Deep energy renovation of old concrete apartment building to nZEB by using wooden modular elements

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1. Introduction

Energy Roadmap 2050 [1] states that decarbonising the increasing share of renewable energy and using energy more efficiently are crucial. There are approximately 25 billion square meters of useful floor space in the EU27, Switzerland and Norway. Because residential buildings account for approximately 75% of building stock they have a large share of the total energy consumption. In the EU, approximately 17% of the total primary energy use and 25% of the final energy consumption are used in residential buildings.

Apartment buildings in Northern Europe consume energy for heating at approximately 100-200 kWh/(m^2·a) [2–5]. Energy for space heating depends almost linearly on the heat loss of building envelope. As the thermal transmittance of building envelope of old buildings is large (U_{wall} ≈0.8–1.1 W/(m^2·K), U_{roof} ≈0.9–1.1 W/(m^2·K)), building envelope contains serious thermal bridges [6,7] and air leakages, additional insulation of building envelope gives a large potential for energy saving [8,9]. Requirements for heat loss of building envelope during deep energy renovation vary depending on the requirements of indoor climate and energy performance in a specific country, outdoor climate, availability of renewable energy, building typology [10].

Renovation the existing residential building stock is a key factor of this future task as the replacement rate of the existing stock is only 1–2% per year. Increasing energy performance has been the driving force for renovation of old prefabricated concrete large panel apartment buildings because energy related measures help to increase cost-effectiveness of the whole renovation process and the upkeep of buildings [11–13]. The European building sector has not yet been able to devise a structural, large-scale renovation process and systematic approach. The use of prefabricated multifunctional modular renovation elements could help to fulfill all these points [14–18]. The Horizon2020 project 'MORE-CONNECT' has been launched to develop energy efficiency, hygrothermal performance and aesthetics of buildings and demonstrate technologies of prefabricated modular renovation elements, including the prefab integration of multifunctional components, e.g. for climate control [19].

This article presents solutions for a deeply renovated typical apartment building made of concrete large panels, constructed during the 1960-90 period in Estonia (Figure 1). The pilot renovation was conducted in 2017. The design solution of the current project will provide input to further process the integrated design of nearly Zero Energy Building (nZEB) and the renovation of concrete panel multi-storey apartment buildings.

Figure 1: Overview of the pilot building before (left) and after (right) renovation.

2. Pilot building

The building type studied is a 5-storey apartment building used as dormitory with a total area of 4318 m^2, constructed in 1986 (Figure 1, left). The building is analogous to mass production apartment buildings (series 111-121) from 1960-1990 in the former Soviet Union countries of Eastern Europe.

Existing 250mm concrete panel exterior wall consists of 2 concrete sections and insulation layers: 60mm external reinforced concrete slab + 70mm wood-chip insulation layer + 50mm phenolic foam insulation layer + 70mm internal reinforced concrete slab. The existing flat roof with parapet is covered with bitumen felt and insulated with wood-chip boards. The thermal transmittance of the existing envelope is U=0.9 - 1.1 W/(m^2·K).

Calculated according to measurements, temperature factor $f_{Rsi}<0.80$, which is under the accepted limit [20,21]. Because of serious thermal bridges (Figure 2), mold growths are on the interior surface, especially in the corners of exterior walls and the roof.

Figure 2: Overview of thermal bridges from inside (above) and outside (below) the building.

The pilot building has problems typical and similar to many other older buildings: high energy consumption, insufficient ventilation, overheating during winter, unsatisfactory thermal comfort. Fresh air inlet was initially designed through the slits around untightened window wooden-frames and natural exhaust via kitchen and sanitary rooms to the central shaft. The building has a one-pipe radiator heating system without thermostats and the room temperature for the whole building is regulated by a heat substation depending on the outdoor temperature. Pre-renovation total delivered annual energy with III indoor climate category (ICC III, acceptable, moderate level of expectation) was 214 kWh/(m^2·a) (real energy use was higher 300 kWh/(m^2·a) because of approximately two times larger use of electricity and domestic hot water):

- for heating and ventilation 149kWh/(m^2·a),
- for domestic hot water (DHW) 30kWh/(m^2·a),
- for appliances and electricity 30kWh/(m^2·a),
- for fans and pumps 5kWh/(m^2·a).

3. nZEB energy performance

nZEB is defined in Estonia as a numeric indicator, Energy Performance Value (EPV), of primary energy use, taking into account energy for:

- heat for space heating and ventilation,
- heat for domestic hot water (DHW),
- electrify for lighting and appliances.

For nZEB apartment buildings EPV<100 kWh/(m^2·a) [22]. Ventilation airflow after renovation should represent a normal level of expectation for the II indoor climate category (ICC II) with ventilation airflow 0.42 l/(s·m^2).

The design of the pilot started with preliminary energy and economical calculations [23,24]. The calculated primary energy use of nZEB renovation shows a 2/3 reduction compared to pre-renovation state. The heating system will be replaced with a two-pipe system with hydronic radiators and thermostats. The building's initial passive stack ventilation system will be replaced with a mechanical supply and exhaust ventilation with heat recovery. The deficit of places for ventilation ducts in this project design will be solved with the integration of preheated air supply ducts into the renovation module panels. Solar collectors and PV panels will be installed onto the roof, ventilation and sewerage heat recovery is applied.

Table 1: Energy use and onsite energy production of renovated nZEB pilot (kWh/(m^2·a)).

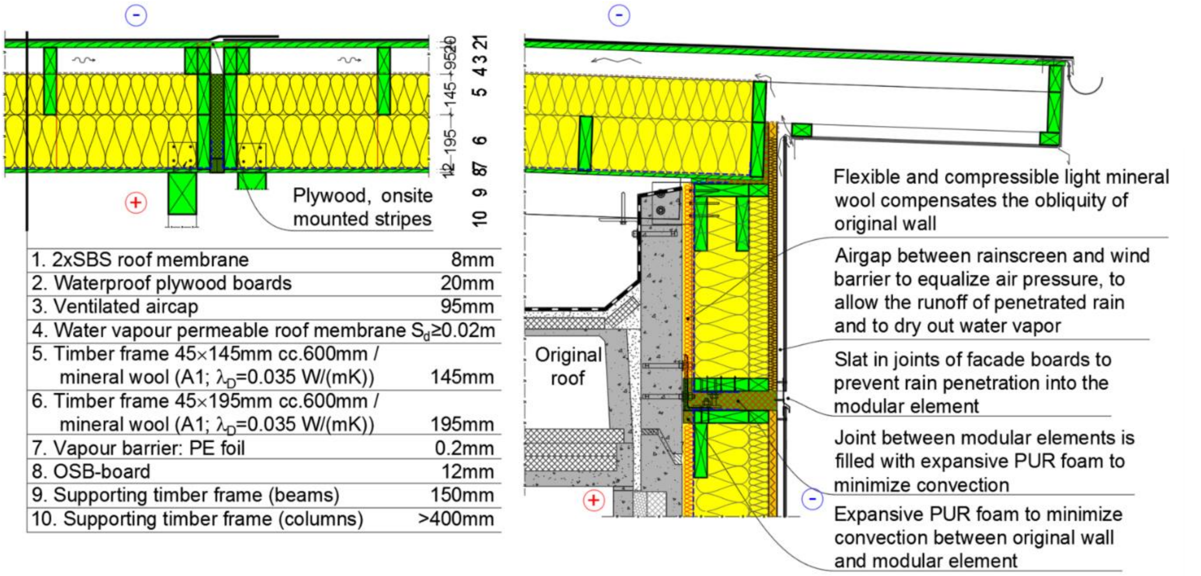
	Energy need		On site energy production	
	Heat	Electricity	Heat	Electricity
Space heating and heating of ventilation air with heat recovery (VHR)	16			
Domestic hot water (production: solar collectors, sewerage heat recovery)	30		8+6	
Appliances and lighting (production: solar panels)		26		2
Fans, pumps		8		
Total (delivered energy)	46	34	14	2
Total primary energy use (with weighing factor for electricity=2.0 and for district heating=0.9)	109		17	

Figure 3: Well insulated building envelope with onsite energy production is needed for nZEB.

Prefabricated modular wooden elements for additional thermal insulation of building envelope

The building envelope above ground (walls and roof) was insulated with prefabricated wooden modular elements. Basement walls were insulated in-situ with an external thermal insulation composite system. Prefabricated modular panels consist of a timber frame structure filled with mineral wool. In principle, other lightweight structures and insulation materials are also conceivable. To get accurate information about the unevenness and roughness of the existing surfaces and inhomogeneity of windows location, 3D laser scanning of the envelope was conducted before the design.

Designed roof elements were installed on the specially built timber structure because the original roof has an inward slope and parapet. Therefore, under the formed slope roof, in 0.6-1.2 m high attic between old and new roof, service systems (e.g. heat exchangers, duct dispensers, automatics etc.) were placed. The total thickness of the thermal insulation in the roof modules is 340 mm, U_{roof}=0.10 W/(m^2·K).



1. 2xSBS roof membrane	8mm
2. Waterproof plywood boards	20mm
3. Ventilated aircap	95mm
4. Water vapour permeable roof membrane $S_d \geq 0.02$m	
5. Timber frame 45×145mm cc.600mm / mineral wool (A1; λ_D=0.035 W/(mK))	145mm
6. Timber frame 45×195mm cc.600mm / mineral wool (A1; λ_D=0.035 W/(mK))	195mm
7. Vapour barrier: PE foil	0.2mm
8. OSB-board	12mm
9. Supporting timber frame (beams)	150mm
10. Supporting timber frame (columns)	>400mm

Figure 4: Designed solutions for roof.

The total thickness of designed and installed modular wall elements is 340-380mm, depending on the surface flatness of the existing wall (Figure 5 right). The total thickness of the thermal insulation in wall panels is 305-345 mm: 30 mm wind barrier, 70+195 mm insulation between timber frames and 10-50 mm light elastic mineral wool to fill the unevenness and roughness of the existing surfaces, U_{wall}=0.11 W/(m^2·K). In the wall panel with dimensions ≈2.7×9 m, installed in a horizontal direction, are up to three preinstalled windows. To minimize joints between the modules and connections of pipes on site, the panels with embedded ventilation ducts (Figure 5 left) were installed in a vertical direction.

Self-supporting modules were hanged onto the existing wall surface with the help of designed fixings, allowing adjustment of modules in all three directions (Figure 7). Therefore, there was no need for additional foundation for the wall module panels.

To avoid thermal bridges and to minimize the impact of air leakage and convection, smart connectors and innovative fixings, adhesive sealants and elastic foam was used in the joints between the modules. All vertical joints between wall modules were protected with sealing and steel strips under the facade boards. Horizontal joints were equipped with slits (drip molds) to prevent rain penetration to the insulation. All internal intersections between modules were sealed and filled with expansive foam. To avoid having to tighten the existing envelope, the airtightness of the building was guaranteed with prefabricated highly-insulated modules. Airtightness of building envelope after renovation was $q_{50} \leq 1.8$ m^3/(hm^2).

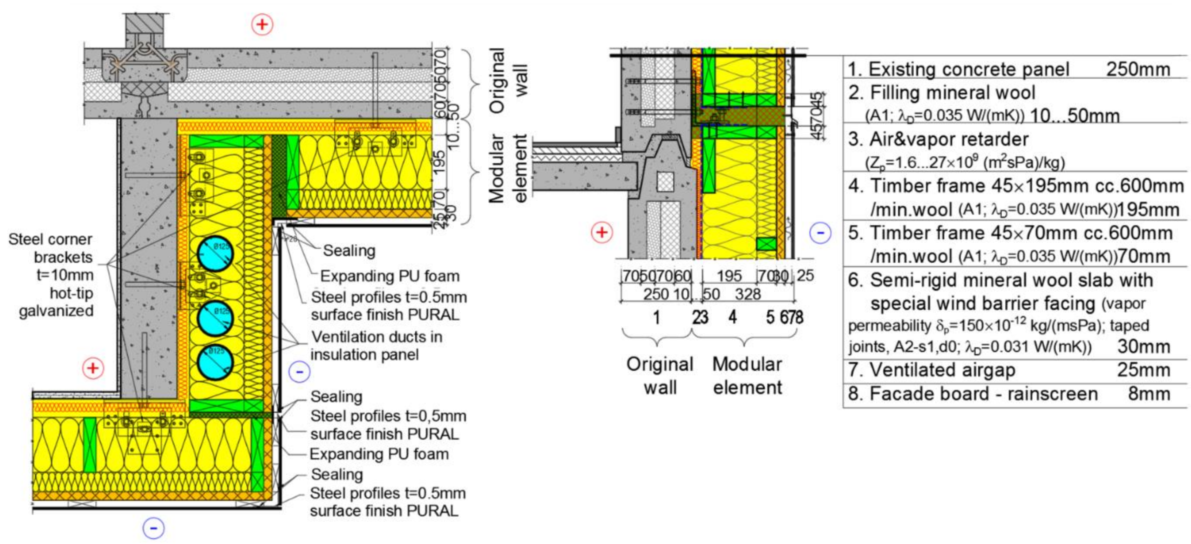


Figure 5: Designed solutions for external wall.

Figure 6: Wooden elements were mounted directly from a truck on two different façades at the same time. To minimize the influence of driving rain, facades were covered when waiting to mount panels.

Figure 7: Original façade was strengthened with diagonal anchors (left). Modular wooden elements were hanged onto the existing wall surface with the help of designed fixings, allowing adjustment of modules in all three directions (right).

4. Conclusions

A pilot nZEB renovation of a typical concrete large panel apartment building was conducted in Estonia. This is one of the first deep energy renovations that has been designed to correspond to the nZEB target of new buildings. In addition to the use of prefabricated modular panels for building envelope insulation, the design solution includes many other tasks to be researched: parallel comparison of two different ventilation solutions: apartment based balanced VHR and centralized balanced VHR; parallel comparison of heating of DHW by solar collectors and sewage heat recovery.

Thermal transmittance of the developed solution with prefabricated modular panels is designed to be $U \leq 0.10$ W/(m^2·K). One of the most critical design tasks was the selection of a vapor barrier for the module panel to avoid problems related with dry-out of possible constructional moisture. A smart vapor retarder with changing vapor permeability was needed.

The analysis and the whole process of design itself showed that it was essential to consider the initial state of the building when highly-insulated module panels are intended to be used for a nZEB renovation. One of the challenges in this process was the decisive importance of the interaction between the design process and the construction work at the building site. Engineers and designers should include hygrothermal modelling into design practices to assure the moisture safety of structures and sustainability in the long term.

The installation of the wooden modular elements indicated that a substantial thorough initial work ("measure twice and cut once") and deeper concentration of moisture safety issues are needed. Roof elements must be installed before the wall elements to prevent the wetting of the original external wall due to driving rain and rain from the temporary roof.

The analysis, design, construction and other activities of the integrated nZEB process gave us a unique experience, showing weak links in the chain and helping to prevent major faults in the next pilots.

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