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Renovation of residential buildings: strengths and weaknesses of a research approach based on prefabrication and real case-studies

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Abstract

Energy consumption in residential buildings accounts for more than 25% of the entire energy consumption in the EU, and this figure is likely to increase. A large proportion of this energy is used in existing buildings because the majority of the EU residential building stock was built before the introduction of the legislation that set limits related to the energy consumption in buildings. Thus, in Europe, a significant reduction in the energy consumption in the residential sector can be achieved only by addressing also the existing buildings, and not only the new constructions.

In an existing building, the range of possible solutions that can be implemented to improve its energy performances are limited due to the existing geometrical features and the need for minimizing the impact on the current occupants of the building. Moreover, unless simultaneously evaluated, these two aspects are often likely to have opposite optimal solutions.

For these reasons, the aim of this research is to investigate the potential of renovation solutions in which prefabricated timber-based multifunctional façade elements are used to enhance the energy performances of existing residential buildings without jeopardizing occupants' comfort. In this research, the solutions developed based on on-site analyses and computer simulations are implemented directly on real occupied buildings in different European locations.

This paper presents the initial results and considerations on the challenges encountered while conducting research on real occupied buildings. This includes the activities required to engage with and inform the owners and the occupants as early adopters, the need for minimizing their discomfort during the construction phase and for balancing between innovation and robustness of the solutions implemented, and the key importance of developing optimal cost-benefit solutions.

1 Introduction

Energy consumption in residential buildings accounts for more than 25% of the entire energy consumption in the EU [1], and this figure is likely to increase. A large proportion of this energy is used in existing buildings because the majority of the EU residential building stock was built before the introduction of the legislation that set limits related to the energy consumption in buildings.

In southern Europe, 37% of the housing stock was built before 1960, 49% in the period 1961-1990, and only 14% after 1990 [2]. In northern and western Europe, the figures of the three periods are 42%, 39%, and 19%, respectively [2]. In central and eastern Europe, these values are 35%, 48%, and 17% respectively [2]. This means that in all cases over 80% of the residential buildings were built before 1991.

Thus, in Europe, a significant reduction in the energy consumption in the residential sector can be achieved only by addressing also the existing buildings, and not only the new constructions. Nevertheless, the current renovation rate is 1.2% per year. One of the key barriers that limits the uptake of the renovation is the lack of affordable and integrated packages that could be easily installed.

In an existing building, the range of possible solutions that can be implemented to improve its energy performances are limited due to the existing geometrical features and operating constraints, and the need for minimizing the impact on the current occupants of the building and to develop cost-effective solutions [3]. Moreover, unless simultaneously evaluated, aspects such as existing geometrical features and occupants' needs are often likely to have different optimal solutions.

For these reasons, the aim of the research presented in this paper is to investigate the potential of renovation solutions in which prefabricated timber-based multifunctional façade elements are used to enhance the energy performances of existing residential buildings without jeopardizing occupants' comfort.

The structure of the paper is as follows. Section 2 describes the framework in which these renovation solutions have been developed, and the general approach to the renovation of the building envelopes used in this research. Section 3 focuses on the multifunctional façade technology development at component and system level. Section 4 is about the analysis of the likely performances of the newly developed façade systems at building level and their application on real existing buildings. Lastly, section 5 is the conclusions.

2 Approach to the renovation of the building envelopes

This research has developed within the framework of the H2020 4RinEU project, whose aim is to define robust, cost-effective, and tailorable deep renovation technology packages supported by widely applicable methodologies and reliable business models. The objectives of 4RinEU includes minimising the failures in design and implementation, managing the different stages of the deep renovation process, from the preliminary audit up to the end-of-life, and providing information on energy use and savings, occupants' thermal comfort, users' impact, and investment performances.

One of the key purposes of the 4RinEU deep renovation strategy is to achieve a 60% to 70% reduction in net primary energy consumption of the buildings compared to pre-renovation energy use, while reducing the duration of the renovation by 50% and the life cycle cost of the interventions by 20%.

Hence, prefabricated multifunctional façade elements are used to improve the thermal performances of the building envelope and therefore to meet this target. In addition, these newly developed façade elements integrate components such as decentralised ventilation devices that enable to improve the indoor environmental quality while avoiding the need for major additional works (e.g. creating a centralised ventilation system with central units and distribution ducts) and therefore inconvenience to the occupants.

However, the integration of elements such as decentralised ventilation devices and other active components (e.g. solar thermal panels, photovoltaic panels) may significantly alter the thermal performances of the passive prefabricated wooden element. Moreover, there might be further issues due to the integration of elements with different functions and requirements, and these issues must be addresses to achieve robust renovation solutions.

For these reasons, the development of the renovation technology packages can be seen as a two-step process. Firstly, the new façade systems are conceived and tested by means of computer simulations and physical modelling. After this, the performance of these façade systems are tested ad building level by means of dynamic thermal models and by implementing them into three real demo-case buildings located in Spain, the Netherlands, and Norway, respectively.

3 Multifunctional façade technology development

In this study, prototypes are used to investigate the integration of different functions, and therefore devices, into passive timber prefabricated façade elements, and to collect data to validate computer models. These models are then used to explore a wider range of configurations, and therefore to extend the analysis. The following two sections provide insights into these two activities.

3.1 Physical modelling: prototypes

In this project, two prototypes are developed and analysed. Both prototypes integrate the same components, and therefore functions, and have the same dimensions (2.72m x 2.76m), but their passive timber-based structures vary, and therefore their layers are different. In the former (Figure 1), the prefabricated module structure consists of a traditional timber-based element system with a wooden frame and blown-in cellulose insulation. In the latter (Figure 2), a more innovative passive structure is tested. The key aspect of this less conventional prototype is the absence of a timber-frame structure, which is replaced by a more solid self-carrying insulation layer. This innovative composition is likely to enable an easier prefabrication process, being more flexible (and therefore customizable) and lighter (thus, easier-to-install for workers). Both prototypes will also integrate a window, a cross-flow mechanical ventilation machine with heat recovery for decentralised ventilation, and a solar thermal panel.

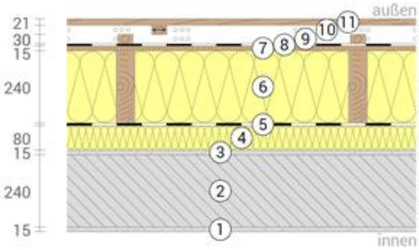

Figure 1: Layers of the first prototype

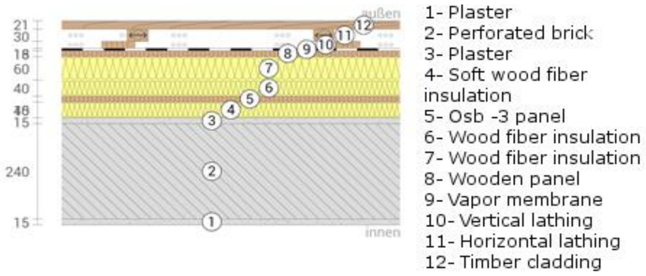

Figure 2: Layers of the second prototype

The purpose of the tests with these prototypes is to investigate the issues that may occur due to the integration within the prefabricated modules of the other components. Thus, the focus is not on the performances on each component alone, but on their mutual influence. In particular, different aspects are investigated depending on the specific technology. For instance, the experimental analysis of the ventilation machine aims at evaluating hygrothermal problems around the machine case at different working levels (flow rates and outdoor fresh air temperature) of the machine itself. The main purpose of the analysis of the solar thermal collector is to quantify the risk of condensation in the layers behind the panel, depending on the temperature of the backside of the collector generated by different levels of incident solar radiation. In these tests, the sun effect is simulated with an artificial light. Overall, the outcome of the analyses is therefore to define how different passive timber-based structures (and therefore layers' composition) affect the behavior of the integrated components.

3.2 Computer simulations of façade components

Computer simulations are used both for preliminary exploratory analysis and, later, to extend the results to a wider range of configurations. The data measured on the prototypes during the tests are compared with simulated values, and therefore used to validate a numerical model under a number of working conditions.

In this research, numerical models for the study the hygrothermal behaviour are developed using a widely used commercial software, namely Delphin [4]. The heat and moisture transfer analysis is initially performed to define which boundary conditions and configurations (such as position of the ventilation machine and solar thermal panel) are more likely to generate issues within the façade system (both in the passive structure and at the interface between different integrated components).

In particular, for the ventilation machine, the objectives of the analysis are to evaluate potential thermal bridges and condensation issues around the envelope of the machine. Regarding the solar thermal panel integration, the main aspects investigated is the relationship between the thickness and the ventilation rates of the cavity behind the solar thermal panel. This analysis includes the study of the likely high temperature in this cavity, their effect on the performances of the solar thermal module, and the possible undesired movement of vapour flow from the outside to the inside due to elevated temperatures and humidity levels in the cavity.

The initial set of simulations considered the boundary conditions described in Table 1. In this initial study, it was also varied the efficiency of the heat recovery unit within the ventilation machine (55% and 70%), and the initial conditions of the sample (temperature 10°C, relative humidity 10% and

40%). The analysis showed that condensation is expected to occur in all cases unless the component is accurately studied and modified to address this issue.

Table 1: Boundary conditions used in Delphin

Outdoor air temperature [°C]	Outdoor relative humidity [%]	Indoor air temperature [°C]	Indoor relative humidity [%]
0	25	17	30
-5	55	20	50
-10	85	24	70

4 Multifunctional façade technology: analysis and application at building level

The key purposes of the analysis at building level is to assess the performances of the whole building in terms of energy use and savings, and expected occupants' level of comfort after the integration of the developed multifunctional façade elements.

4.1 Application of the developed façade systems on real existing buildings

The deep renovation packages conceived within 4RinEU are applied to three demo cases. Taking into account that each demo case has its own characteristics such as architectural features, construction typologies, climate and location, type of occupancy and social context, deepness of required renovation intervention, different deep renovation packages are applied to different buildings. The main features that this renovation includes is a completely new insulated envelope, new windows with shading system, mechanical ventilation devices, and active solar systems.

The first demo case is a multifamily house located in Lleida city centre, in Spain. The owner is a housing association, the tenants belong to a low-income group, and the total area of the plot is approximately 533 m². The building comprises a basement, which is used as storage room by the municipality and therefore not available for the tenants, one ground floor and three floors. There are 23 apartments, distributed by six units per level, except for the ground floor where there are five dwellings. The deep renovation packages applied to this building are a prefabricated façade that integrates a decentralized mechanical ventilation system, a new windows with shading system, and also insulated pipes (connected to a roof-mounted solar thermal system) for hot water circulation.

The second demo case is located in Oslo, Norway. This complex consists of six individual and identical low-rise constructions built in the period 1971-1972. The low-rise racks are divided into three block units and consist of eight two-floor apartments. Also in this case the tenants belong to a low-income group. The third available demo is located in Soest, in The Netherlands, and it is a multifamily residential building. In this case, part of the construction is renovated using the 4RinEU deep renovation packages (eight dwellings), while the rest of this building is renovated using traditional renovation packages. In both demo cases, the deep renovation packages to be applied are still under evaluation.

4.2 Dynamic thermal modelling: estimate of the likely performances of the newly developed façade systems

In this project, dynamic thermal simulations are performed using TRNSYS v17 [5] as this software enables to model both the passive parts of the buildings such as the envelop and the active systems such as solar thermal panels and photovoltaic panels within one program. Thus, the chances of incompatible results or of errors due to the manual transfer of results from one program to another are minimised. The first modelled building is a residential for elderly people in The Netherlands. The calibration of the TRNSYS model was initial performed on a single room, for which data was monitored for a several months, by varying the ventilation load within the room, the conductivity, capacity and density of the insulation material within the envelope, and the shading percentage of windows. A parametric procedure enabled to minimise the differences between measured and simulated air temperatures, with a root mean square error (RMSE) equal to 0.71.

The simulation activity is informed by a preliminary energy audit on the demo buildings to be modelled. Therefore, a high level of accuracy of the models is ensured by creating realistic components (e.g. wall layers, HVAC systems, occupancy schedules, etc.) and by comparing the predicted performances with available billing data. The calibrated model of the existing building is used to evaluate the effects of different deep renovation packages. This process allows an accurate comparison between pre and post 4RinEU interventions, and it therefore enables to assess the impact of the renovation with the prefabricated multifunctional façade on the building performances. In this analysis, the selection of appropriate key performance indicators (KPIs) is essential to highlight the benefits of the deep renovation. This includes indicators of the annual energy demand for heating and cooling, of the comfort levels (such as the predicted mean vote (PMV) and the predicted percentage dissatisfied (PPD)) and indoor environmental quality (CO_2 concentration), and economic indicators.

5 Conclusions

This paper presented the initial activities developed within the European project Horizon 2020 4RinEU, and focuses primarily on the improvements applied to the building envelopes. This paper illustrated the approach used to conceive innovative renovation solutions, to assess their performances at component level, and to estimate the impact of the new envelope on the entire building performances.

The initial analysis showed that this methodology is capable to lead to robust renovation solutions that can find wider applications across the European residential buildings due to their adaptability (starting from some general points, each solution is then tailored to each demo case) and the methodology used to develop these solutions (the validated models, especially the component models, can be easily adapted to different scenarios and boundary conditions).

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