b}$$

3.1.2 Influence of the Building Shape on the Energy Demand

The building shape is defined by the geometry of external building elements, such as the walls, the floor slab and the roof. It has a significant effect on the thermal performance since major heat flows pass through the building envelope, see Eq. (3.2). In professional practice, the most widely used index to describe this architectural geometry is the *shape factor* (F_s) defined as the ratio between the envelope area of the building (A in m^2) and the inner heated volume of the building (V in m^3), given in the form of:

$$F_s = \frac{A}{V}\ \left(m^{-1}\right) \tag{3.12}$$

To minimize the building envelope surface and consequently the transmission losses through the envelope elements, a compact shape indicated by a low shape factor is desirable, Fig. 3.2. General design guidelines for energy-efficient houses suggest a compact rectangular shape as the optimum, which is more relevant to buildings in a predominantly cold climate.

On the other hand, a dynamic building form with larger envelope surfaces results in higher transmission losses, Eq. (3.2), although it enables provision of higher solar gains, Eq. (3.4). The latter is particularly important when large glazing areas are installed in dynamically formed south-oriented building façades, as schematically presented in Fig. 3.3. The above-stated interesting fact will undergo further discussion within the current section.

Another important parameter often used to determine solar access of a building, assuming that its height and optimal orientation are defined, is the *aspect ratio* (AR), a ratio between the building's length and width:

$$\mathrm{AR} = \frac{L}{w} \tag{3.13}$$

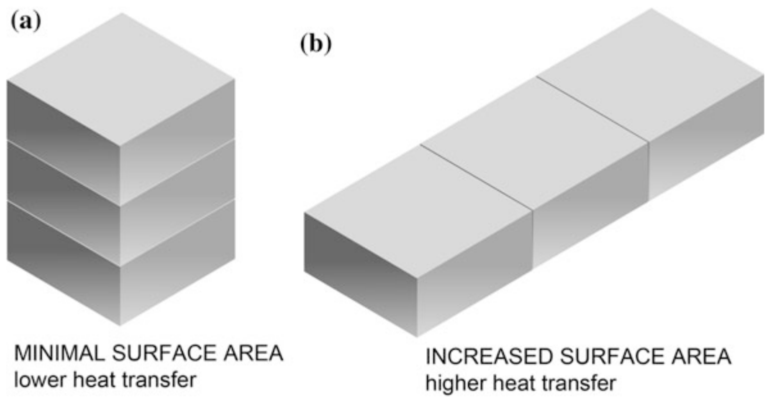

Fig. 3.2 Compact (non-dynamic) form of the building with a low shape factor; **a** with a low aspect ratio, **b** with a high aspect ratio, [30]

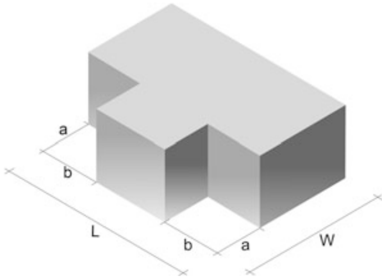

Fig. 3.3 Dynamic form of the building with a higher shape factor, [30]

The aspect ratio is a significant parameter in energy-efficient design concerning the building shape, as emphasized in several studies. The optimal aspect ratio allows buildings to receive more solar gains in winter and more shading in summer, thus decreasing the demand for heating and cooling. In cold climates, for example, the ideal aspect ratio for a rectangular-shaped solar house design ranges from 1.3 to 1.5, Chiras [7]. In the study by McKeen and Fung [8], the energy consumption at a varying aspect ratio changes significantly among the 13 simulated ten-storey models in multi-unit residential buildings in five selected Canadian cities (Vancouver, Calgary, Toronto, Montreal and Halifax). A final conclusion states that in comparison with a building with a less efficient aspect ratio, such as 4.2:1, a more than 15% reduction in the energy consumption is possible in many scenarios. However, another point noted shows that the optimal aspect ratio for the heating efficiency is not necessarily optimal for the cooling, especially when also taking into account a different *U*-value of the glazing and the shading device, Krstić-Furundžić and Kostić [9]. All described parameters with the increasing aspect ratio in the case of a single-storey building with a rectangular floor area are schematically presented in Fig. 3.4.

The parameter which can significantly influence the amount of solar gains, Eq. (3.4), and consequently the total energy demand for heating, Eq. (3.9a), and cooling, Eq. (3.10a), is the *glazing-to-wall area ratio* (AGAW) described as the ratio between the total area of the glazing (A_g) to the total area of the wall (A_{wall}), schematically presented in Fig. 3.5:

$$\mathrm{AGAW} = \frac{A_g}{A_{wall}} \tag{3.14}$$

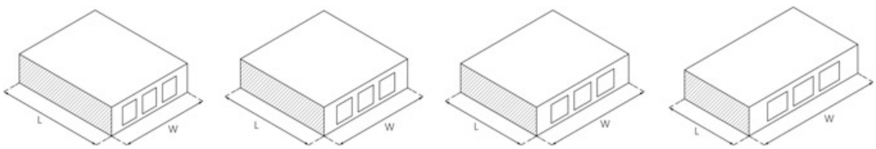

Fig. 3.4 Schematic presentation of the increasing aspect ratio (AR) for the rectangular ground-floor area, [19]

It has been justified in several existing studies that glazing surfaces, if oriented towards the equator where the solar potential is the highest, enable solar radiation to enter the building. Many interesting analyses have been done with a focus on defining the impact of windows on the heating and cooling demand, Inanici and Demirbilek [10], Bülow-Hübe [11], Persson et al. [12], Ford et al. [13], Bouden [14] and Hassouneh et al. [15]. The impacts of the glazing-to-wall area ratio (AGAW) and that of the aspect ratio (AR) on the energy demand of buildings are usually interconnected and demand a highly sensitive consideration in the analysis, as seen in Wei et al. [16]. In their analysis for the cold climate region in China, they included the number of floors, and overall scales, besides the above parameters.

In the design stage, when determining a dynamic building geometry, Fig. 3.3, it is important to consider direct solar penetration through the glazing in the south façade which significantly depends also on the so-called self-shading. Buildings with dynamic geometry have a larger building envelope if compared to those with more compact building shapes. As a result, they affect the increase of transmission losses through external walls, Eq. (3.2). On the other hand, a dynamic form of the building's south façade means significantly larger south-oriented glazing surfaces, which can contribute to higher solar gains, Eq. (3.4). However, direct solar penetration through the glazing can be additionally partly obstructed by other parts of the building in specific periods of a day, as schematically presented in Fig. 3.3. Hachem et al. [17], for example, investigated the effects of the geometric shapes of two-storey single-family housing units on their solar potential by using the so-called *depth ratio a*/*b*, where *a* represents the length of the shading façade and *b* the length of the shaded façade, Fig. 3.5. The findings demonstrate that both parameters control the extent of shading and consequently the reduction of the solar

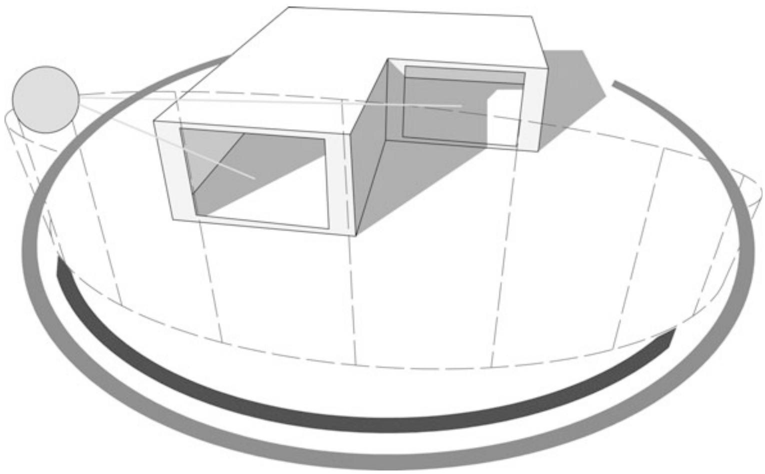

Fig. 3.5 Schematic presentation of the sun path influence on solar gains with the self-shading of the building on the south side, [6]

radiation incident on the shaded façade. It is therefore desirable to reduce the depth ratio in order to optimize the solar potential of façades. A rectangle, with the aspect ratio of 1.3 serves as a reference.

To minimize the transmission losses through the building's envelope, Eq. (3.2), a compact shape indicated by a low shape factor (F_s) is desirable. On the other hand, a dynamic form with larger transparent surfaces permits provision of higher solar gains, Eq. (3.4). Consideration of solar access in the phase of determining the building shape is an essential part of the energy-efficient building design. A general conclusion of early studies, mostly performed for heavy winter conditions, and followed with the first planning guidelines for a passive building design, shows that a compact shape is the optimum.

However, Albatici and Passerini [18] were encouraged to research new indicators of the energy performance within mild and warm climate conditions related to the building shape. They presented heating requirements of buildings with different shapes in the Italian territory. Their research based on a monthly method (simplified approach) confirms that compactness is more important in cold localities. Having taken heating requirements into account, Albatici varied envelope areas of the models, while the volume and the percentage of the glazing remained constant. Similar findings are obtained by Premrov et al. [19] for timber-framed box-house models with a constant ground-floor area and a varying aspect ratio for different European climate conditions (cold and warm). In addition, Premrov et al. [6] investigated also the shapes characterised by a changeable ground-floor area with *L*- and *U*-shapes (Fig. 3.3) for three different European climate conditions. The findings from the performed parametric analysis evidently demonstrate a possibility, limited to certain climatic regions, of designing timber-glass buildings having a more attractive ground-floor geometry with a higher building shape factor. However, it should be underlined that such dynamic form of timber-glass buildings achieves the energy optimum only if all the parameters described, such as the optimal size of glazing, orientation of the external envelope, self-shading and climate conditions, are carefully analysed. As presented, the total annual energy demand for heating and cooling depends on the shape factor to a considerably higher extent in cold climate conditions with a lower solar potential (Helsinki). On the other hand, in regions with a higher average annual temperature and solar potential (Ljubljana), in addition to the subsequently lower transmittance losses (Eq. 3.2), the influence of the increasing shape factor on the energy demand is less powerful.

From all the existing research findings, we can generally summarize that the process of defining the optimal model of a building is very complex. The most important parameters influencing the energy performance of buildings are the location of the building along with climate data for a specific location, the orientation of the building, properties of the materials installed, building design, selection of active technical systems, etc. It is therefore important to investigate the influence of the above-listed parameters with utmost care. Due to the absence of a direct correlation between different parameters, it is more convenient to conduct separate examinations of their influence on the energy demand for buildings.

The latter is of particular relevance to the influence of the building's orientation and its glazing size on the one hand, and to the influence of the building shape on the other.

3.1.3 Passive and Active Design Strategies

Passive design strategies (passive heating, cooling, daylighting, ventilation) allow for the passive use of natural energy sources and climatic indicators in order to ensure an adequate indoor climate and reduce the need for active heating, cooling, ventilation and daylighting. For example, solar radiation can be exploited to assist in reducing the energy consumption for space heating and daylighting, natural ventilation contributes to reducing the energy consumption for mechanical ventilation and cooling, etc.

Application of specific passive design strategies largely depends on climatic conditions, orientation, type and occupancy of the building. A general principle is firstly, to maximize solar heat gains, Eq. (3.4), which have to be equally distributed and stored within the building in periods of lower average outdoor temperatures and secondly, to minimize heat gains in addition to assuring natural cooling through ventilation in warm seasons, Eqs. (3.10a) and (3.11a). The exploitation of daylight should be part of the year-round strategy.

With respect to guidelines for energy-efficient housing and in order to emphasize the passive design impact on the energy behaviour of the building, a major part of the building's transparent surfaces should be oriented to the south. South orientation allows for higher solar gains and better daylighting although it increases a risk of summer overheating. In order to prevent overheating, a well-designed solar control is indispensable for the buildings located in a great number of European regions. Certain building sites may be less favourable in terms of orientation, since they cannot provide for a predominantly southward orientation of the building. The task of architects in such cases is to take maximum advantage of the existing conditions by adjusting the design concept to suit the given microlocation.

For example, in 2015, an already built energy-efficient timber-glass house Misaja (Fig. 3.6) located in Maribor, Slovenia, in a climate featuring cold winters and hot summers but relatively high solar radiation, is more than suitable for a practical presentation of the described passive design strategy concept. A dynamic building shape permits the use of passive design strategies to a considerably high extent in the heating period, as well as in the summer time. The main building façade is oriented towards the south-west. The building shape is determined in a manner which allows for an adequate amount of solar gains in daytime, with the self-shading affect appearing only in the late afternoon during summer periods, which is in fact a desired feature. As the winter sun sets earlier, no self-shading affect appears in the heating period when solar radiation is extremely beneficial. The roof windows provide interior spaces with a high level of natural illumination. A canopy in front of the house has retractable textile shading screens which can be

Fig. 3.6 Energy-efficient timber-glass house Misaja with the ground-floor plan, designed by Vesna Zegarac Leskovar

pulled out and block the strong summer sun or remain pulled in during cloudy and cold winter days. The self-shading and the overhang in the south-oriented façade assure an essential reduction of the possible overheating in the summer temperature peak scenario, see Fig. 3.5.

On the other hand, active technical systems are necessary for a complex integrated building operation. Active technical systems refer to heating, ventilation and air-conditioning, domestic hot-water supply, artificial lighting and renewable energy systems. They all need to consume electrical power for their performance. A way to improve the overall efficiency of contemporary mechanical systems is to incorporate strategies that use surrounding renewable energy sources like the outdoor temperature, solar radiation, and the temperature of the ground or groundwater.

3.1.4 Effective Building Thermal Transmittance

Following the described theory of energy flows in buildings in Sect. 3.1.1, it is obvious that the building envelope is a system consisting of the external walls, roof, basement and openings (windows, doors, fixed glazing), as schematically presented in Fig. 3.1. The transmission heat losses through all envelope elements thus depend on the thermal transmittance coefficient (U_i-values) and the size/area of the elements (A_i). Since the U-values of all envelope elements usually demonstrate significant differences (with the biggest difference relative to glazing and the lowest to the roof elements), it is convenient to determine the effective U-value of the entire building envelope respecting different heat flows through the elements. The entire building can thus be mathematically considered as one-box envelope heating model with a constant effective thermal transmittance value (U_{eff}).

According to the already given expressions for the heat flows (Eqs. 3.2–3.11a), the U_{eff} values can be separately calculated only for the transmission heat flow ($U_{\text{eff,t}}$), as a sum of the transmission and solar heat flows ($U_{\text{eff,t+s}}$) for the total energy demand for heating ($U_{\text{eff,h}}$) or for the total energy demand for heating and cooling ($U_{\text{eff,h+c}}$).

According to Eq. (3.2), the effective U-value ($U_{\text{eff,t}}$) representing all transmission heat flows in one expression can be determined in the form of:

$$U_{\text{eff,t}} = \frac{\sum_{i=1}^{Nw}(U_i \cdot A_i)_{\text{wall}} + \sum_{i=1}^{Nr}(U_i \cdot A_i)_{\text{roof}} + \sum_{i=1}^{Nb}\eta_{\text{t}} \cdot (U_i \cdot A_i)_{\text{basement}} + \sum_{i=1}^{Ng}(U_i \cdot A_i)_{\text{glazing}}}{\sum_{i=1}^{N} A_{i,\text{env}}} \quad (3.15)$$

where U_i and A_i present the thermal transmittance coefficient and the area of the ith envelope element (wall, roof, basement and glazing) with solely the net area (without any openings) being considered for $A_{i,\text{wall}}$. A_{env} represents the total area of the building thermal envelope including the walls, roof and basement. The reduction coefficient η_t for the basement envelope elements represents approximate decreasing of the transmission heat flow through the basement due to a lower temperature difference in this case:

$$\eta_{\mathrm{t}} = \frac{\Delta T_{\mathrm{bas}}}{\Delta T} \tag{3.16}$$

where ΔT_{bas} is a temperature difference between the considered internal temperature (T_{int}) and the average soil temperature in the heating period (T_{soil}), and ΔT is a temperature difference between the considered internal temperature (T_{int}) and the average outside temperature in the heating period (T_{ext}). According to PHPP [3], this value can be approximately considered as $\Delta_{\mathrm{t}} = 0.65$.

Taking into account also the solar radiation through the glazing areas producing solar gains (Eq. 3.4) and respecting the utilization factor η_{G} (Eq. 3.9b), the effective U-value ($U_{\mathrm{eff,t+s}}$) is consequently, according to Eq. (3.15), expressed in the analytical form of:

$$U_{\mathrm{eff,t+s}} = \frac{\sum_{i=1}^{Nw}(U_i \cdot A_i)_{\mathrm{wall}} + \sum_{i=1}^{Nr}(U_i \cdot A_i)_{\mathrm{roof}} + \sum_{i=1}^{Nb}\eta_{\mathrm{t}} \cdot (U_i \cdot A_i)_{\mathrm{basement}} + \sum_{i=1}^{Ng}(U_i \cdot A_i)_{\mathrm{glazing}}}{\sum_{i=1}^{N} A_{i,\mathrm{env}}} - \frac{\sum_{i=1}^{Ng}\eta_{\mathrm{G}} \cdot (r_i \cdot A_i \cdot g_i)_{\mathrm{glazing}} \cdot G_{\mathrm{s}}}{\Delta T \cdot \sum_{i=1}^{N} A_{i,\mathrm{env}}} \tag{3.17}$$

where ΔT presents a temperature difference between the average external air temperature and the prescribed interior temperature in the heating period.

Relative to Eqs. (3.1a) and (3.9a), the total energy demand for heating (Q_{h}) consists of four energy flows (transmission, radiation, ventilation and internal gains). Therefore, ventilation heat losses (Eq. 3.3a) and internal heat gains (Eq. 3.5) also have to be considered in order to determine the final effective thermal transmittance of the entire building. In this case, the effective thermal transmittance coefficient ($U_{\mathrm{eff,h}}$) is calculated in the form of:

$$U_{\mathrm{eff,h}} = \frac{Q_{\mathrm{h}}}{\sum_{i=1}^{N} A_{i,\mathrm{env}}} \tag{3.18}$$

Another possibility is to take into account also the annual energy demand for cooling (Q_{c}, Eq. 3.10a). In this case, the expression for U_{eff} is, according to Eq. (3.18), extended to:

$$U_{\mathrm{eff,h+c}} = \frac{Q_{\mathrm{h}} + Q_{\mathrm{c}}}{\sum_{i=1}^{N} A_{i,\mathrm{env}}} \tag{3.19}$$

Practical example:

The main aim of this example is practical demonstration and implementation of the given expressions for U_{eff} based on the hypothetic timber-framed box-house model. The presented approach is open to further implementation regarding

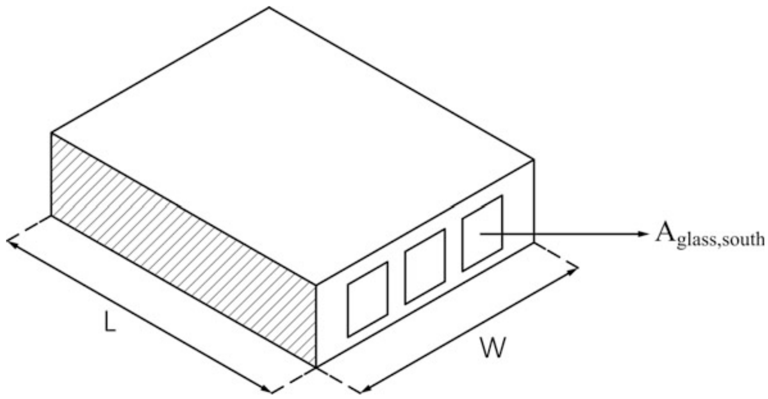

Fig. 3.7 Considered box-house model

energy-efficient renovation-related problems in the case of real buildings. The current example is demonstrated through a variation of the glazing sizes in the south-oriented façade. Similarly, such methodology is also applicable to cases including additional variations regarding the glazing placed in other cardinal façade directions, the thermal transmittance of the envelope elements and the thermal transmittance of the glazing.

Building geometry

The presented numerical research is based on a case study of a box model of 3-m-high single-storey houses built in the prefabricated passive timber-framed structural system with the three-layered glazing installed only in the south façade of the building. The model has a constant occupied floor area ($A_{TFA} = 81\ m^2$), a constant heated volume ($V = 243\ m^3$) and a constant aspect ratio (AR = L/W) of 1.0, schematically presented in Fig. 3.7.

Characteristics of the building envelope

The exterior walls are constructed using a timber-framed macro-panel system with timber class C22. The exterior walls and the roof are considered to be meeting the requirements of the passive house standard with $U = 0.10\ W/m^2\ K$ and the bottom plate thermal transmittance of $0.135\ W/m^2\ K$.

Characteristics of the glazing

Only the south-oriented windows are chosen for easier comparison of the solar gains in different climates. The window insulating glazing (Unitop 0.51–52 Uniglas) with three layers of glass, two low-emissive coatings and krypton in the cavities for a normal configuration of 4E-12-4-12-E4, is installed. The glazing configuration with a g-value of 52% and $U_g = 0.51\ W/m^2\ K$ assures a high level of heat insulation and light transmission. The U-value of the window frame is $U_f = 0.73\ W/m^2\ K$. The most important fact of the current study points to the

Table 3.1 Climate conditions for Ljubljana used in the study

Average annual temperature (°C)	Average annual temperature in the heating period (°C)	Length of the heating period (days/a)	Total annual solar radiation G on the south vertical surface (kW h/m^2)	Total solar radiation G on the south vertical surface in the heating period (kWh/m^2)
11.3	4.5	183.799	969	407

glazing size installed in the south façade ($A_{\text{glass,south}}$) which is a variable changing from 0 (no glazing) to 40.34 m^2 (totally glazed south wall). The latter practically means that *AGAW* varies from 0 to 1.

Climate data

The study analyses the energy performance relative to the city of Ljubljana. Climate data provided by Meteonorm [20] with temperature data for the period of 2000–2009 and radiation data for the period of 1991–2010 are used for calculations. The climate values are listed in Table 3.1.

Ambient temperature

For the heating period, a constant minimal ambient temperature of $T_{\text{int,min}} = 20$ °C is taken into account in all calculations. For the cooling period, the maximal considered temperature is $T_{\text{int,max}} = 25$ °C.

Calculating procedure

The calculation of the heating and cooling demand is performed in accordance with EN ISO 13790 [1], using the software program PHPP [3]. PHPP is a certified software program designed for planning low-energy and passive houses. It is based on the energy flux equations from EN ISO 13790 standard described in Sect. 3.1.1 as well as on other European standards. Since the analysis treats light timber-framed structures, the lowest possible value for specific capacity (specific capacity = 60 W h/K per m^2 of the usable area) of the building structure is selected as the input data to simulate the influence of the building thermal capacity.

Results and discussion

Firstly, the annual energy for heating (Q_{h}) is calculated using Eq. (3.9a) with a special focus laid to the transmission heat losses (Q_{t}), Eq. (3.2) and the solar gains (Q_{s}), Eq. (3.4). The results depending on the $A_{\text{glass,south}}$ value are graphically presented in Fig. 3.8.

The presented results demonstrate that transmission losses increase linearly with the glazing area. On the other hand, increasing the glazing area results in the linear increase of the solar gains, with a special distinction seen in a greater line inclination than in the case of transmission heat losses. Consequently, with respect to Eqs. (3.7)–(3.9a), the annual heating demand decreases with the glazing size.

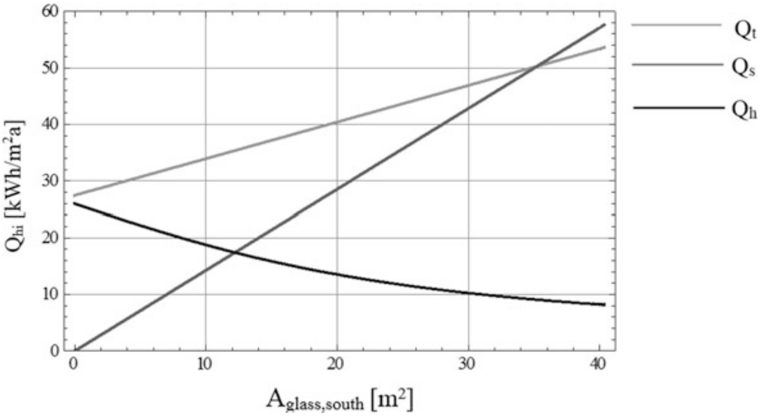

Fig. 3.8 Results for the energy demand in the heating period

According to Eq. (3.15), it is now possible to calculate the effective thermal transmittance ($U_{eff,t}$) considering solely the transmission heat flow. Having in mind the influence of the glazing area on the solar gains, Fig. 3.8, and respecting Eq. (3.17), the effective U-value of the whole building decreases. This influence is more evident at the glazing areas ranging from 0 to 20 m^2. The results for both values are presented in Fig. 3.9a. Finally, the results for the effective thermal transmittance ($U_{eff,h}$) considering all four heat flows in the heating period are presented in Fig. 3.9b.

It is convenient, especially for climate conditions with cold winters and hot summers, to consider also the energy need for cooling besides the energy demand for heating. The city of Ljubljana can be a typical example for such calculation. The energy need for cooling (Q_c) depending on the size of the south glazing ($A_{glass,south}$) is presented in Fig. 3.10a. Evidently, the energy need increases exponentially with the glazing size. Taking into account, the annual energy demand calls for the sum total of the energy need for heating (Q_h) and cooling (Q_c), $Q_{tot} = Q_h + Q_c$, Fig. 3.10b.

Evidently, an optimal point of the glazing size ($A_{glaas,south,opt}$) appears in this case and corresponds to the further called “optimal AGAW value” ($AGAW_{opt} = A_{glass,south}/A_{wall,south}$). More in-depth insight on $AGAW_{opt}$ values for new timber-framed and massive-panel buildings can be found in Leskovar and Premrov [4]. A comprehensive energy demand analysis for upgrade modules constructed in a timber-framed structural system analysis can be found in Špegelj et al. [21, 22].

Respecting the annual energy demand, the effective thermal transmittance (U_{eff}) is essentially changed when relative only to the heating period (Fig. 3.9b). The U_{eff} taking into account the heating and the cooling demand is presented in Fig. 3.11.

In contrast to the findings concerning only the heating period, the optimal U-value ($U_{eff,opt}$) arising from analysing the combination of heating and cooling periods depends on the glazing size placed in the south façade ($A_{glass,south}$).

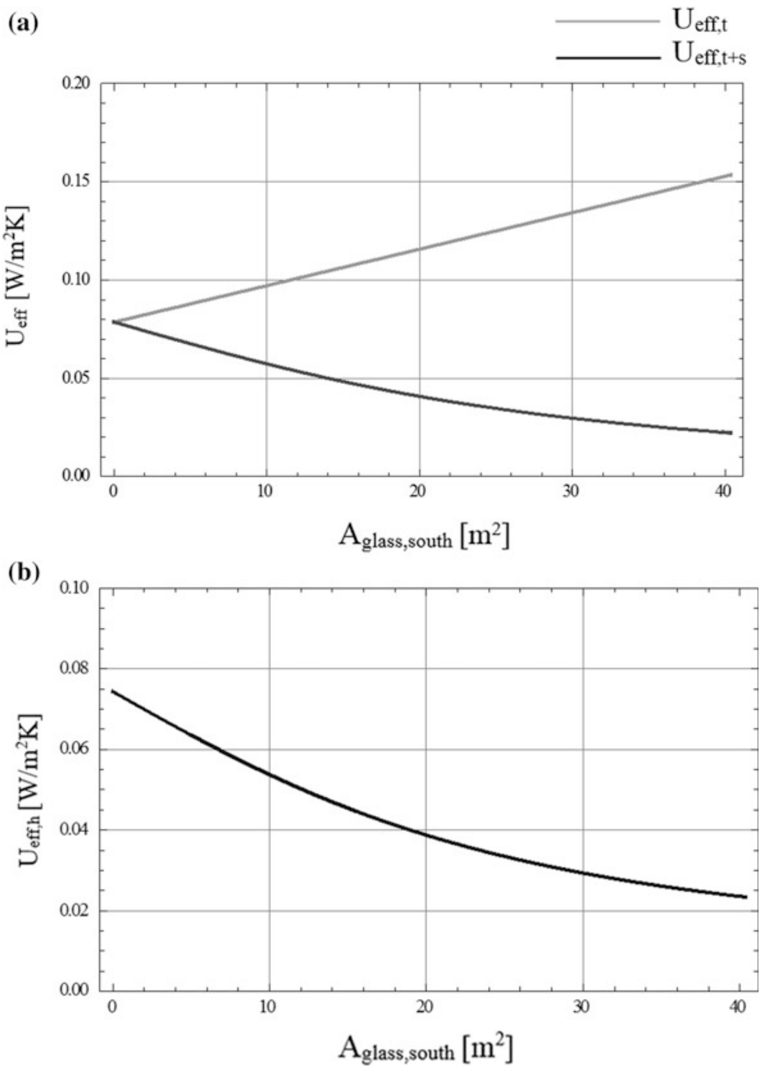

Fig. 3.9 Results for the effective thermal transmittance U_{eff} in the heating period

The latter is an interesting and vitally important fact which will be further systematically and deeply analysed also in the case of upgrade structural timber-framed modules in Chap. 4. The presented results in Fig. 3.11 for U_{eff} depending on the glazing size and position can be namely applied only to new timber-framed buildings where the transmission flow through the basement is not fixed to zero, as schematically presented in Fig. 3.1. The aforementioned transmission flow should be set to zero for the upgrade modules, see Fig. 3.17 in Sect. 3.2.4, which is then the only change in the described procedure. Anyway, the presented results can be

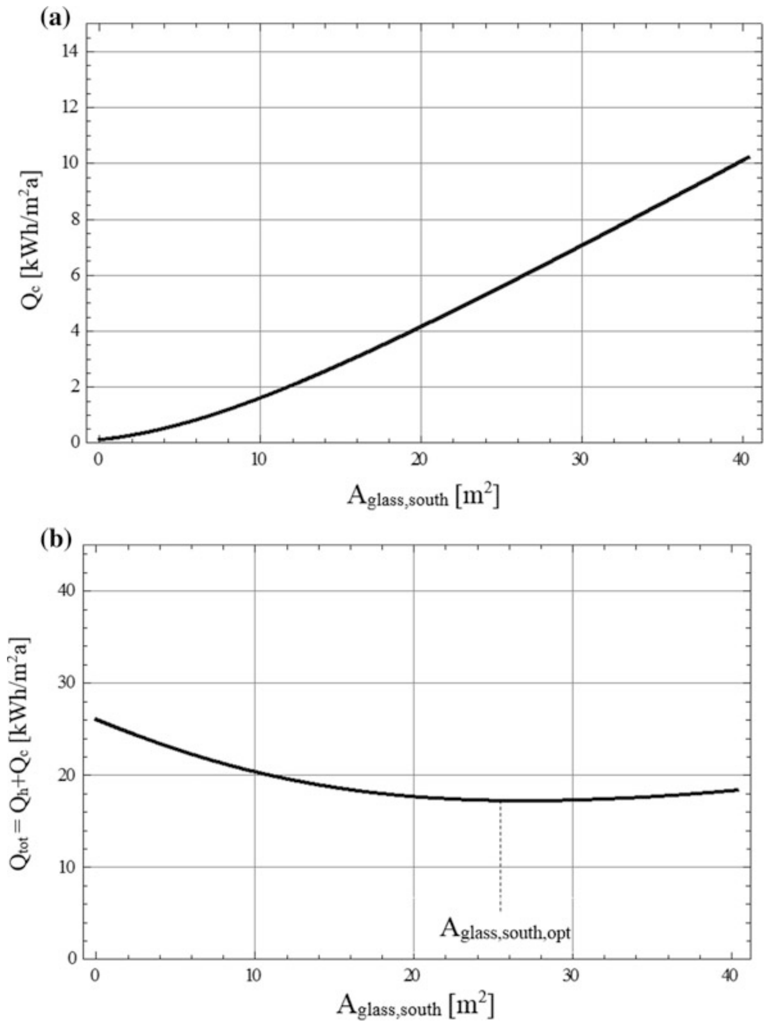

Fig. 3.10 Results for the energy demand in the cooling period (**a**) and the annual period (**b**)

treated as a good starting and theoretical point for our further research study on the energy-efficient and structural renovation with upgrade modules (Chap. 4).

Moreover, there are additional possibilities to define U_{eff} according to other parameters which exert influence on the annual energy demand, e.g. the thermal transmittance of the envelope elements (U_{wall}, U_{roof}), the thermal transmittance of the windows (U_{w}), the position of windows in other cardinal directions, the building aspect ratio (AR), etc. The influence of the thermal transmittance coefficient for windows (U_{w}) produces a significant impact on the energy demand, in combination with the size of the windows regarding the whole building envelope (AGAW). Such

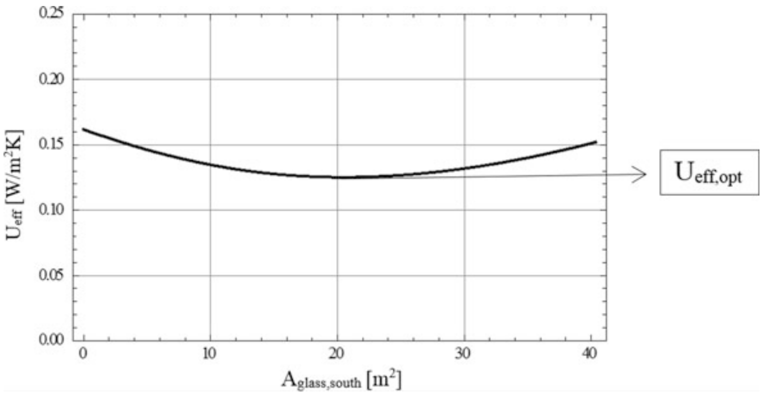

Fig. 3.11 Results for the effective thermal transmittance U_{eff} in the heating and cooling periods

calculations therefore strongly depend on the building type and will not be presented in this section. However, the functional dependence of U_{eff} is defined in the same manner as already presented for AGAW.

3.2 Steps of Building Energy-Efficient Renovation

Construction is, besides the fields of transport and industry, one of the main users of the prime energy from fossil sources, which makes this sector highly responsible for the implementation of climate-environmental policies. Buildings are responsible for approximately 35–40% of CO_2 emissions and are thus closely linked to climate changes, Vine [23]. It is furthermore important to point out that residential buildings forming 70% of the total buildings' surface consume and are responsible for 63% of the total energy need required to satisfy the demands of the hosing stock, Itard and Meijer [24]. A major part of the energy in EU residential buildings is used for heating (67%), the rest for electricity (lighting, cooking, operation of the electricity users) and sanitary hot water.

The existing energy-inefficient buildings were constructed under relatively loose laws and regulations as far as energy efficiency is concerned and are consequently estimated to have 20 times higher energy demand in comparison with newer buildings. The reason for high energy consumption therefore proves to be the age of the buildings and consequently their substantially high thermal transmissions through the building envelope, see Eq. (3.2).

The main goals in the past mostly focused on the energy efficiency of the new build whose annual contribution to the existing housing stock amounts to 1% or even less, with the remaining 99% of buildings producing approximately 24% of the energy-use-induced carbon emissions. About 2/3 of the existing buildings are more than 30 years old, and about 40% are older than 50 years, Poel et al. [25].

According to EU statistics, Eurostat [26], more than 50% of the housing stock in EU-25 was built prior to 1970, with a share of 33% dating from the 1970–1990 period. The latter is an important observation given that most national building regulations mandating thermal properties of building envelopes were introduced after 1970, Konstantinou and Knaack [27], which accounts for the fact that buildings built before 1970 mostly lack thermal insulation and have a rather high thermal transmittance value of the envelope.

Similarly, the current state of the housing stock in Slovenia is partly a consequence of frequent changes in the legislation in the past. For example, more than 95% of the building stock (comprising single-family houses and multi-family buildings) was built before 2000, i.e. prior to first substantially strict regulations on energy efficiency of the housing in Slovenia. A considerable number of legislative modifications on energy efficiency in buildings have been adopted since 1970 when the first Slovenian regulation on thermal insulation in construction entered into force, which is nevertheless 18 years later as compared to Germany where DIN 4108 came into effect back in 1952, Schuler et al. [28]. Until 1984, the focus in Slovenia was only laid on the thermal transmittance of the building envelope with first demands, fairly minimal in comparison with the existing ones, referring to the energy use for heating in buildings being introduced only after the indicated year. Thermal insulation layers of buildings dating from the period before 1984 are either inexistent or lack the necessary thickness, which is only made worse by windows with single or basic double glazing and improper air-sealing. As seen from the above facts, the existing residential buildings in Slovenia are mainly classified as energy-inefficient and demand renovation, the process of which has already taken place in Slovenia and elsewhere. In 2002, 2008 and 2010, three regulations on energy efficiency in buildings introducing progressively stricter demands were adopted; the prescribed *U*-values of the external wall elements are presented in Table 3.2.

As seen, 97% of the multi-family buildings in Slovenia prove to be energy-inefficient. Therefore, if we wish to satisfy sustainability requirements, we need to start renovating old energy-inefficient buildings and reduce their heating and cooling demand, Poel et al. [25].

Table 3.2 Energy use in the building and thermal transmittance of the external walls according to the year of construction, Republic of Slovenia, Ministry of Environment and Spatial Planning (2004)

Year of construction	1965	1968	1970	1977	1980	1987	1995	2000	2002	2008
Multi-family buildings (kWh/m^2 a)	180	170	130	130	100	100	90	70	–	–
U of the external wall (W/m^2 K)	1.29	1.29	1.29	1.28	1.28	1.22	1.20	1.20	0.60	0.28
				1.45	1.45	0.93	0.90	0.90		
				1.68	1.68	0.93	0.80	0.80		

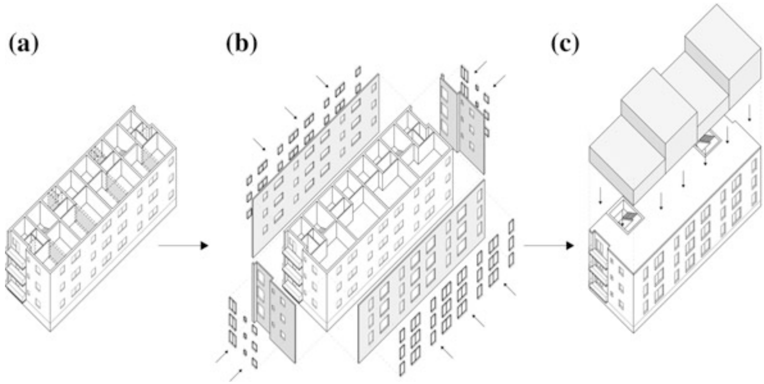

Fig. 3.12 Schematic demonstration of the process of deep renovation of a multi-family building; **a** functional performance renovation of the interior, **b** energy-efficient renovation of the thermal envelope, **c** structural upgrade module renovation with a need for a simultaneous consideration of all phases

Respecting the given facts about energy flows in Sect. 3.1, there are many different possibilities of decreasing energy losses through the building envelope during the heating period or increasing energy gains, mostly with passive design strategies using solar gains. However, energy-efficient building design requires a careful balance of the energy consumption, energy gain and energy storage.

The basic purpose of energy-efficient renovation is to reduce energy losses, the transmission heat losses (Q_t) and the ventilation heat losses (Q_v), while increasing useful energy gains, the solar heat gains (Q_s) and in some cases also the internal heat gains (Q_i), with the aim of reducing the energy consumption for heating and cooling and reaching a high level of indoor climate quality. The latter can be achieved through the implementation of various renovation measures performed on the energy non-efficient existing building (Fig. 3.12a), such as:

(a) improvement of the building envelope thermal performance (non-transparent) (Fig. 3.12b),
(b) replacement of old windows/doors with new energy-efficient ones (Fig. 3.12b),
(c) enlargement of glazing areas on the building envelope (Fig. 3.12b),
(d) improvement of airtightness (Fig. 3.12b),
(e) installation of the heat recovery ventilation system,
(f) attic extension with the energy-efficient structural upgrade module (Fig. 3.12c).

The above-mentioned partial steps will undergo further discussion, nevertheless, it is important to stress that the highest energy savings can be achieved only through a comprehensive energy-efficient renovation where the combination of above-stated measures (a–f) is carefully selected, in accordance with the existing building specifics.

3.2.1 Improvement of the Building Envelope Thermal Performance

Improving the building envelope thermal performance is usually the most popular, the simplest and sometimes also the first and the cheapest step in energy-efficient renovation of buildings. This approach involves installing thermal insulation on either the outside or alternatively the inside surface of the building envelope elements, starting with non-insulated old buildings, or those having already undergone a certain thermal insulation refurbishment process, see Fig. 3.12b. It is of the utmost importance to apply thermal insulation to all non-transparent building components, walls, roof and basement, in order to reduce transmissions losses. The main goal of the described renovation step is to reduce the *U*-values and consequently, according to Eq. (3.2), the transmission losses through the building envelope elements. The energy demand for heating of such renovated buildings can therefore be essentially decreased, Eq. (3.9a). It is important to mention that the reduction of the energy demand for cooling reached by the approach discussed does not amount to the same values as in the case of heating. Consequently, the above is usually not the best energy-efficient renovation approach for buildings located in warm climate areas.

The Slovenian energy standard PURES 2010 [29] prescribes the following conditions the thermal transmittance of the building envelope elements needs to satisfy:

- $U_{\text{wall}} \leq 0.28$ W/m^2 K for the walls,
- $U_{\text{roof}} \leq 0.20$ W/m^2 K for the roof,
- $U_{\text{basm}} \leq 0.35$ W/m^2 K for the basement.

It is recommended to choose new *U*-values of the envelope components with respect to the following relations; the lowest *U*-values for the insulated roofs and the highest for the insulated basement:

- $U_{\text{roof}} \approx 0.70\ U_{\text{wal}}$, for the roof,
- $U_{\text{basm}} \approx 1.25\ U_{\text{wall}}$ for the basement.

Simple graphical scheme of these recommendations for *U*-values is given in Fig. 3.13.

The influence on decreasing the energy demand additionally depends also on the surface area of the partial envelope elements. For example, if the aspect ratio (AR) of the building is low (Fig. 3.2a), higher energy savings will be obtained with thermal insulation added to the wall elements. On the other hand, in buildings with a higher aspect ratio (Fig. 3.2b) where the surfaces of the roof and basement are rather large relative to the wall envelope elements, thermal insulation of the roof elements will lead to substantially higher energy savings. In such cases, it is more convenient to invest into a thicker insulation layer applied to the roof and thus obtain a lower *U*-value, as already suggested in reference to the wall *U*-value and the thickness of the wall insulation. The latter will be presented at the end of

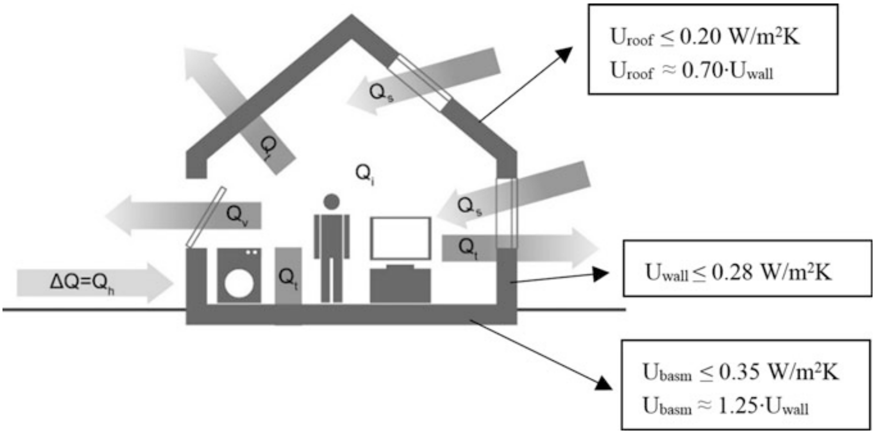

Fig. 3.13 Simple recommendations for the selection of *U*-values

Sect. 3.2.2, based on a real example of energy-efficient renovation of two old multi-family buildings constructed in the 50s and 60s of the 20th century, lacking thermal insulation of the building envelope elements.

3.2.2 Replacement of Windows

Window replacement is also seen as one of the traditional steps in the energy-efficient renovation process and is often performed as the only partial renovation step in many buildings. It is important to stress that glass can nowadays be treated as a dominating material in modern architecture. Yet, from the energy efficiency perspective glass was often treated as being a weak point due to its high thermal conductivity. Consequently, widows used to represent areas of the building envelope with the highest heat loss potential, since the average *U*-value of windows was generally substantially higher than the average *U*-value of opaque building elements (walls, ground slab and roof). According to the above and relative to Eq. (3.2), the transmission losses (Q_T) through the glazing areas were usually essentially higher than those through the envelope elements in façades and roofs.

Nevertheless, dynamic evolution of the glazing in the last decades has resulted in insulating glass products with highly improved physical and strength properties, suitable for application to contemporary energy-efficient buildings, not only as a material responsible for solar gains and daylighting, but also as a component of structural resistance.

Glazing elements with highly performing thermal insulation were developed using glass panes with different numbers of layers and with intermediate spaces

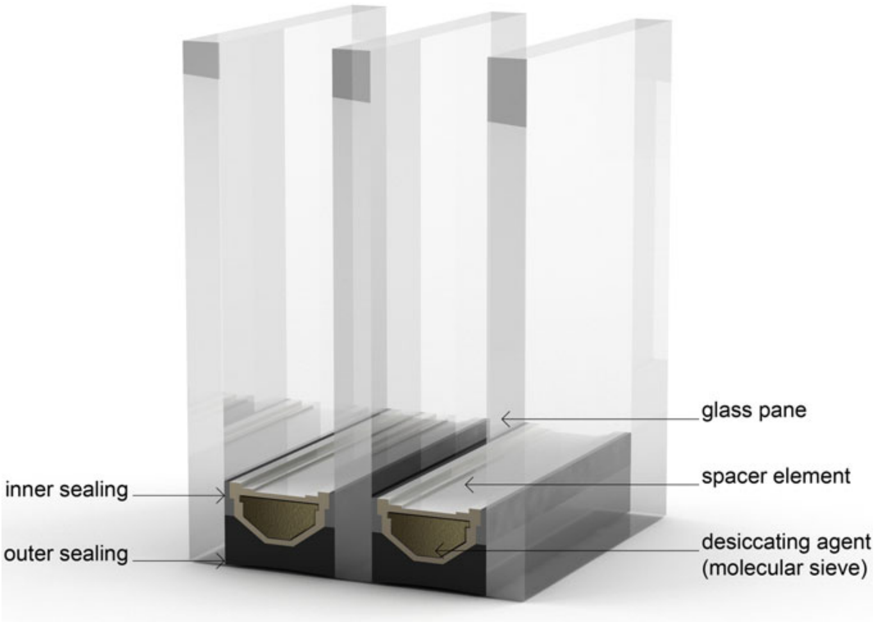

Fig. 3.14 Composition of a typical three-pane insulating glass unit, [30]

which can be filled with various types of gas (Argon, Krypton, Ksenon, etc.). Additionally, special low-energy and solar coatings were developed to reduce the *U*-value of glass or overheating.

It is therefore evident that with contemporary insulating glazing the thermal transmittance of the glazing (U_g) depends on the number and dimension of the pane interspaces, the type of gas filling, the number, type and emissivity of glass coatings, and on the type of edge seal and spacer element. The composition of a three-pane insulating glass unit is schematically presented in Fig. 3.14.

However, estimation of the energy demand for heating needs to encompass not only the glazing but the whole window element with its *U*-value (U_w), in all calculations, Eqs. (3.2) and (3.4). A contemporary thermally insulating window element namely consists of a glazing unit and a window frame. The energy performance of windows can be expressed by two general indicators:

– The coefficient of thermal transmittance U_w (W/m^2 K) with separate values for the glazing, the frame and the entire window element. It indicates the amount of heat passing through 1 m^2 of the component per unit of time based on a temperature difference of 1 K. In our case, U_w is important to determine the transmission losses through the window elements, Eq. (3.2).
– The coefficient of permeability of the total solar energy *g* (% or values 0–1) of the glazing. It indicates the sum of the solar energy transmitted directly through the glass and the solar energy absorbed in the glass panes which is then emitted

to the interior. In our case, U_w is important to determine the transmission solar gains through the window elements, Eq. (3.4).

Respecting the window composition, its overall coefficient of the thermal transmittance (U_w) depends not only on the glazing but also on the type of window frame and spacer element. Additional technical details relative to the above can be found in Leskovar and Premrov [30]. The U_w can be read, measured or calculated. Determination by means of calculation is based on the following equation, according to ISO EN 10077-1:2006 [31]:

$$U_w = \frac{A_g \cdot U_g + A_f \cdot U_f + l_g \cdot \Psi}{A_g + A_f} \tag{3.20}$$

with the following quantities:

- U_w: heat transfer coefficient of the window,
- U_f: heat transfer coefficient of the frame,
- U_g: heat transfer coefficient of the glazing,
- A_f: area of the frame,
- A_g: area of glass,
- l_g: length of the glazing perimeter,
- Ψ: linear heat transmittance of the glass edge (describes thermal bridges of a constructional component).

As presented further in this study by means of a selected practical example, the U-value of the entire window element with highly insulating glazing and frames was generally reduced by a factor of even 4 or 5, based on the comparison of contemporary high-insulating windows with the old ones (dating from the 1960s or 1970s). Consequently, with reference to Eq. (3.2), replacing old windows with the new ones can lead to a significant reduction of the transmission losses through the window elements.

On the other hand, the g-value of the insulating window does not decrease in such a manner as the U-value; hence, the solar heat gain in the heating period (Eq. 3.4) does not essentially decrease with window replacement. Consequently, the entire building energy demand for heating (Q_h), Eq. (3.9a), can be highly improved when using this renovation approach which is therefore highly popular and common in practice. Investors sometimes choose between the 3.2.1 and 3.2.2 energy-efficient renovation approach if they lack sufficient financial resources to invest simultaneously into both renovation steps. Furthermore, due to somewhat lower solar gains (Q_S), Eq. (3.4), new windows can additionally prevent the building from overheating in the summer time and contribute to a slight decrease of the annual energy demand for cooling (Q_c), Eq. (3.10a).

3.2.3 *Enlargement of Glazing Areas in the Building Envelope*

As presented in Sect. 3.1.4, increasing the size of the glazing, installed mainly in the south-oriented façade of the building, may positively affect the energy demand of the building. The solar gains through the glazing can in some cases be higher than the transmission heat losses through the same glazing area. Consequently, the total annual energy demand for heating (Q_h) decreases, as graphically presented in Fig. 3.8. Climate conditions with cold winters and warm summers encompass the possibility of overheating, which in turn necessitates consideration of the consequent energy demand for cooling (Q_c) in the summer period (Fig. 3.10), as it may essentially change the total annual energy need. A further numerical development can thus be used with a view to determining the optimal size of the glazing ($AGAW_{opt}$), i.e. the area of glazing resulting in a minimal annual energy demand for heating and cooling. An example of such analytical development was shown in Sect. 3.1.4 where a theoretical timber-framed box-house model was purposely selected for the above-mentioned step, with the obtained numerical results presented in Fig. 3.10b.

An interesting study offering a detailed presentation of the mentioned approach where the optimal glazing size ($AGAW_{opt}$) is defined depending on the thermal transmittance of the external wall elements (U_{wall}) is found in Leskovar and Premrov [4, 30]. It is important to point out that both studies were performed on a specially selected real example of two-storey prefabricated frame-panel building with the three-layered insulating glazing, located in Ljubljana. Therefore, the presented results from Fig. 3.15 cannot be generally adopted to a selected building, although they may present relevant information and a starting point for further analysis of any type of the building form.

The results point out that the optimum of the function curves for $AGAW_{opt}$ appears only in the external wall systems with a $U_{wall} \leq 0.193$ W/m^2 K. As the U_{wall}-value decreases, the optimal south-oriented glazing size becomes lower. The latter fact is of vital importance for the energy-efficient renovation process of buildings. With respect to this interesting finding, an optimal energy-efficient renovation approach can be thus performed in two steps:

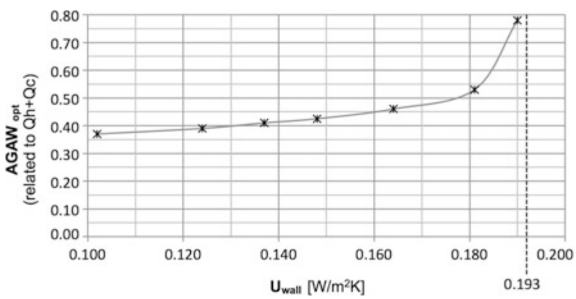

Fig. 3.15 Optimal values of AGAW in the south-oriented external wall element as a function of the U_{wall}-value for frame-panel construction systems, taken from Leskovar and Premrov [4]

– applying step 3.2.1 to decrease the *U*-value of the building envelope by adding thermal insulation,
– determining, according to Fig. 3.15, the optimal AGAW value on the south-oriented façade depending on the previously obtained *U*-value of the external wall elements.

3.2.4 Installation of the Heat Recovery Ventilation System

Installing the heat recovery ventilation system is an active approach to energy-efficient renovation of buildings, a step leading to significant reduction of ventilation heat losses in the heating period, Eq. (3.3a), i.e. of the n_v coefficient in Eq. (3.3a). The system described as an active technical system works on the principle of outgoing hot airstream warming up the incoming airstream through a heat-conductive plate. It needs to be highlighted that the inbound and outbound airstreams do not mix together as they flow along separate ducts connected at certain points by heat-conductive plates, as schematically presented in Fig. 3.16.

Reduction of ventilation heat losses by applying the current renovation step depends primarily on two parameters contained in the following equation:

– recuperation efficiency (η_{hr}), usually at about 0.75 for heating,
– the value of $n_{v,mech}$ is 0.3 h^{-1} for heating and 0.5 h^{-1} for cooling.

Recuperation efficiency affects the reduction of ventilation heat losses also depending on the heated (ventilated) room volume (*V*), Eq. (3.3a). All in all, reducing ventilation heat losses is in fact linked to the recuperation system efficiency in relevance to the building heated volume.

The heat recovery system efficiency depends on the chosen type of recuperation. In general, we distinguish between:

– central recuperation
  and
– local recuperation.

As the installation of the recovery ventilation system, that of the central recuperation type in particular, means a huge construction operation (duct installation), it is rarely applied in residential building renovation where it represents an ultimate renovation step. Investors thus prefer the local recuperation type which is a less comprehensive procedure from the constructional viewpoint and encompasses lower costs. Nevertheless, there is a vitally important energy-saving fact since the installation of the recovery ventilation system reduces ventilation heat losses by a factor ranging from 3 to 6 in comparison with natural ventilation. The exact reduction factor, with respect to Eq. (3.3a), depends on the heat recovery unit capacity in relation to the heated building volume.

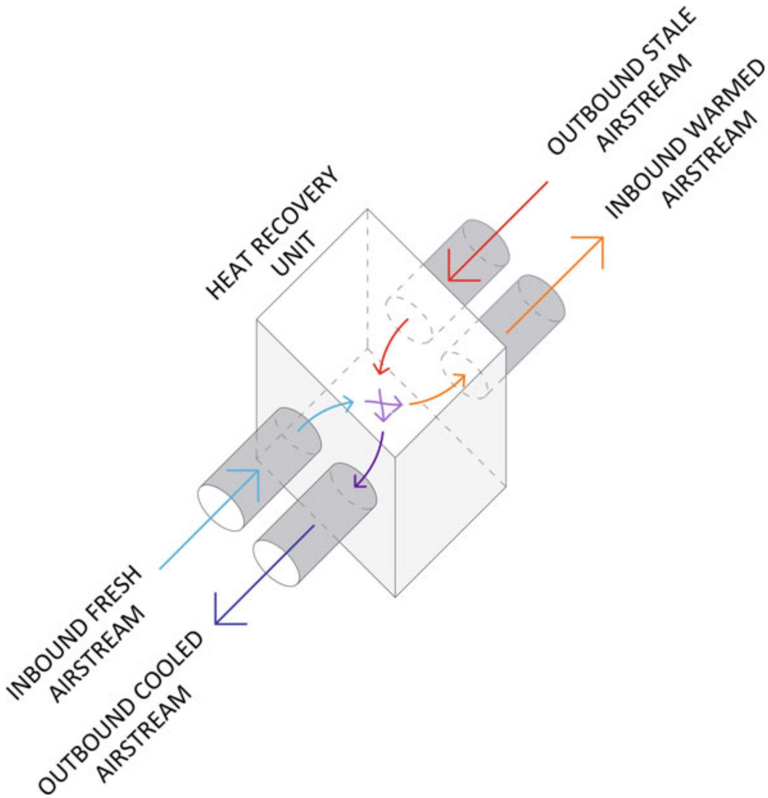

Fig. 3.16 Schematical presentation of the global recuperation system

3.2.5 Attic Extension with a Structural Upgrade Module

Most of the northern and western European cities demonstrate a growing demand for new usable surfaces, both residential and non-residential. Due to a shortage of free construction positions in city centres, renovation by applying structural upgrading of buildings in view of increasing the surface proportion would be a sensible and very popular renovation option. It represents a further level of functional and energy performance renovation along with the necessary construction problems consideration, in addition to renewing the thermal envelope and active technical systems, as described in previous renovation steps, 3.2.1–3.2.4. The following renovation measure to be discussed is placement of the structural upgrade module enabling simple and fast installation onto the existing building, as schematically presented in Fig. 3.12c. Moreover, financing a construction measure by adding attractive upgrade modules with additional floor space providing a high living comfort is an interesting option also from a financial point of view, Kaufmann et al. [32]. Structural upgrading is equally beneficial in urban areas where the costs per square metre of usable floor area surpass the real estate prices in less attractive locations.

The main advantage of this interesting and relatively new renovation approach from the **energy efficiency viewpoint** is reducing the energy flow through the roof elements of the existing building with a simultaneous creation of one or more additional storeys which can be constructed in the most optimal way regarding the previously described energy flows and material characteristics in a renovated building. Therefore, this upgrade module can be treated as an "optimal energy box" to improve overall energy behaviour of the whole renovated building. The previously mentioned studies on the optimal design of new buildings thus represent a baseline for developing the optimal shape of the upgrade module from the energy aspect with the optimal size and orientation of the glazing installed in the envelope elements and with an optimal shape of the upgrade module. Such an approach allows for achieving a minimal effective *U*-value of the building described in Sect. 3.1.4, leading to a maximal decrease of transmission heat losses through the envelope elements.

A difference between previously carried out numerical studies on the optimal size of the glazing installed in new-build-façades facing different directions (e.g. Leskovar and Premrov [4], Premrov et al. [6, 33]) and the energy-efficient renovation with the structural upgrade module lies in the change of energy flows **as** the bottom plate of the upgrade module becomes a building element between two heated rooms having the same indoor temperature (Fig. 3.17). Hence, the transmission heat flow through the contact zone (floor slab) between the last storey of the existing building and the upgrade module should be set to zero ($Q_{t,\ floor} = 0$, no heat flow) which is the most important boundary condition to be used in this approach. This assumption can substantially change the energy equilibrium in the whole building. In addition, the upgrade module offers an opportunity to be designed in an optimal way, according to the previously described principles of passive design strategies and respecting the available solar potential. The above

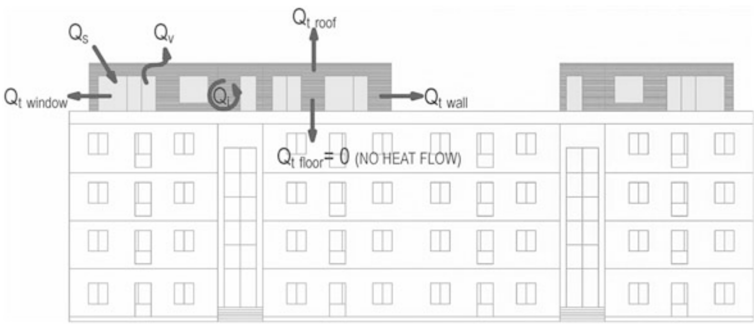

Fig. 3.17 Installation of the upgrade module on the existing multi-family building and the energy flows of the system, [21]

basically means taking into account the size and orientation of the glazing which theoretically minimize the energy need for heating and cooling. The analytical procedure already described and implemented on new box-house models in Sect. 3.1 will be further implemented on the upgrade module example in Sect. 4.3.

The optimal upgrade module shape with its optimal glazing size and position, further referred to as "optimal module", can be additionally defined by the numerical approach, already described in Sects. 3.1.2 and 3.1.4, considering the sum of the total annual energy need for heating and cooling. The optimal upgrade module shape depends on three changeable parameters which are thoroughly analysed in the parametric numerical study in Sect. 4.3. These are the shape of the module and the proportion of glazing in the east-, south- and west-oriented façades along with the thermal transmittance of the external walls and the roof. As a final result, the module offers maximum all-year-round living comfort.

However, from the **structural point of view**, installation of an additional structural element on the top of the building produces additional mass and loads acting on the load-bearing elements of the existing building, as schematically presented in Fig. 3.18. Owing to the prescribed safety standards regarding resistance to vertical load action (self-weight load, live load, snow load), the majority of old buildings have sufficient load-bearing capacity to allow for one or two upgrade storeys. Using lightweight upgrade structure, like a steel or timber building, is therefore highly favourable as the total vertical load acting on the existing vertical elements (walls and columns) is not significantly increased. Moreover, construction

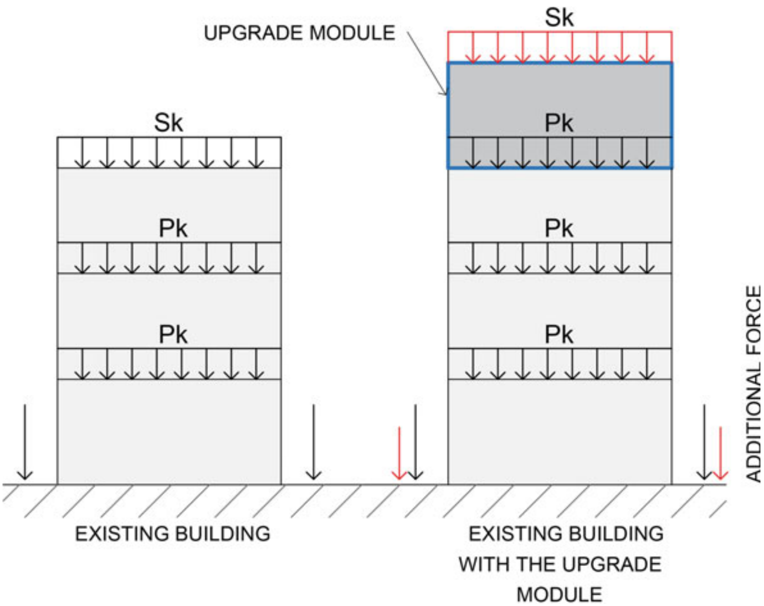

Fig. 3.18 Vertical load impact at the upgrade module installation

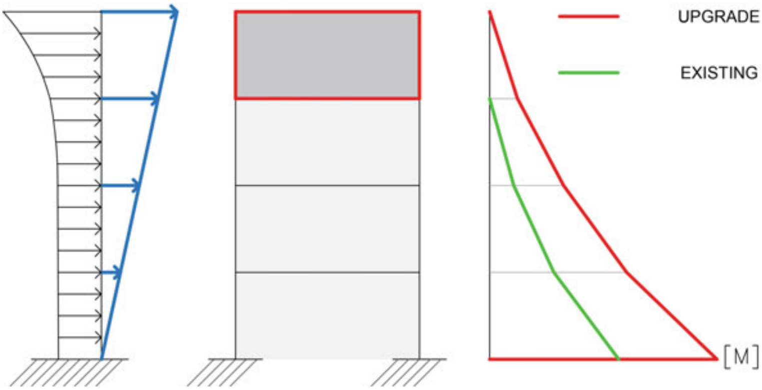

Fig. 3.19 Horizontal load impact (wind and earthquake) at the upgrade module installation

with prefabrication technology results in rapid instalment which reduces the risk of the existing building being exposed to adverse weather conditions and humidity.

Increasing the height of the building brings about substantial increase in the impact of the horizontal load, which can cause drastic changes in the maximal forces acting at the first floor of the existing building. The distribution and enlargement of the bending moments due to the increased horizontal loads (wind or earthquake) is schematically presented in Fig. 3.19. Wind load is marked with a dark line and seismic load with the blue one.

Based on Fig. 3.19 with its schematically presented load increase and the consequent increase of internal forces in the first storey of the existing building, the feasibility of adding one or more upgrade storeys is mainly a question of the existing building and its load-bearing structural system. Nevertheless, it is convenient in both cases, the vertical load case (Fig. 3.18) and the seismic load, in particular to choose the upgrade module with low extra mass which will not drastically change the maximal internal forces in the existing structural elements. With a prescribed reserve in the load-carrying capacity, the existing structural elements will be usually in position to bear additional load impact. In the opposite scenario, they should need strengthening to increase their resistance.

Owing to low timber structure mass as opposed to that of reinforced concrete (RC) or masonry structures, timber upgrade modules take preference over other material options since they impose lighter loads on the existing building. Furthermore, a designed upgrade construction module consisting of prefabricated timber-framed wall elements additionally reduces the weight of such structural wall elements as compared to solid timber or cross-laminated timber (CLT) wall elements. A comparison of timber-framed and CLT upgrade modules affecting the seismic resistance of existing masonry and RC buildings is presented in the experimental and numerical study found in Jančar [34]. A short overview of the results will be presented in Sect. 4.2.

Taking into account all the benefits from the **energy efficiency** and **structural viewpoints**, a combination of prefabricated timber-framed-panel walls as “classic” prefabricated wall elements and prefabricated timber wall elements with insulating glazing, further referred to as prefabricated timber-glass wall elements (Leskovar and Premrov [30], could be the most effective solution for the purpose of renovation and the consequent reduction of the energy need for heating and cooling of the existing building. In order to achieve the latter, the module needs to have an appropriate design following the guidelines for the optimal floor plan and glazing size. Additional research analyses on systematically increased number of upgrade storeys constructed in timber-framed-panel structural system in combination with prefabricated timber-glass wall elements will be presented in Sect. 4.3.

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Chapter 4
Scientific Research Related to Building Renovation

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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 m^2, A_2 = 400 m^2, A_3 = 600 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,

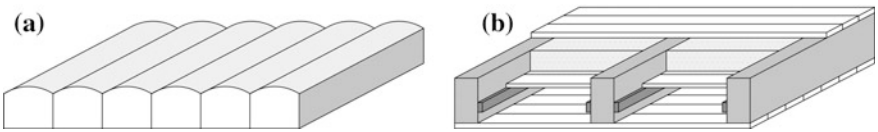


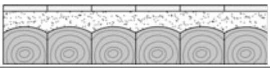
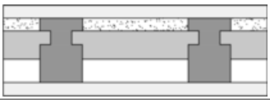
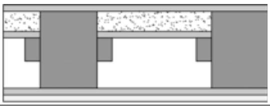
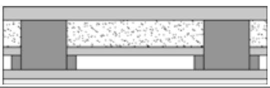
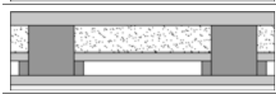
Fig. 4.1 **a** Solid timber floor, **b** timber-framed floor

– 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

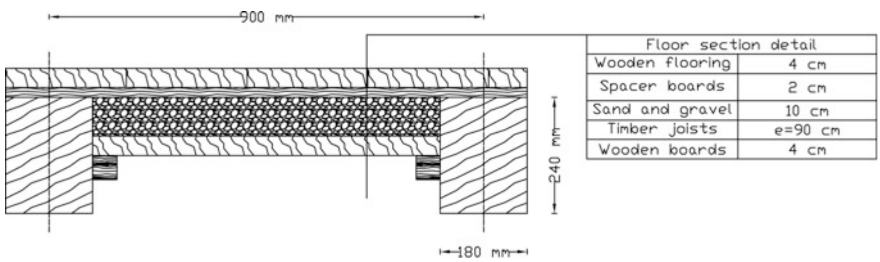


Fig. 4.2 Typical cross section of old floor elements used in the numerical study in Unuk et al. [65]

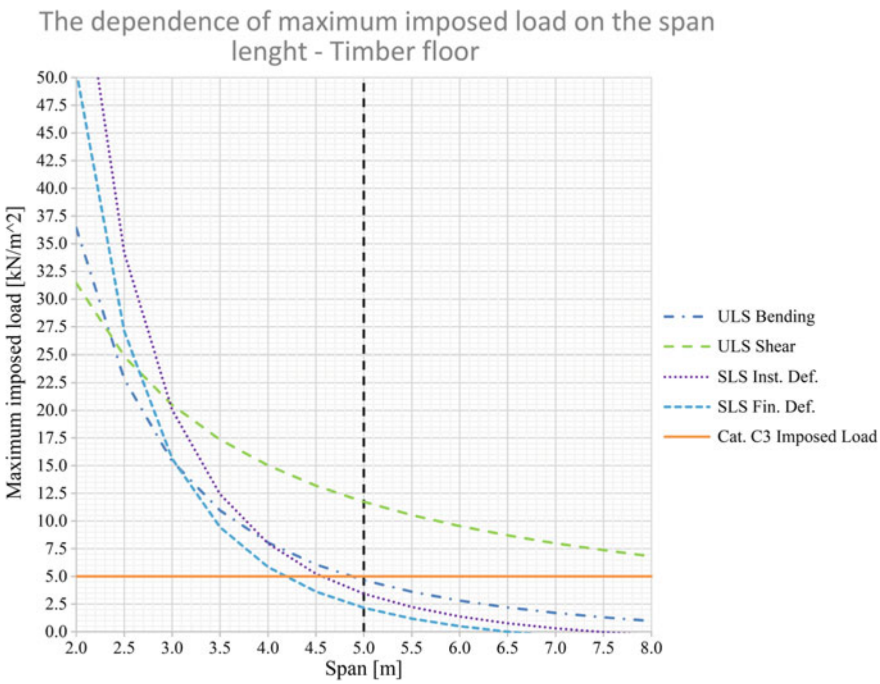


Fig. 4.3 Maximum allowable imposed load depending on the beam span [65]

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:

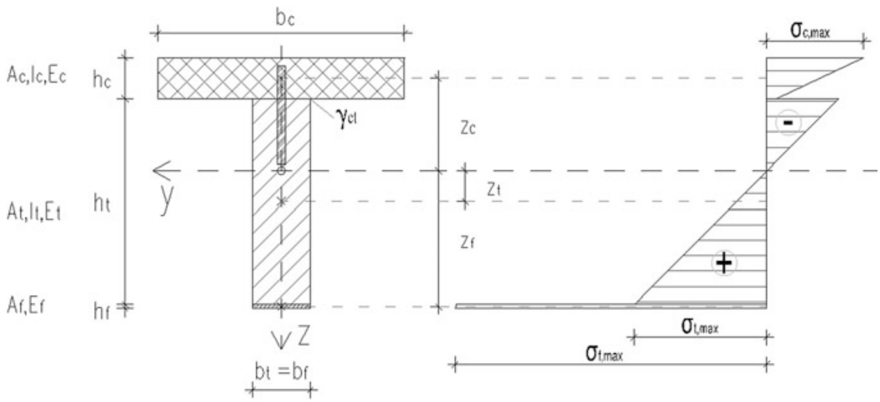


Fig. 4.4 Linear elastic stress distribution in the beam cross section [69]

– 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 γ-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:

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

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

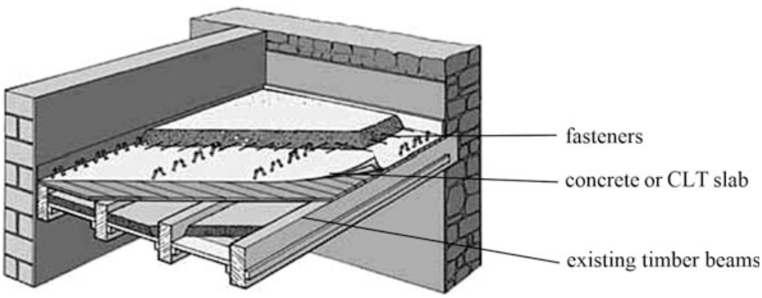


Fig. 4.5 Type of reconstruction of old timber floors with a concrete slab placed in the compressive zone [70]

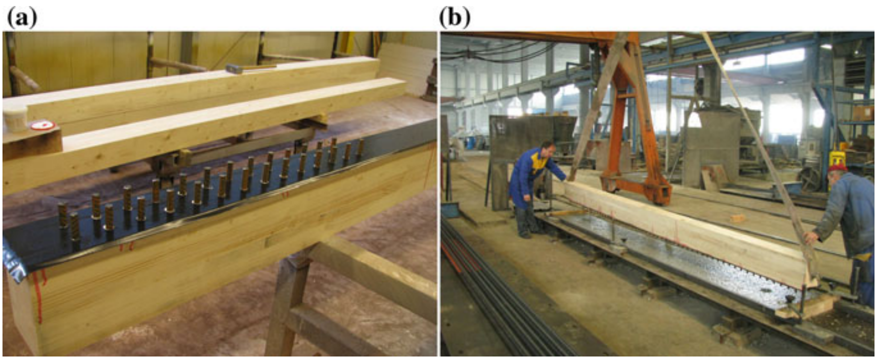


Fig. 4.6 **a** Installation of the steel dowels onto the timber beam and **b** laying of the timber beam onto the concrete slab [70]

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

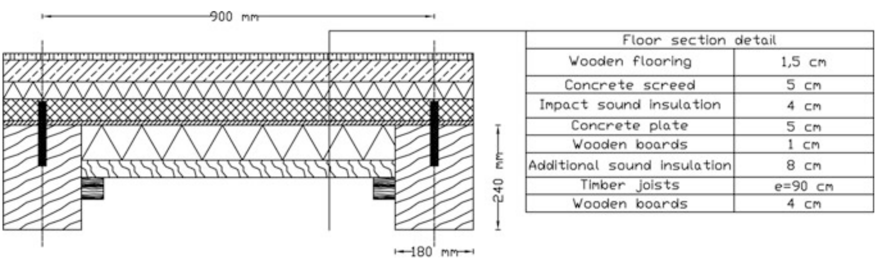


Fig. 4.7 Existing timber beam strengthened with the concrete slab [65]

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.

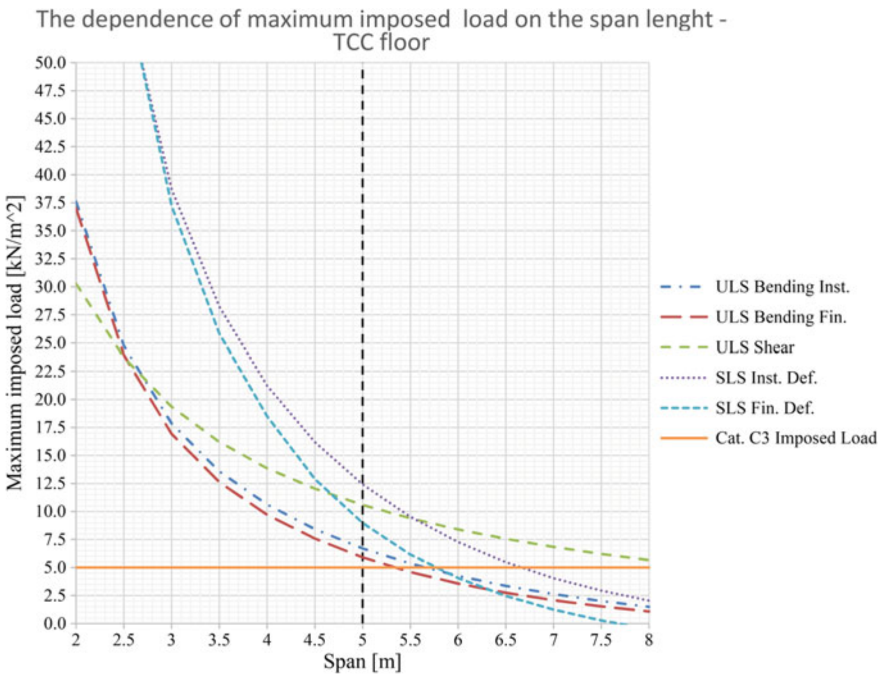


Fig. 4.8 Maximum allowable imposed load depending on the beam span for timber–concrete composite floor element [65]

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.

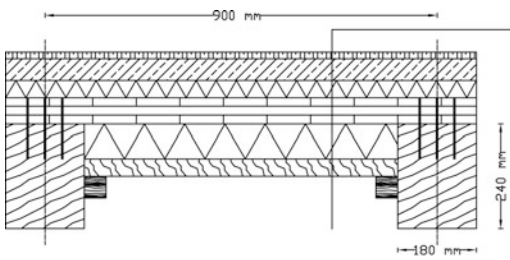
This strengthening solution is comparable to the previously described method with the concrete slab; however, there are still some important differences in a view of structural, building physic and ecological aspects:

- Additional mass in this method is essentially lower on account of the lower density of CLT ($\rho \approx 500$–$600\ \text{kg/m}^3$) according to the concrete slab ($\rho \approx 2500\ \text{kg/m}^3$).
- 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.



Floor section detail	
Wooden flooring	1,5 cm
Concrete screed	5 cm
Impact sound insulation	4 cm
CLT panel	6 cm
Additional sound insulation	8 cm
Timber joists	e=90 cm
Wooden boards	4 cm

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

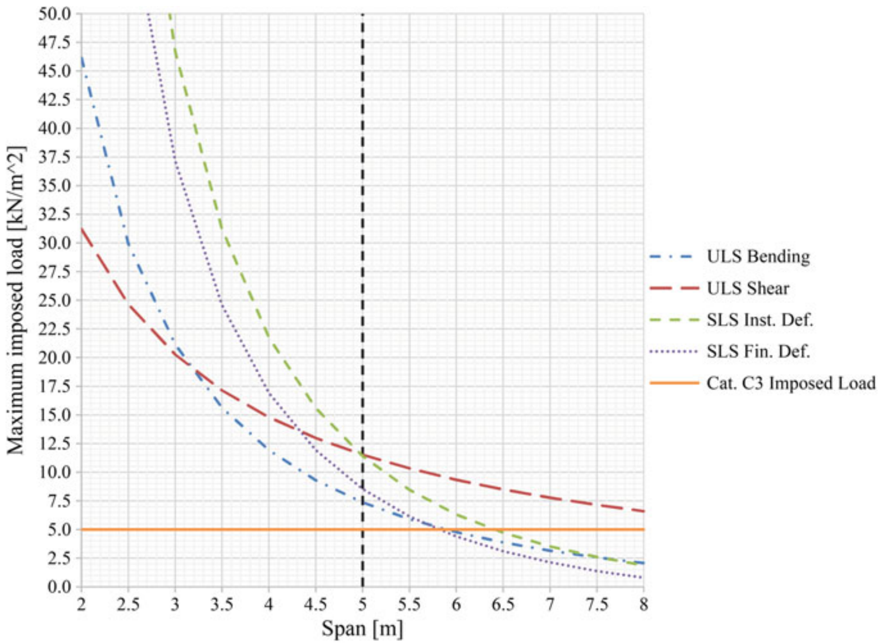


Fig. 4.10 Maximum allowable imposed load depending on the beam span for the timber–concrete composite floor element [76]

(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

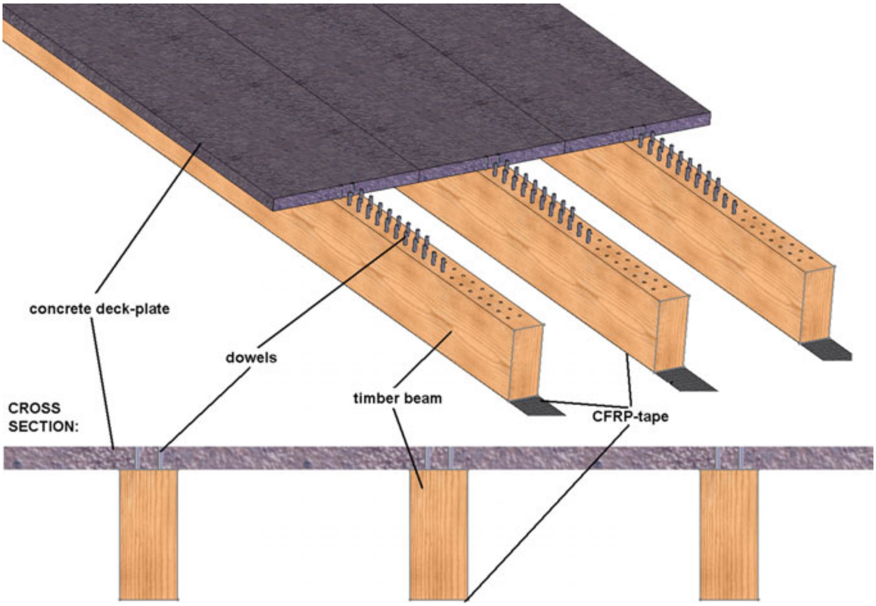


Fig. 4.11 Types of reconstruction of old timber floors with a concrete slab and additionally with CFRP strips [70]

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].

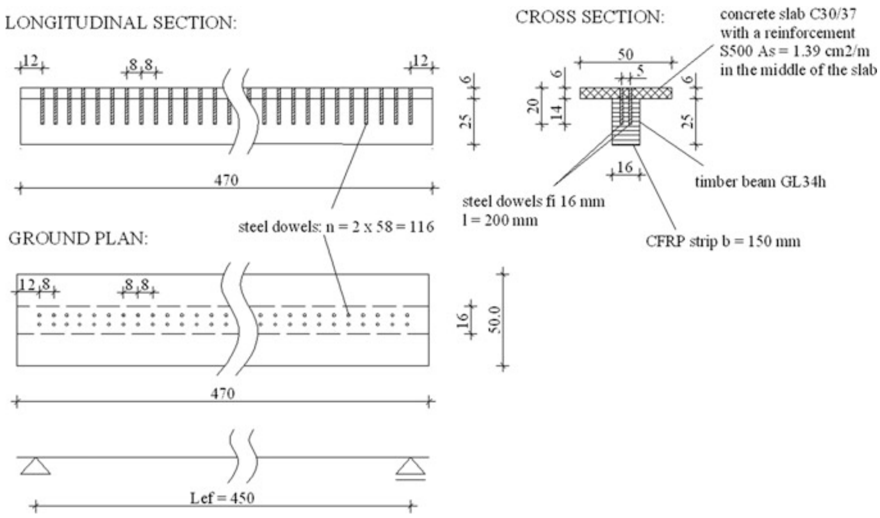


Fig. 4.12 Geometry of the test samples for the experimental study [70]

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

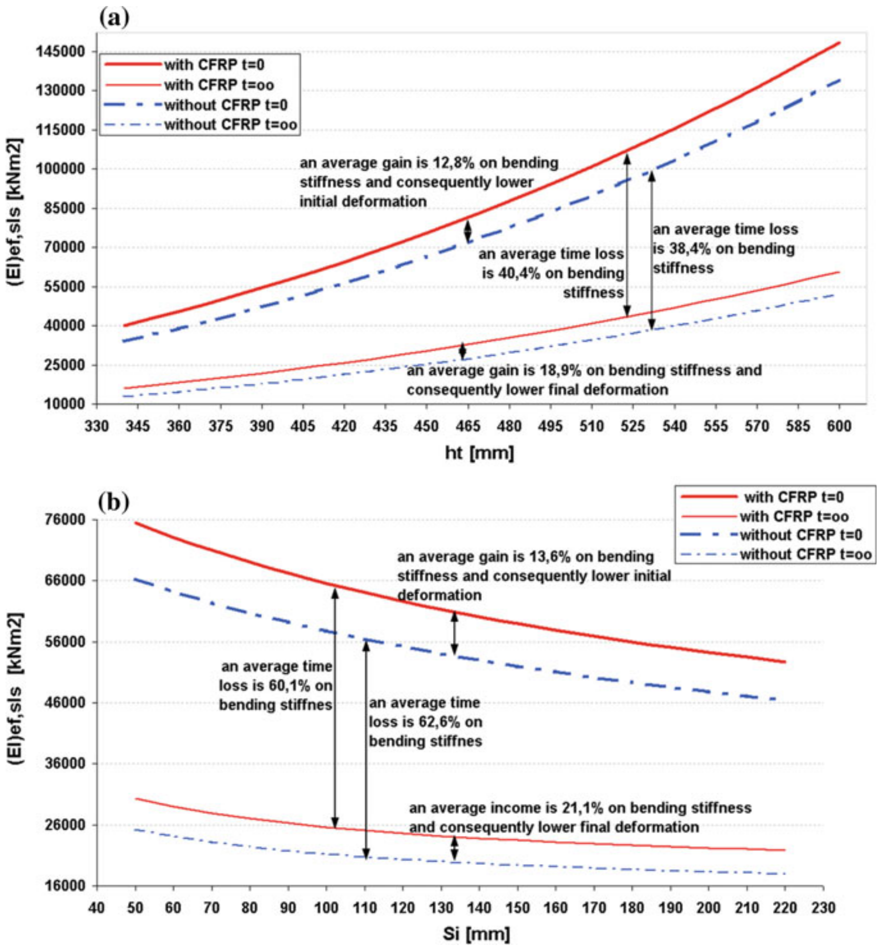


Fig. 4.14 **a** Influence of a variable depth of the timber beam on the bending stiffness and **b** influence of a variable dowel spacing on the bending stiffness [69]

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

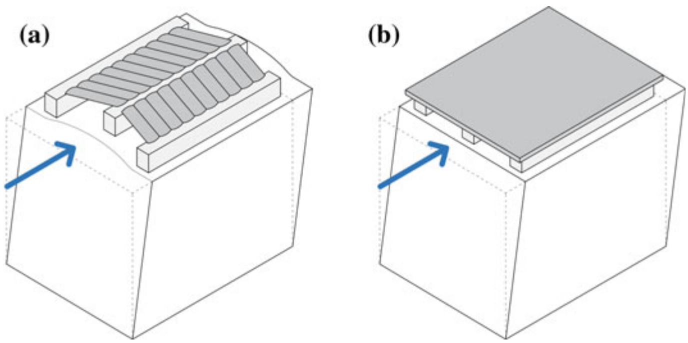


Fig. 4.15 Schematical presentation of a roof (**a**) and floor (**b**) in-plane behaviour as rigid horizontal diaphragms [87]

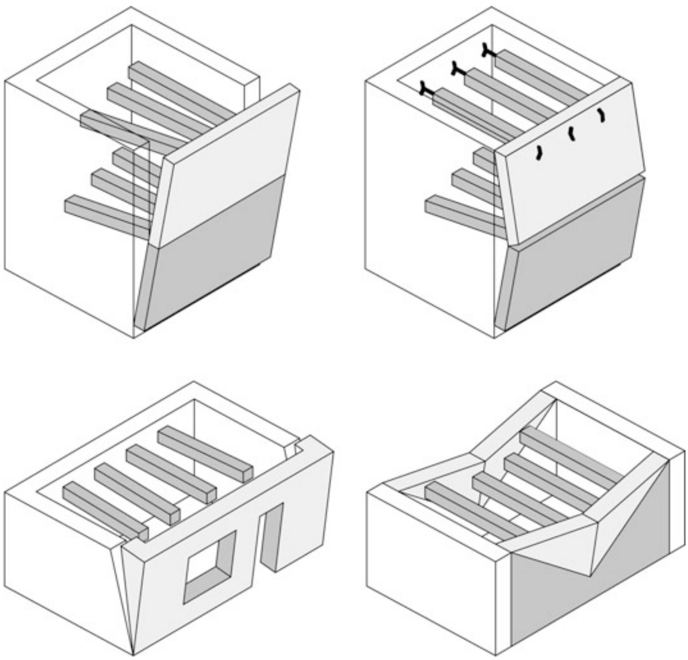


Fig. 4.16 Wall overturning modes due to inadequate stiffness of the floor [87]

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].

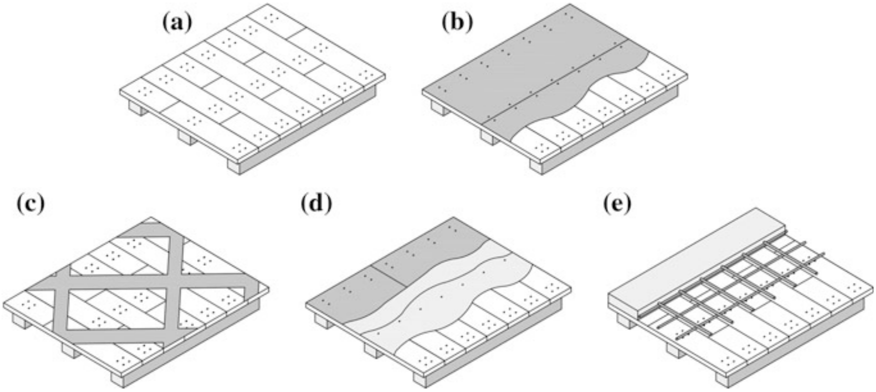


Fig. 4.17 Different timber floor in-plane shear strengthening techniques: **a** existing simple layer of wood planks on the timber beams; **b** second layer of wood planks crossly arranged to the existing one and fixed by means of steel studs; **c** diagonal bracing of the existing wood planks by means 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

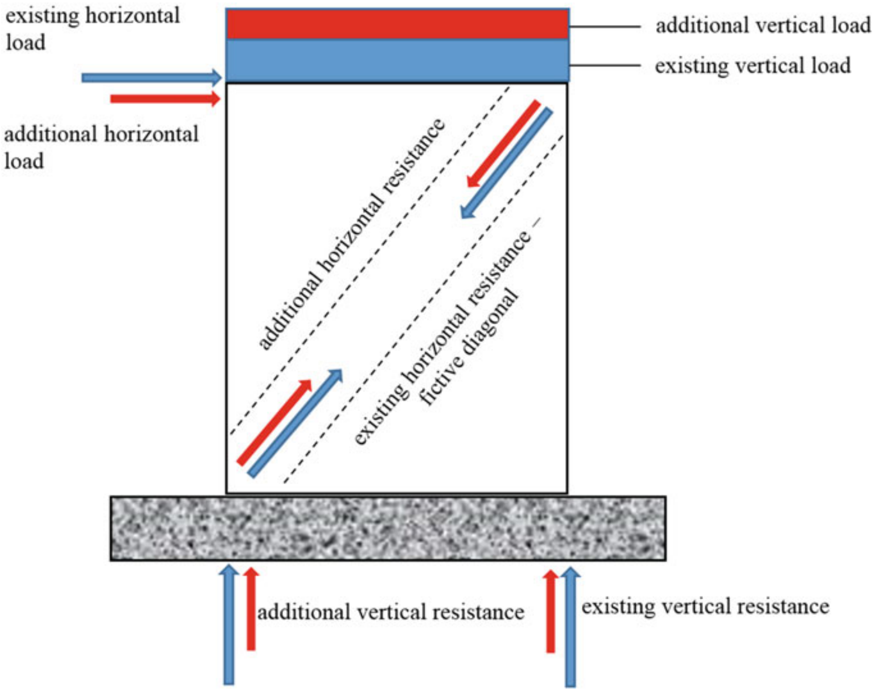


Fig. 4.18 Basic strengthening concept of wall elements

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:

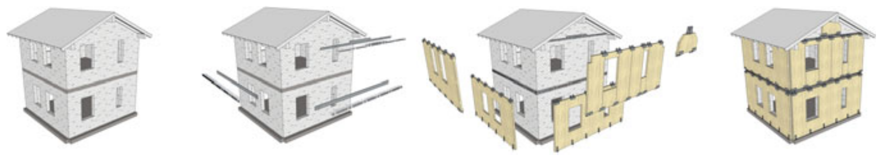


Fig. 4.19 Strengthening concept using CLT plates simply fixed to the existing wall elements [102]

- 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

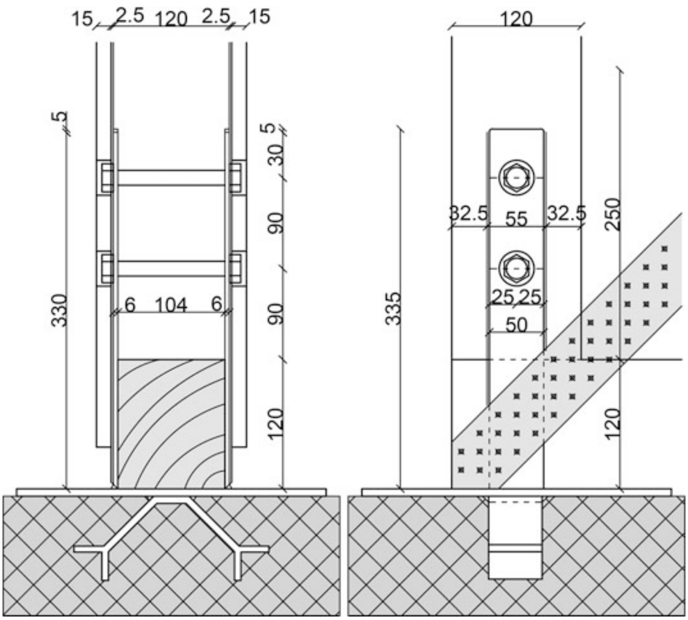
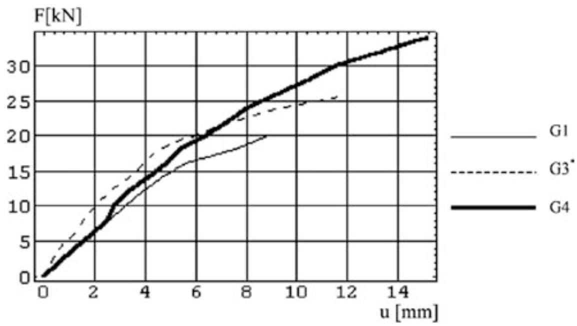


Fig. 4.20 Connection of the steel diagonal elements to the timber frame and to the bottom floor

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

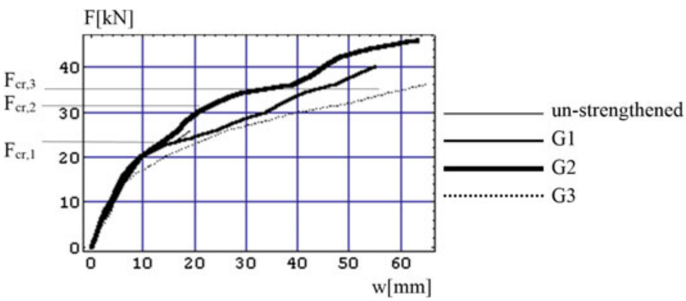


Fig. 4.22 Measured average horizontal displacements at the top of the wall elements for CFRP strengthened test samples [106]

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]

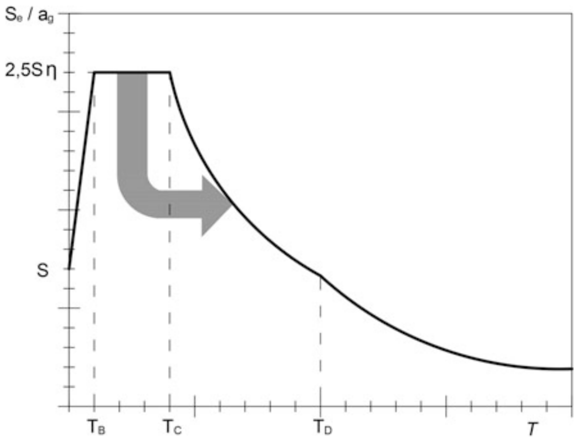


Fig. 4.25 Elastic response spectrum (S_e) decrease depending on the primary period (T) increase [109]

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:

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

– 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.

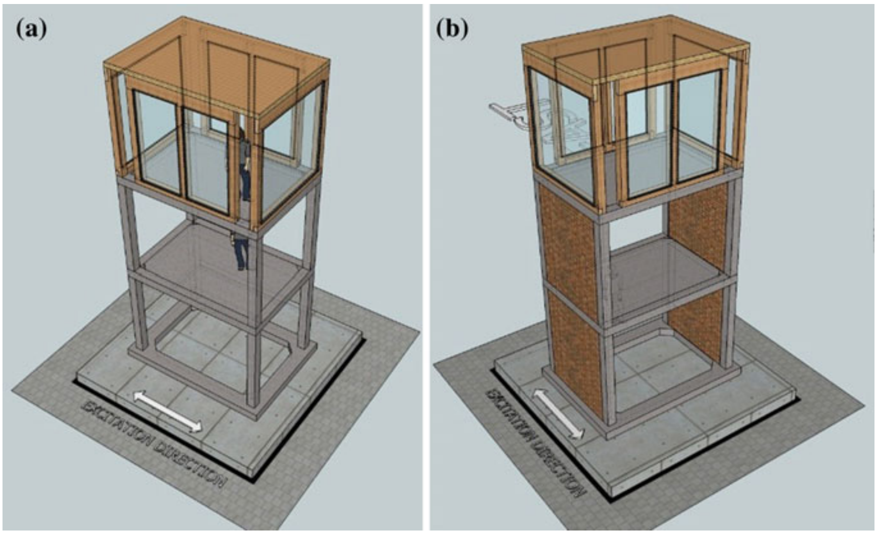


Fig. 4.26 Timber-glass module installed onto the concrete frame (**a**) or masonry (**b**) model building [112]

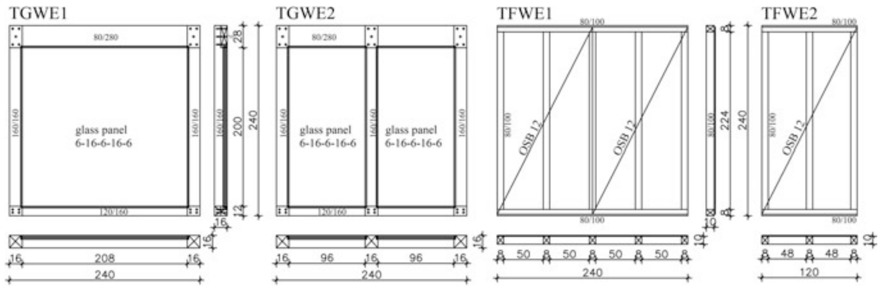


Fig. 4.27 Dimensions of timber-glass and light timber-framed wall elements [111]

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

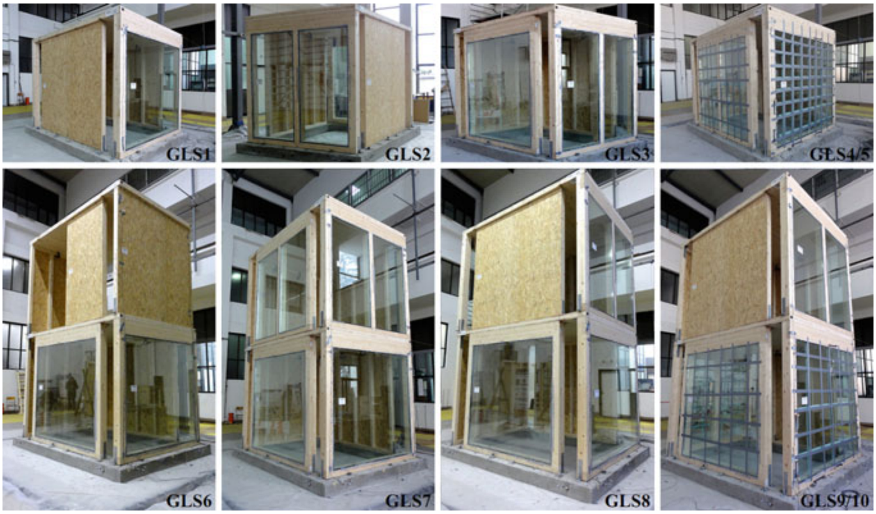


Fig. 4.28 Configuration of one-storey and two-storey test models [111]

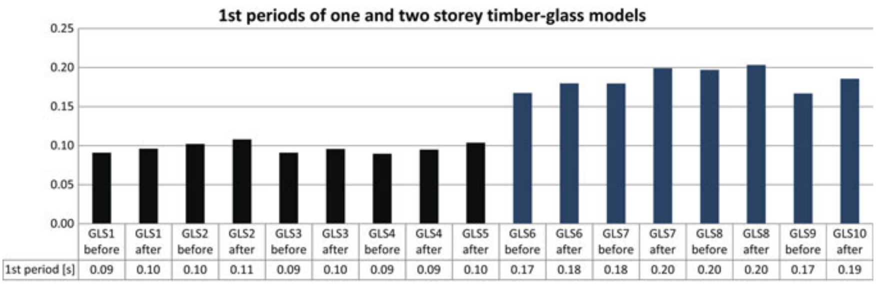


Fig. 4.29 Diagram of first periods for each model before and after the earthquake simulation [111]

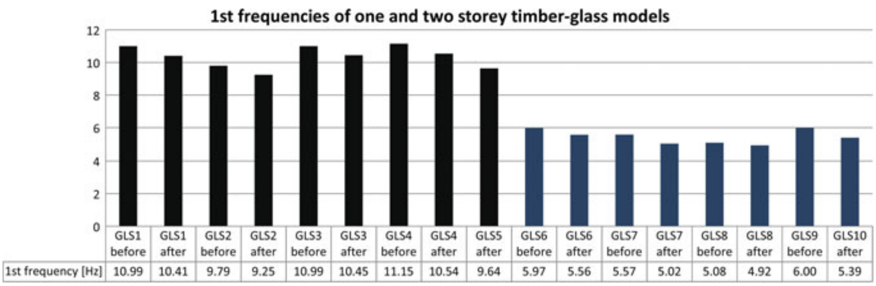


Fig. 4.30 Diagram of first frequencies for each model before and after the earthquake simulation [111]

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

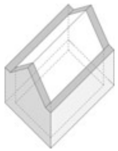
The influence of renovation measures is further assessed by combining different IRMs within partial renovation packages (hereinafter PRPs), based on findings relative to the energy efficiency of the IRMs. Finally, the last part of the current paper contains evaluation regarding the energy efficiency 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.

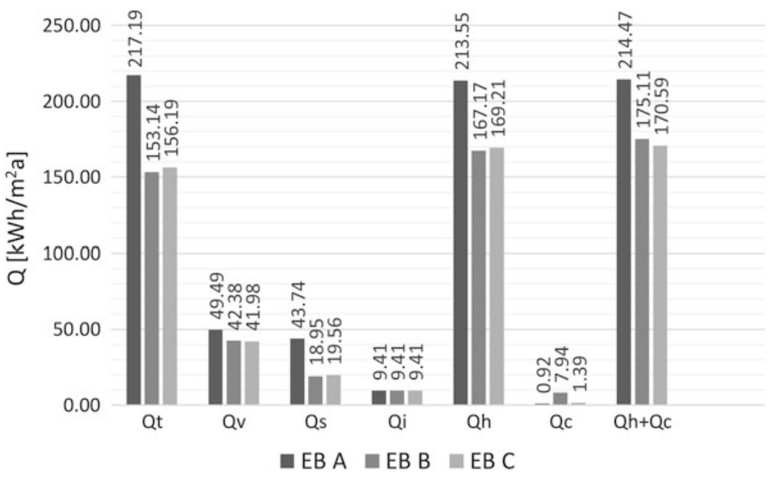


Fig. 4.34 EBs' heat flows and energy balance [114]

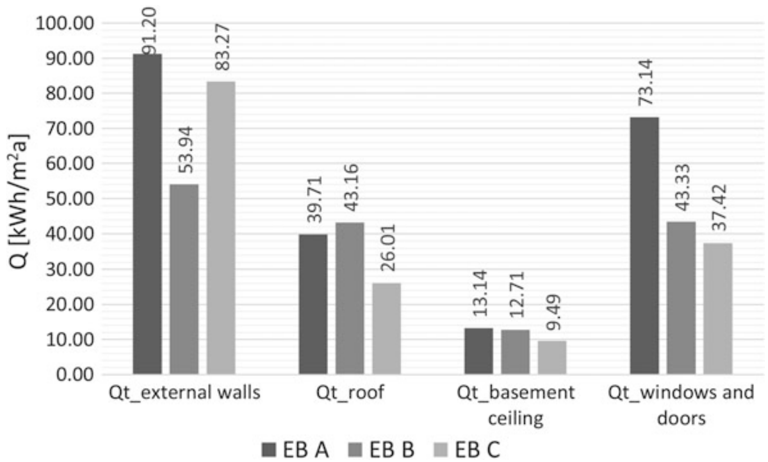


Fig. 4.35 Contribution of different thermal envelope elements of the EBs to the total transmission heat losses (Q_t)

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):

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

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)$_{SAVING}$).

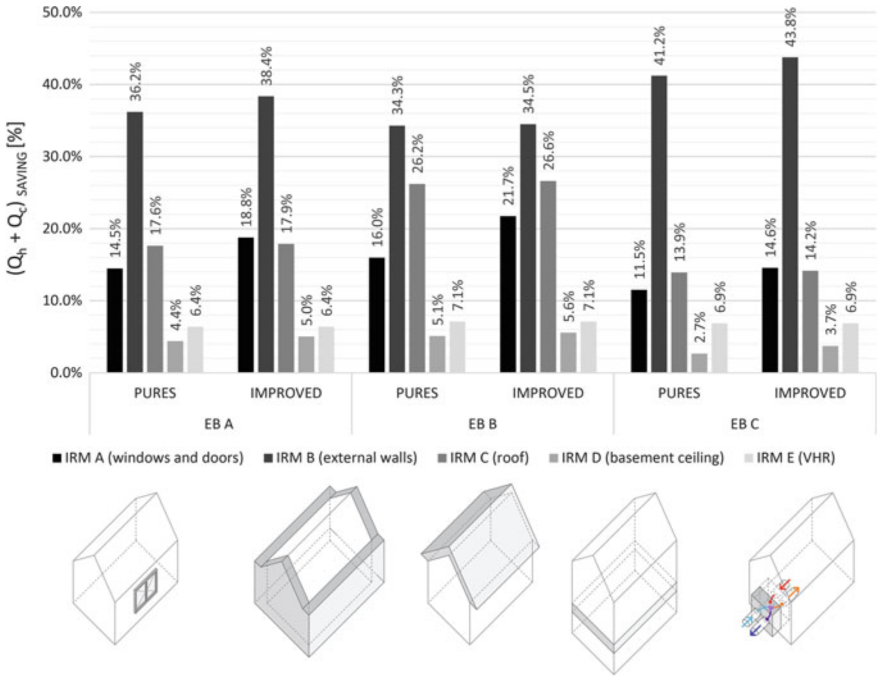


Fig. 4.36 Savings in the total energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$) resulting from the selected IRMs [114]

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.

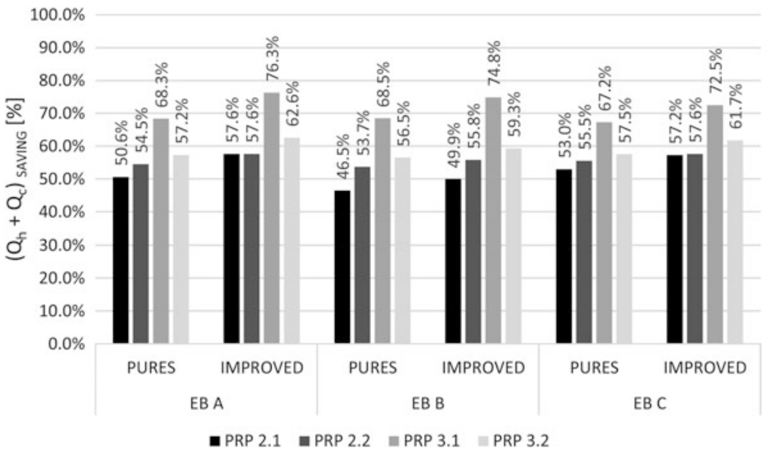


Fig. 4.37 Savings in the total energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$) resulting from the proposed partial renovation packages (PRP)

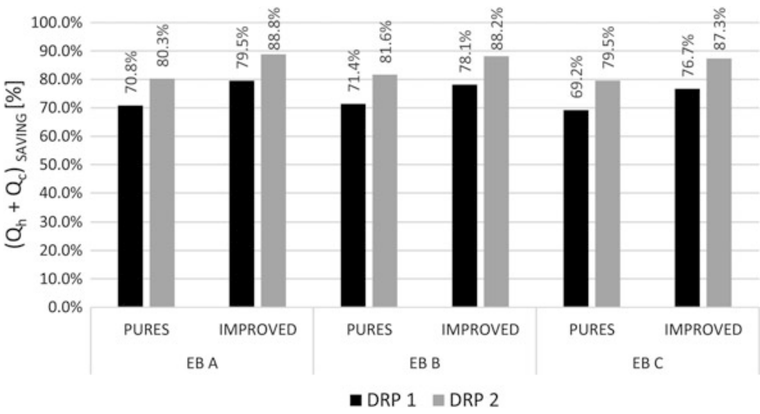


Fig. 4.38 Savings in the total energy need for heating and cooling ($(Q_h + Q_c)_{SAVING}$) resulting from the proposed deep renovation packages (DRPs) [114]

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.

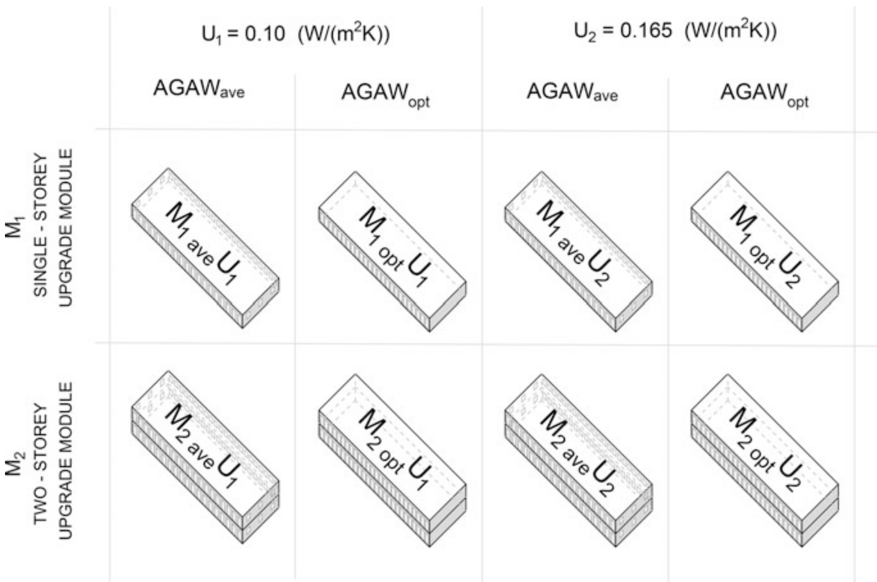


Fig. 4.39 Module types with regard to their main variable parameters

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^{2}K), with that of glass being U_{glass} = 0.50 W/(m^{2}K) 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.

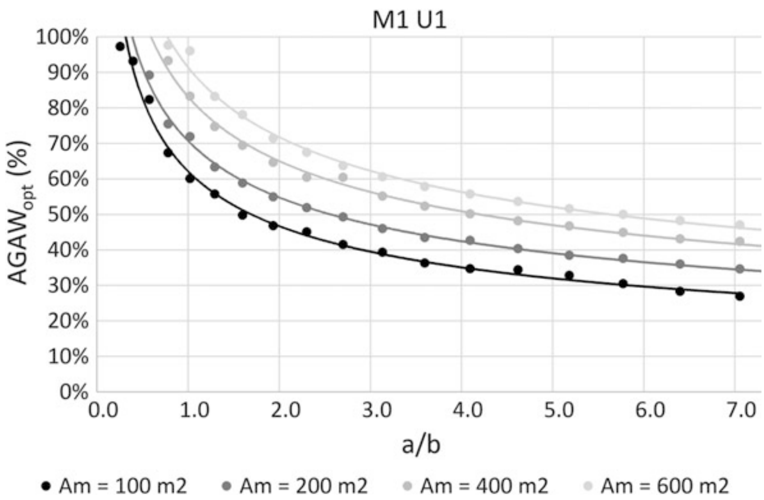


Fig. 4.40 Optimal glazing-to-wall area ratio ($AGAW_{opt}$) for the south-oriented façades of single-storey (M_1) upgrade modules with thermal transmittance U_1

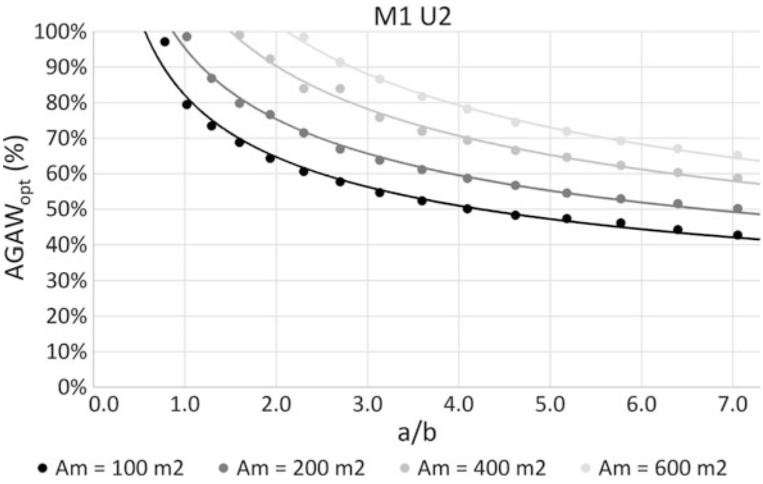


Fig. 4.41 Optimal glazing-to-wall area ratio ($AGAW_{opt}$) for the south-oriented façades of single-storey (M_1) upgrade modules with thermal transmittance U_2

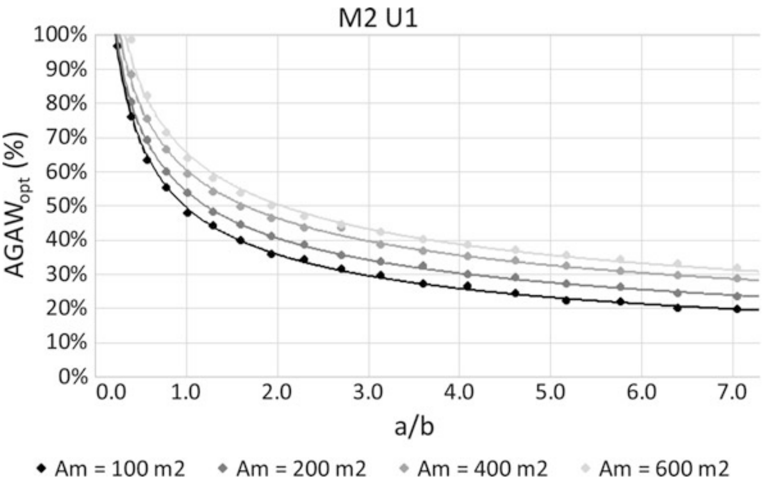


Fig. 4.42 Optimal glazing-to-wall area ratio ($AGAW_{opt}$) for the south-oriented façades of two-storey (M_2) upgrade modules with thermal transmittance U_1 [61]

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

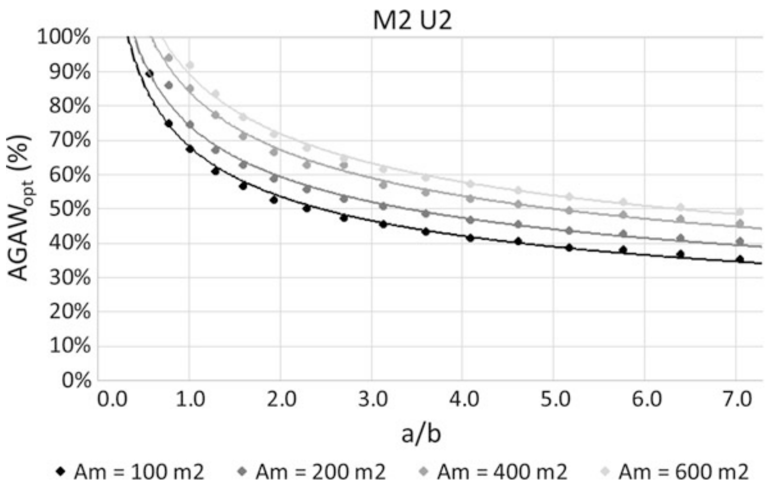


Fig. 4.43 Optimal glazing-to-wall area ratio ($AGAW_{opt}$) for the south-oriented façades of two-storey (M_2) upgrade modules with thermal transmittance U_2 [61]

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.

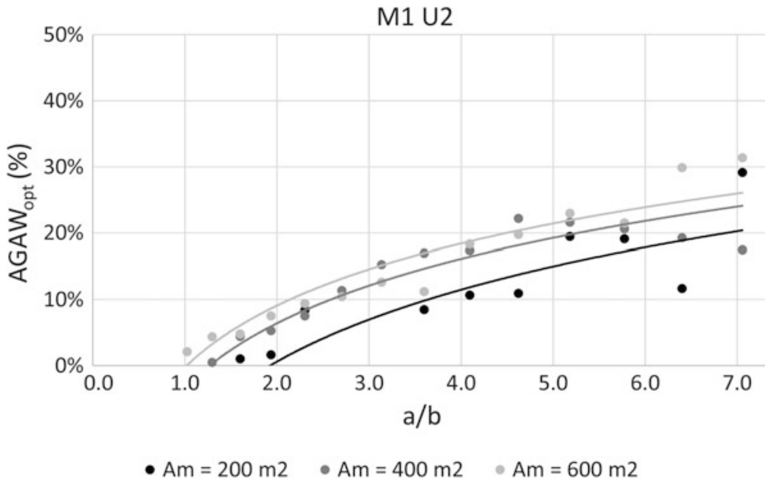


Fig. 4.44 Optimal glazing-to-wall area ratio ($AGAW_{opt}$) for the east- and west-oriented façades of single-storey (M_1) upgrade modules with thermal transmittance U_2

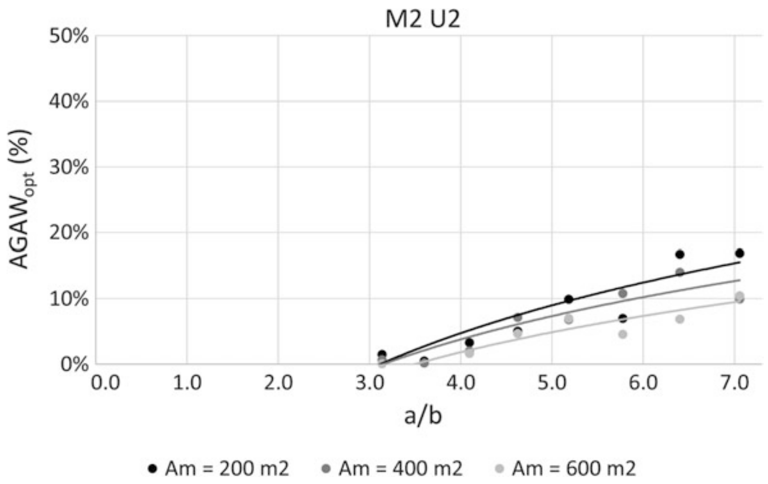


Fig. 4.45 Optimal glazing-to-wall area ratio ($AGAW_{opt}$) for the east- and west-oriented façades of two-storey (M_2) upgrade modules with thermal transmittance U_2

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

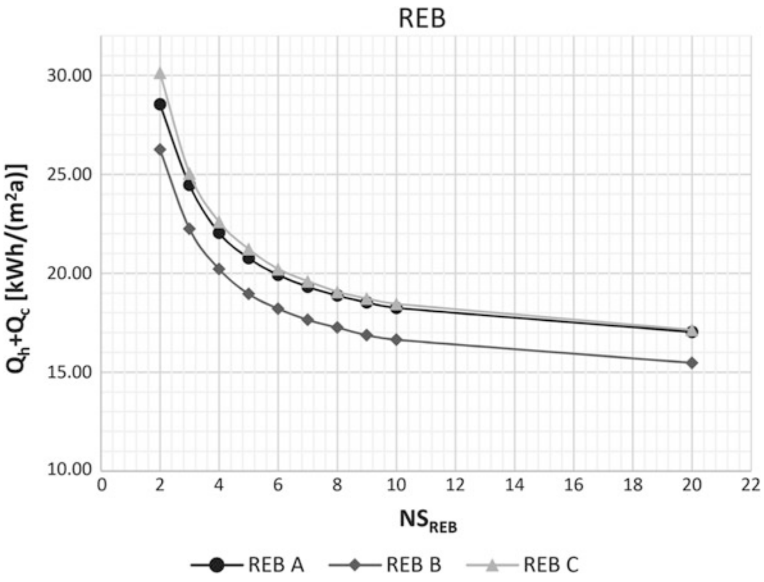


Fig. 4.46 Energy need for heating and cooling (Q_h + Q_c) for different NS_{REB} [60]

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

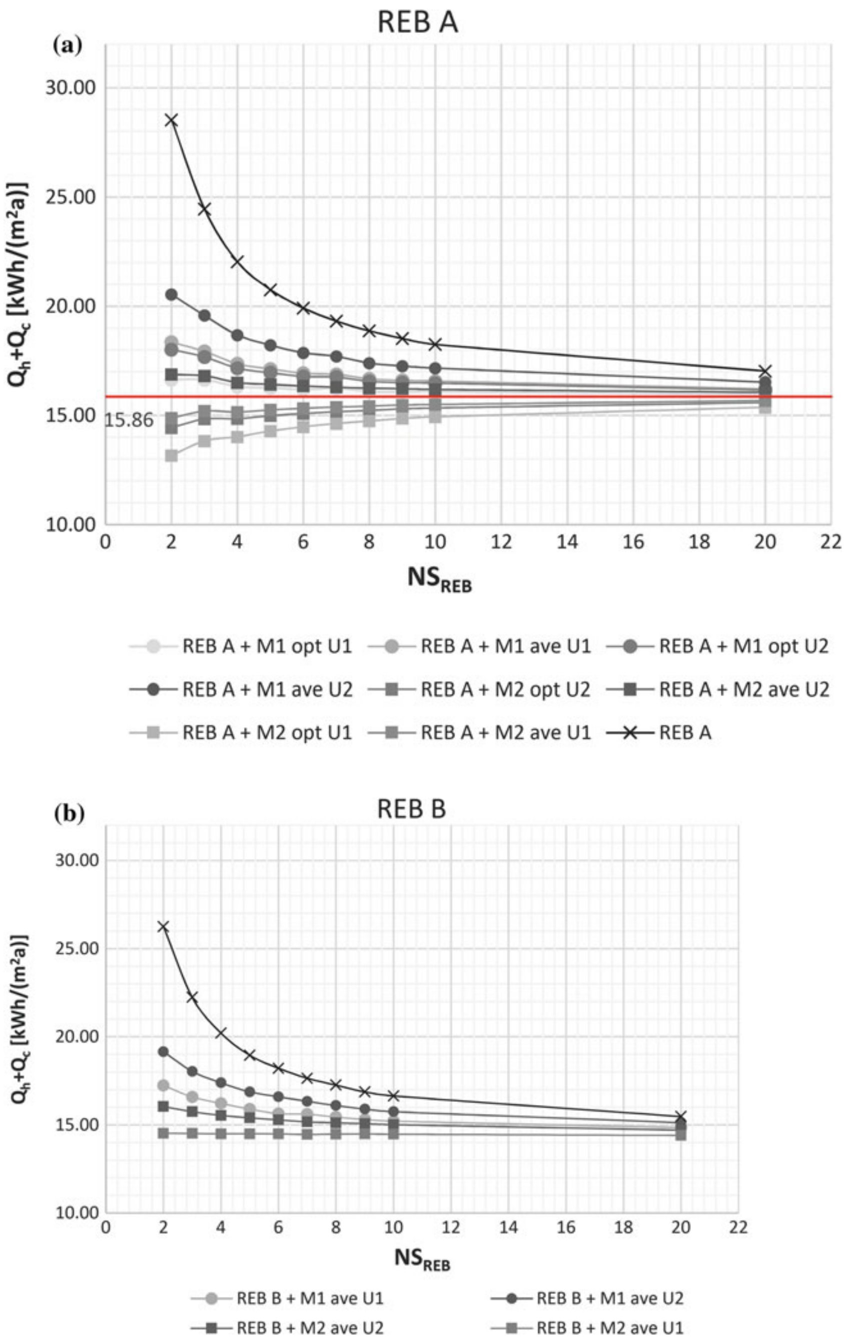


Fig. 4.47 Energy need for heating and cooling (Q_h + Q_c) for different heights of the REBs **a** REB A, **b** REB B and **c** REB C and the hybrid buildings (REBs + *M*) [60]

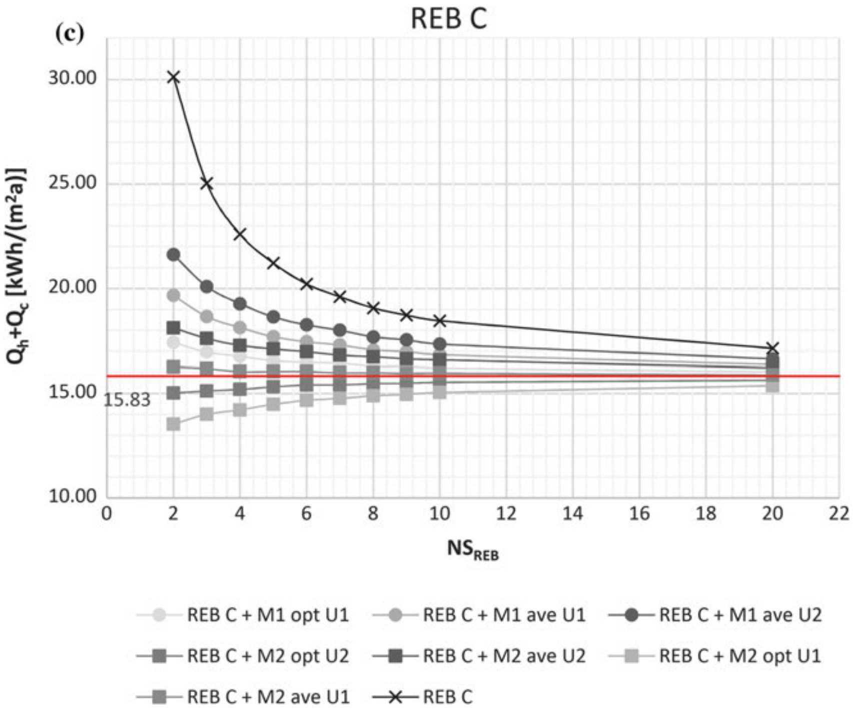


Fig. 4.47 (continued)

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 ($M_{2\ \mathrm{opt}}\ U_1$, $M_{2\ \mathrm{opt}}\ U_2$). 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 ($\mathrm{NS_{REB}}$) 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 ($(Q_\mathrm{h} + Q_\mathrm{c})_\mathrm{SAVING}$) 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 ($(Q_\mathrm{h} + Q_\mathrm{c})_\mathrm{SAVING}$) 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 ($(Q_\mathrm{h} + Q_\mathrm{c})_\mathrm{SAVING}$) are calculated according to the following Eq. (4.6):

$$(Q_\mathrm{h} + Q_\mathrm{c})_\mathrm{SAVING} = \frac{(Q_\mathrm{h} + Q_\mathrm{c})_\mathrm{REB} - (Q_\mathrm{h} + Q_\mathrm{c})_{\mathrm{REB}+M}}{(Q_\mathrm{h} + Q_\mathrm{c})_\mathrm{REB}} \times 100\,(\%) \tag{4.6}$$

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

The highest savings in the energy need for heating and cooling ($(Q_\mathrm{h} + Q_\mathrm{c})_\mathrm{SAVING}$) (Eq. 4.6) evident from Fig. 4.48 are achieved with the optimal module types of lower thermal transmittance ($M_{1\ \mathrm{opt}}\ U_1$ and $M_{2\ \mathrm{opt}}\ U_1$). On the contrary, the lowest savings result from applying the average module types with higher thermal transmittance values ($M_{1\ \mathrm{ave}}\ U_2$ and $M_{2\ \mathrm{ave}}\ U_2$). Lesser influence of modules with the average glazing size ($\mathrm{AGAW_{ave}}$) 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).

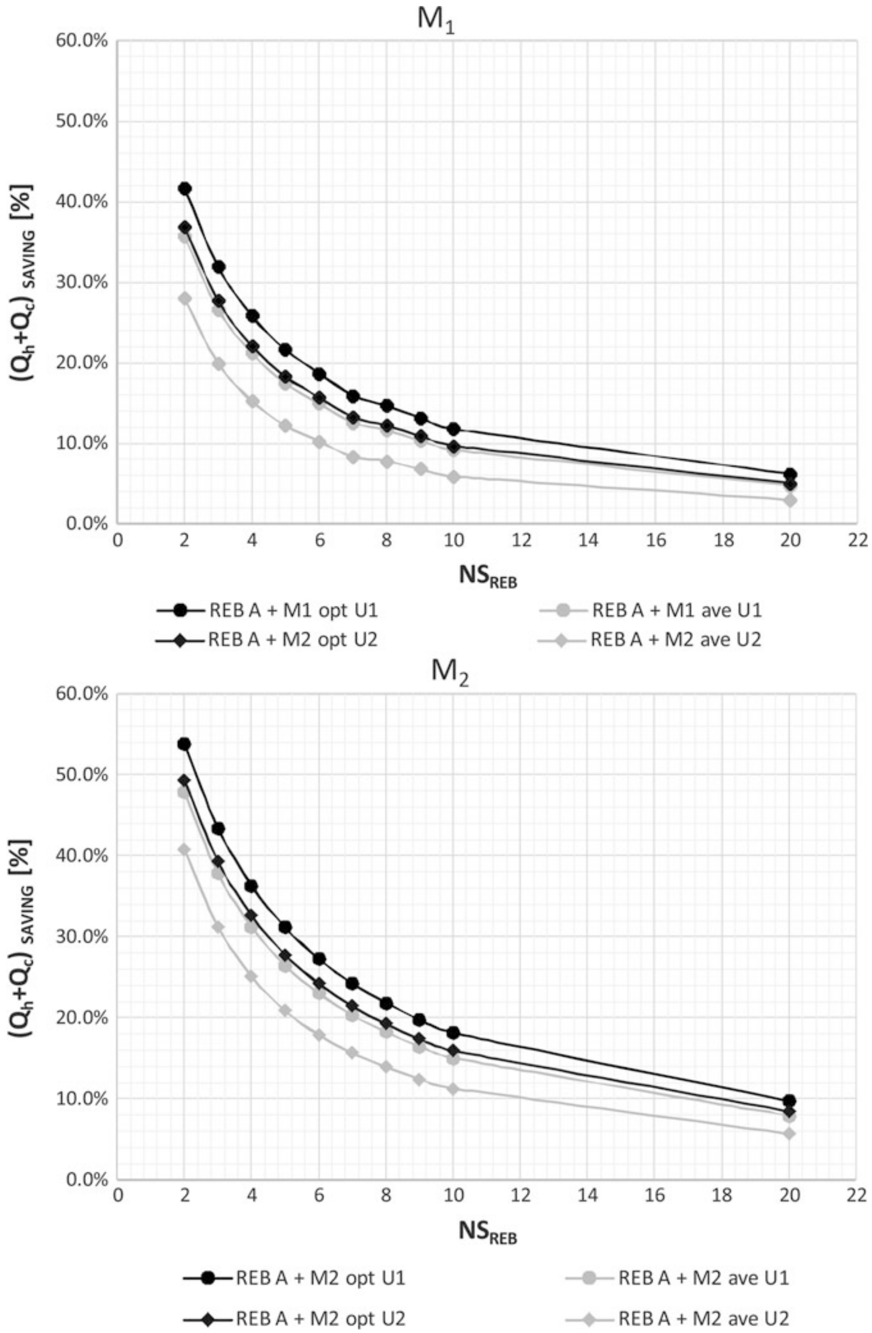


Fig. 4.48 Energy savings (%) for the extension of REB A with different types of single-storey (M_1—above) and two-storey (M_2—below) upgrade modules for different $NS_{REB\ A}$ [60]

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.

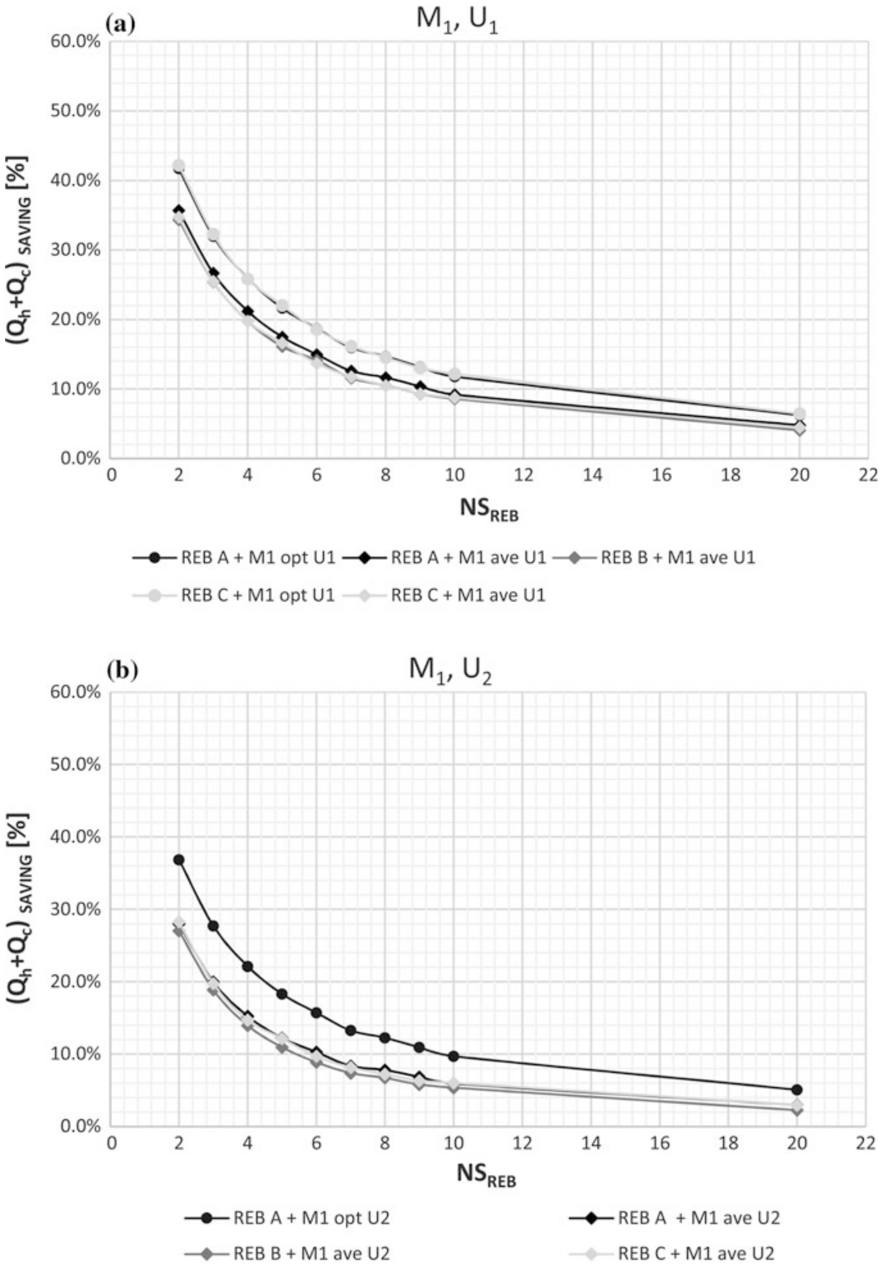


Fig. 4.49 Energy savings (%) resulting from the extension with different types of upgrade modules for different NS_{REB} [60]

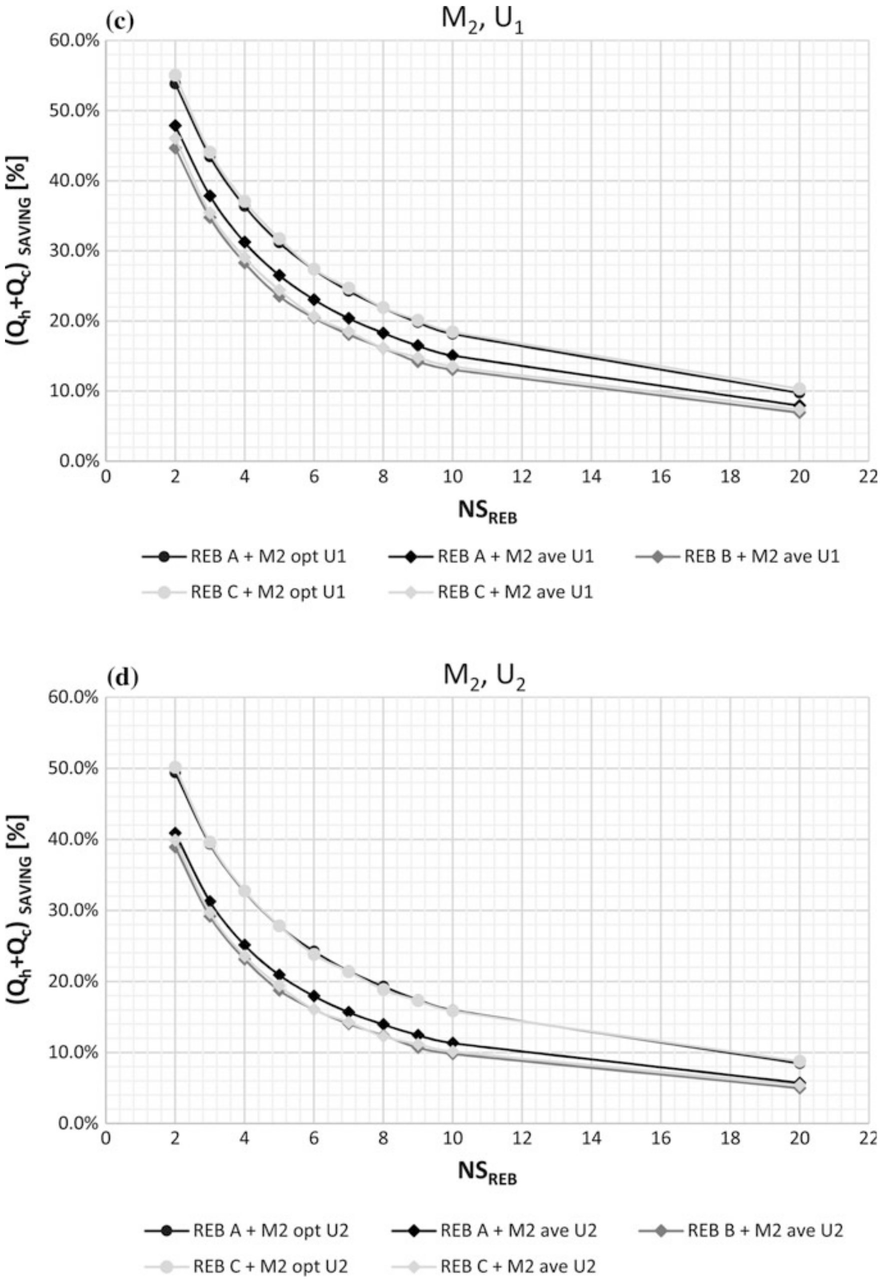


Fig. 4.49 (continued)

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

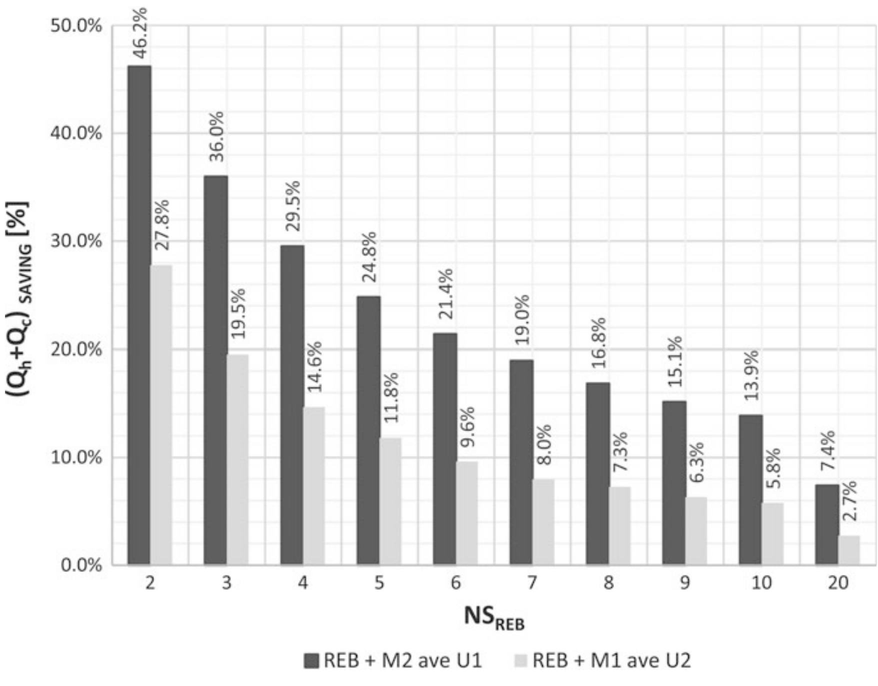


Fig. 4.50 Comparison of the average savings in the energy need for heating and cooling (%), averaging the results of REB A, B and C upgraded with the modules with the average glazing size ($AGAW_{ave}$) exerting the lowest and the highest influences at different NS_{REB} [60]

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)

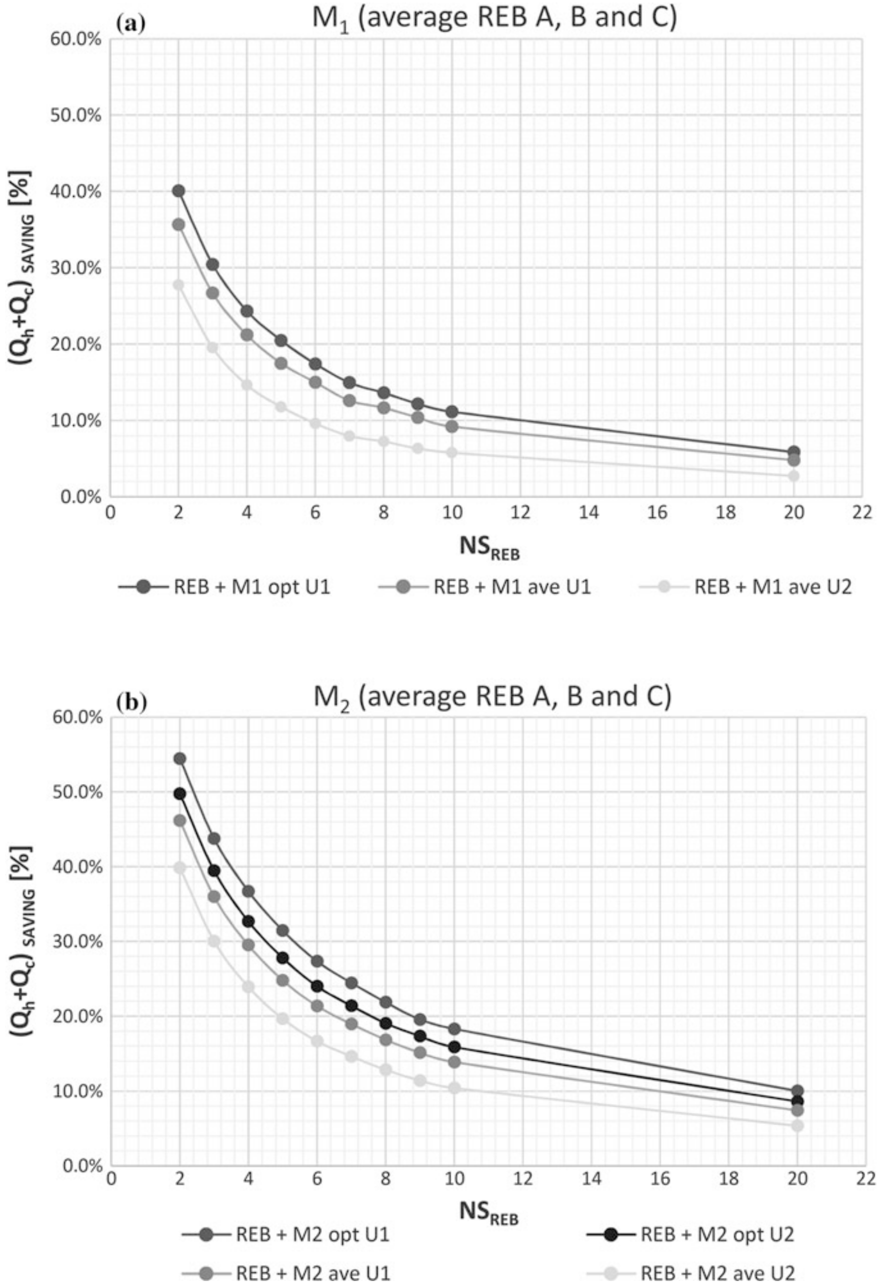


Fig. 4.51 Energy savings (%) for the extension with different types of single-storey (M_1) (**a**) and two-storey (M_2) (**b**) upgrade modules for different NS_{REB} (average values defined for hybrid buildings (REB A + *M*, REB B + *M* and REB C + *M*)) [60]

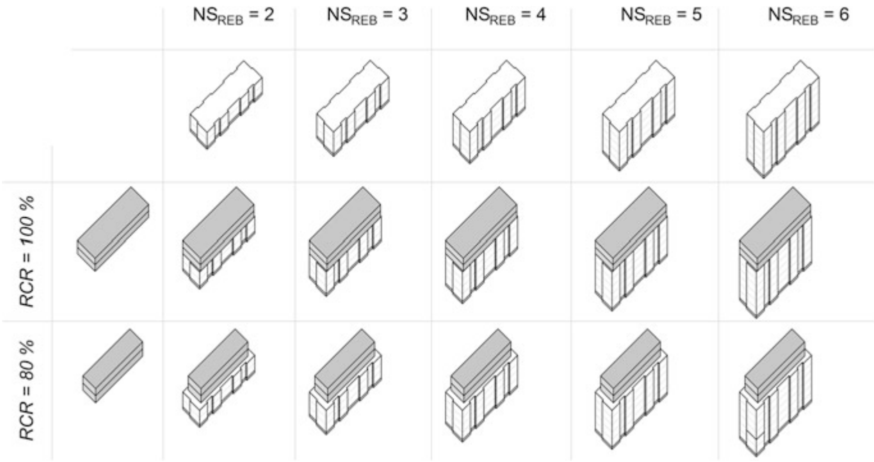


Fig. 4.52 Building extension variations in regard to different RCRs for different NS_{REB} and volume ratios [61]

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

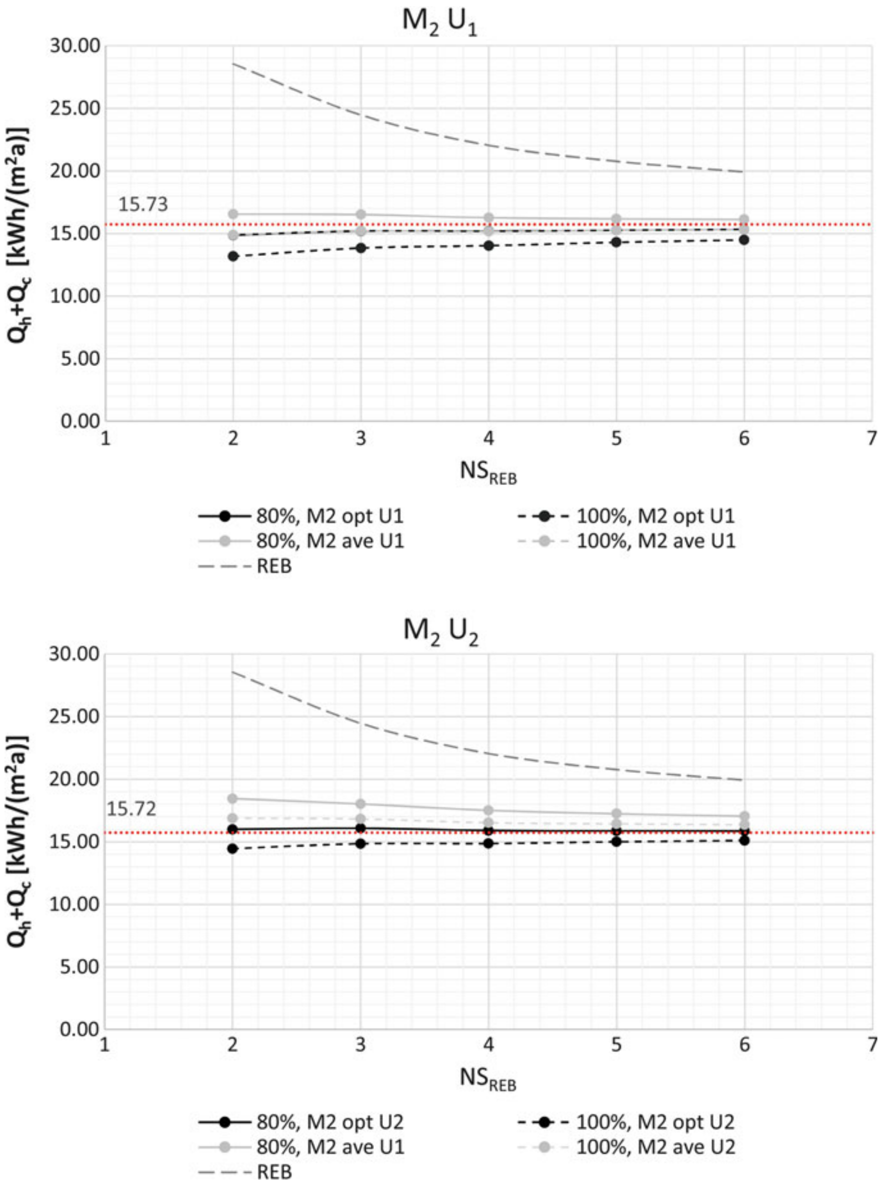


Fig. 4.53 Energy need for heating and cooling ($Q_h + Q_c$) resulting from the extension with different types of two-storey (M_2) upgrade modules (U_1, U_2) [61]

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.

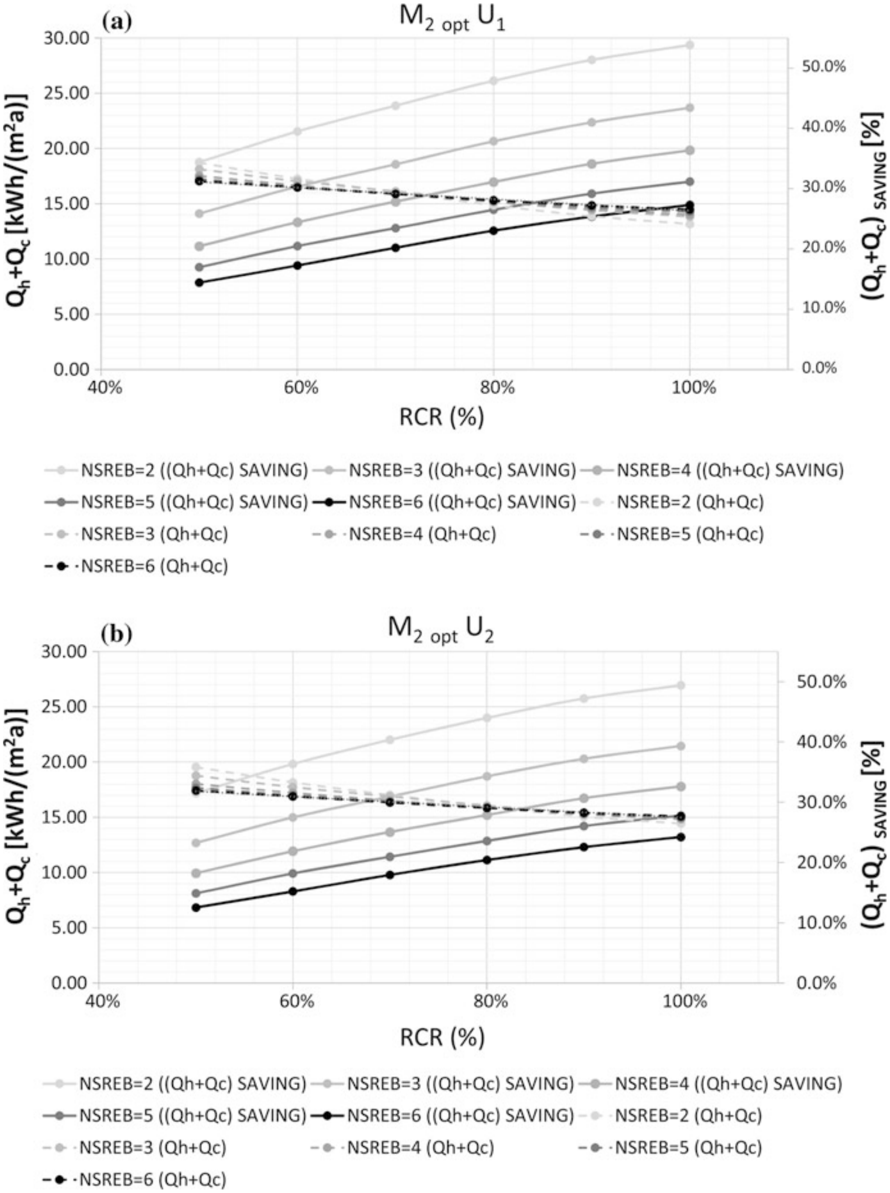
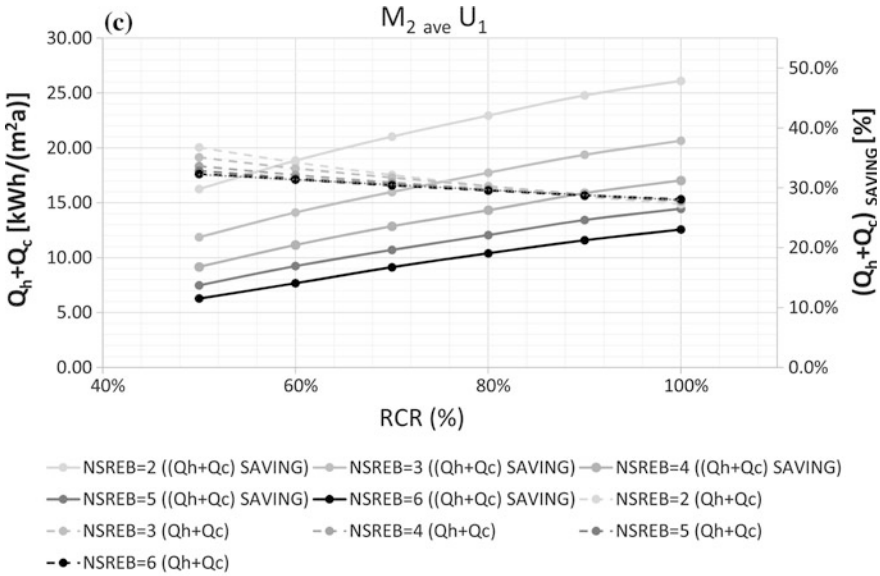


Fig. 4.54 Energy need for heating and cooling ($Q_h + Q_c$) and the total energy savings (($Q_h + Q_c$)$_{SAVING}$) resulting from the extension of different NS_{REB} with different RCR and two-storey (M_2) module types



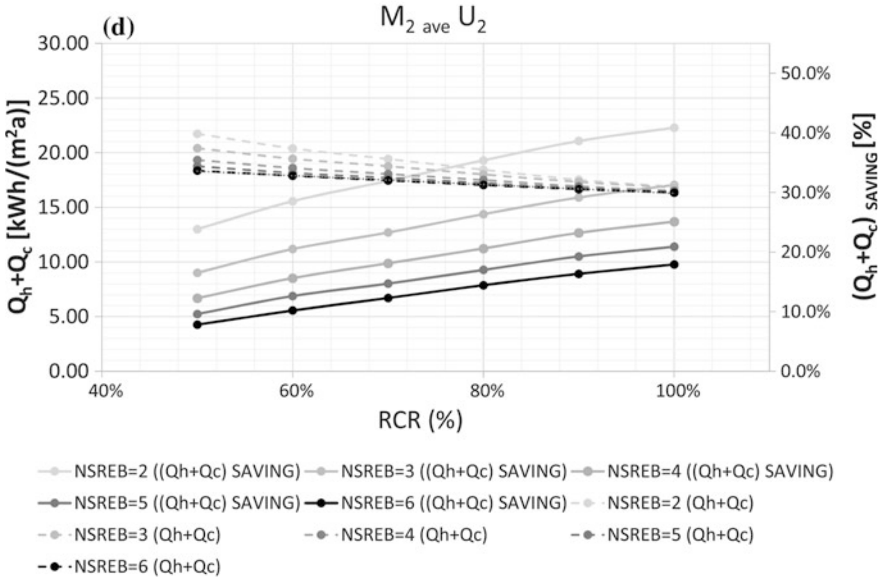


Fig. 4.54 (continued)

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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