Energy 162 (2018) 1125–1138

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Design parameters of the timber-glass upgrade module and the existing building: Impact on the energy-efficient refurbishment process

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A R T I C L E I N F O

Article history:
Received 28 October 2017
Received in revised form
26 July 2018
Accepted 13 August 2018
Available online 15 August 2018

Keywords:
energy efficiency
Building refurbishment
Attic extension
Building design parameters
Timber-glass upgrade module

A B S T R A C T

Refurbishment of old existing buildings means an enormous potential for improving their energy efficiency. Besides the established renovation methods encompassing mostly measures applied to the thermal envelope, the extension of existing buildings with lightweight structural upgrades has become popular especially in densely populated urban areas. While being beneficial to the reduction of the transmission losses through the roof of the existing building, the above solution also results in acquisition of new floor surface. Despite the increasing number of such renovations in practice, this topic is rather poorly supported by scientific research, which results in a lack of general design guidelines.

The paper discusses the impact the timber-glass upgrade module has on energy-efficient refurbishment of multi-family buildings. The main variable design parameters of the numerical study are the height of the upgrade module and the existing building, relevant to the number of storeys, alongside with the thermal transmittance of the module envelope elements, its glazing size and orientation. The key of the study is to explore to which extent the application of the timber-glass upgrade module influences the energy need of the hybrid building regarding the aforementioned design parameters with the aim of establishing design guidelines for refurbishment with attic extension.

1. Introduction

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 is more than 50 years old. Almost 40% of residential housing stock was built prior to 1960 with a share of 50% dating from the period before 1970 [1,2], when building regulations mandating thermal properties of building envelopes were rather loose and inadequate. The listed data referring to the age of buildings is 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 [3]. Many researches and overviews into renewable and sustainable energy, for example in Refs. [4,5], have been carried out. Several studies [6,7] address energy saving potential based on energy-efficient refurbishment. A strong argument supporting the need for complex building refurbishment 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 [8].

An abundance of literature dealing with building retrofit is currently available. Among the numerous literature reviews considering existing buildings refurbishment [9], some highlight national or European existing building stock refurbishments [10,11] along with the selected segments of the existing building stock, such as historical buildings [12,13], while others focus on the refurbishment of individual buildings or groups of buildings based on the their use, e. g. public [14] or residential buildings [9,15]. Additionally, many research studies examine the influence of various renovation measures [16,17] and strategies [18,19] on the energy saving and economic potential [20,21], on environmental implications [22,23] and the indoor environmental quality [24,25]. The focal point of many research articles is set on the energy efficiency and environmental impacts of retrofit strategies, however, the findings in Ref. [26] suggest additional consideration of the impact building refurbishment exerts on the occupants' health and

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https://doi.org/10.1016/j.energy.2018.08.108
0360-5442/

Nomenclature

a	South-north oriented façade [m]
A	Total net floor area of the existing multi-family building [m^2]
a/b	Façades length ratio
$AGAW$	Glazing-to-wall area ratio [%]
$AGAW_{ave}$	Average glazing-to-wall area ratio [%]
$AGAW_{opt}$	Optimal glazing-to-wall area ratio [%]
$AGAW_{opt,east,west}$	Optimal glazing-to-wall area ratio for east- and west-oriented facades [%]
$AGAW_{opt,south}$	Optimal glazing-to-wall area ratio for south oriented facade [%]
A_{storey}	Net floor area of a single-storey [m^2]
b	East-west oriented façade [m]
EB	Existing multi-family building
F_s	Factor of shape [1/m]
h	Height of the existing multi-family building or structural upgrade module [m]
M_1	Single-storey upgrade module
$M_{1\ ave}\ U_1$	Upgrade module design parameters for the case of a single-storey upgrade module with an average glazing size and lower thermal transmittance (U_1)
M_2	Two-storey upgrade module
n_{50}	Air change rate at press. test [1/h]
NS_{EB}	Number of storeys of the existing multi-family building
NS_{REB}	Number of storeys of the refurbished multi-family building
Q_c	Energy need for cooling [kWh/(m^{2}a)]
$(Q_h + Q_c)_{saving}$	Savings in the energy need for heating and cooling [%]
$(Q_h + Q_c)_{saving\ REB+M}$	Savings in the energy need for heating and cooling of hybrid building [%]
$Q_h + Q_c$	Energy need for heating and cooling [kWh/(m^{2}a)]
Q_h	Energy need for heating [kWh/(m^{2}a)]
Q_i	Internal heat gains [kWh/(m^{2}a)]
Q_s	Solar heat gains [kWh/(m^{2}a)]
Q_t	Heat transfer by transmission kWh/(m^{2}a)]
Q_v	Heat transfer by ventilation [kWh/(m^{2}a)]
$REB + M$	Hybrid building consisting of the refurbished existing multi-family building extended with the upgrade module
$REB\ A + M_{1\ ave}\ U_1$	Extension of the refurbished existing building with a single-storey upgrade module with an average glazing size and lower thermal transmittance
REB	Refurbished existing building
U	Thermal transmittance [W/(m^{2}K)]
z	Shading factor [%]
η	Efficiency of the heat recovery ventilation system [%]

wellbeing. Fortunately, energy saving strategies are in alignment with principal measures applied towards satisfying indoor comfort requirements [18]. The impacts of the energy retrofit on the indoor environmental quality in several multi-family buildings were measured and compared in Ref. [25]. The findings underline the importance of assessing thermal conditions and ventilation for the optimal indoor environmental quality and energy savings. As emphasized in several research studies [27] and review articles [9,11], the effects of building refurbishment on the energy, cost efficiency, environmental impacts and indoor environment quality are not solely dependent on the selected renovation measures, but vary significantly according to the location and the climate conditions.

Studies looking for systematic procedures to be applied to energy-efficient refurbishments of buildings are less frequent. However, they exhibit the importance of complexity in the process of energy-efficient renovation [28–30]. Some existing studies [31] emphasize the importance of focusing on multiple buildings and multi-year retrofit rather than on single buildings of a certain time period. A considerable effort has lately also been made to provide energy retrofit analysis toolkits [32] and early stage decision support tools [33,34].

In addition to the reduction in the energy need, there is also a high requirement for new usable surfaces in urban centres, especially in large central, northern and western European cities [8]. Therefore, a further level of energy performance renovation can be seen in building extensions, as one of the possible means of increasing urban density. In this context attic extensions offer a great potential by creating additional housing space while taking advantage of the existing infrastructure [35] and simultaneously providing the possibility of covering the costs of building retrofit [36]. In addition to the ever more emerging phenomenon of attic extensions in common practice, the attempts to explore such solutions are also recorded within design competitions [37] and research studies [28–30,38]. According to the research in Ref. [37], 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 refurbishment with timber upgrade modules. However, there is a lack of design guidelines for energy-efficient upgrades [32], which is mostly due to the fact that they have to be adjusted to individual buildings and tend to require high planning efforts [35,38]. Attempts to integrate timber energy-efficient upgrades in the existing building refurbishment have already been made in a few studies [28–30,38].

The research [30] conducted on two case studies in the Slovenian town of Velenje indicates a positive impact of different upgrade modules on the total energy consumption of the refurbished building. The optimal lightweight timber-glass modules from the viewpoint of energy efficiency have been previously developed [39] in regard to possible geometries of existing buildings. Variations of the module façade length ratio (a/b) and the three selected net floor areas ($A_1 = 200$, $A_2 = 400$, $A_3 = 600$ m^2) for single–storey modules with south-oriented glazing were investigated [39]. For the purpose of general use, higher models and the possibility of glazing distribution to other cardinal orientations should also be researched. 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, due to its low weight, its cost and energy efficiency.

The above mentioned research works present a basis for further investigation. With a view to developing general guidelines for energy retrofitting of buildings by using lightweight structural upgrades this paper discusses the effectiveness of such renovation measures according to the relation between the height of the existing building and that of the upgrade module. Aspects like indoor environmental quality, accessibility for persons with disabilities, structural and seismic stability, fire safety, economic and environmental impacts, etc., are vital for complex building retrofit,