nZEB Renovation of Multi-Storey Building with Prefabricated Modular Panels

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Abstract. Reduction of energy use in buildings in EU is expected to be reached with help of fulfilling of requirements of low and nearly-zero energy buildings (nZEB) policy. The efficient way to accomplish the purpose of the nZEB is to apply the integrated design process, considering the long-term sustainability and building costs as a one setup. The multi-storey large concrete element building is renovated to nZEB as a Horizon2020 MORE-CONNECT project pilot in Tallinn. The study of that project includes complex of measures: hygrothermal measurements and analysis, highly insulated facade and roof elements, the full modernisation of heating and ventilation systems. Ventilation ducts are installed into the modular panels to minimize supply ductworks in apartments. Roof panels include solar panels and collectors for renewable energy production. All technical systems will be equipped with monitoring systems and data will be logged periodically. The designed thermal transmittance is $U \leq 0.11\text{W/m}^2\text{K}$ for walls, $U \leq 0.10\text{W/m}^2\text{K}$ for roof and $U \leq 0.80\text{W/m}^2\text{K}$ for windows and external doors. The analyse, design and renovation process of the integrated nZEB design method gave us a unique experience, showing weak links in the chain and helping to prevent faults in the whole process in the future.

1. Introduction
Prefabrication of buildings has been one method to increase quality and effectiveness of construction for many decades. Development of concrete large panel systems started already before WW II and growth remained intensive in postwar period. The designed service life of this type of buildings is typically 50 years, which is almost over today for formerly constructed buildings. As more than 70% of residential buildings are over 30 years old and about 35% are more than 50 years old, whole technical improvement of condition has been receiving more attention [1].

Designers, developers and owners are in search of innovative ways to minimize operating costs and the environmental impact of buildings, while also increasing their functionality. 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 [2–4]. An innovative way of renovation is the application of prefabricated multifunctional renovation elements which has the potential to reduce costs and renovation time, reduce disturbance for occupants and, at the same time, enhance quality and performance in terms of energy efficiency, building physics and indoor climate [5–9].

Future nZEB should be much more highly insulated than buildings developed some years ago [10]. 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 [11].

The aim of this study is to present design solutions of nZEB renovation of typical apartment building made of concrete large panels, constructed during the 1960-90 period in Estonia. The pilot renovation will be conducted with this solution in 2017. The design solution of current project will provide input to further process of the integrated design of nZEB and the renovation of prefabricated concrete large panel multi-storey apartment buildings.

2. Case study building
The building type studied is a 5-storey dormitory building with total area 4318 m$^2$, constructed in 1986 and analogous to mass production apartment buildings (series 111-121) from 1960-1990 (Figure 1, left). 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). The initial structural solutions at pre-renovation state are shown on Figure 2 (see structural parts in grayscale mode). Calculated according to measurements temperature factor $f_{Rsi}<0.80$, which is under the accepted limit [12,13]. Because of serious thermal bridges in these type of buildings [14], which can be seen also on Figure 1 (IR2 and IR3), mold growths on interior surface, especially in the corners of exterior walls and roof (Figure 1, IR1).

![Figure 1. Overview of the pilot building before renovation from outside (left) and with thermal camera images (right).](image)

The pilot building has similar problems typical 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 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 [15]. Pre-renovation total delivered annual energy with III indoor climate category (ICC III, acceptable, moderate level of expectation) was 214kWh/(m$^2$·a): 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 indoor climate (heating, cooling, ventilation, lighting), DHW and
appliances. For nZEB apartment buildings EPV<100kWh/(m²·a) [16]. Ventilation airflow after renovation should represent a normal level of expectation for the II indoor climate category (ICC II) with ventilation airflow 0.42l/(s·m²).

The design of the pilot started with preliminary energy and economical calculations [17,18]. 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 (Figure 2 D). Solar collectors and PV panels will be installed onto the roof, ventilation and sewerage heat recovery is applied. However, energy cost reduction alone is not enough to make nZEB renovation profitable for a building owner [19,20].

Table 1. Energy use and onsite energy production of renovated nZEB pilot (kWh/(m²·a)).

| Energy need                                      | On site energy production |
|-------------------------------------------------|---------------------------|
| Heat                                            | Electricity               |
| Heat                                            | Electricity               |
| Space heating and heating of ventilation air with heat recovery (VHR) | 10                         |
| Domestic hot water (production: solar collectors, sewerage heat recovery) | 30 15+8 -4             |
| Appliances and lighting (production: solar panels) | 30 2                  |
| Fans, pumps                                     | 10                        |
| Total (delivered energy)                        | 40 40 23 -2              |
| Total primary energy use (with weighing factor for electricity=2.0 and for district heating=0.9) | 116 17               |

4. Prefabricated modular panels for additional thermal insulation of building envelope

The building envelope above ground (walls and roof) is planned to be insulated with prefabricated modular panels. Basement walls are planned to be insulated with an external thermal insulation composite system. Prefabricated modular panels consist of a timber frame structure filled with mineral wool (Figure 2). In principle, also other lightweight structures and insulation materials are 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.

The total thickness of designed modular wall elements is 340-380mm, depending on the surface flatness of the existing wall (Figure 2 C). The total thickness of the thermal insulation in wall panels is 305-345mm: 30mm wind barrier, 70+195mm insulation between timber frames and 10-50mm light elastic mineral wool to fill the unevenness and roughness of the existing surfaces, \( U_{wall}=0.11 \text{W/(m}^2\text{K)} \).

In the wall panel with dimensions \( \approx 2.7 \times 9 \text{m} \), installed in horizontal direction, are up to three preinstalled windows. To minimize joints between the modules and connections of pipes on site, the panels with ventilation ducts (Figure 2 D) will be installed in vertical direction. According to the structural design of the pilot building, there is no need for additional foundation for the wall module panels. Self-supporting modules will be hanged onto the existing wall surface with the help of designed fixings, allowing adjustment of modules in all directions.

Designed roof elements will be installed on the specially built timber frame (Figure 2 A and B) because the original roof has an inward slope and parapet. Therefore, under the formed slope roof, in 0.6-1.2m high attic between old and new roof technical appliances are planned to be placed (e.g. heat exchangers, duct dispensers, automatics etc.). The total thickness of the thermal insulation in the roof modules is 340mm, \( U_{roof}=0.10 \text{W/(m}^2\text{K)} \).

Figure 2 shows the cross-sections of the designed wall and roof modules (see Figure 1 (left) and Figure 2 (above) for locations of presented structural points A, B, C, D).
Figure 2. Designed solutions at the different structural points of nZEB pilot.
To avoid thermal bridges and to minimize the impact of air leakage and convection, smart connectors and innovative fixings, adhesive sealants and elastic polyurethane (PUR) foam will be used in the joints between the modules. All vertical joints between wall modules will be protected with sealing and steel strips under the facade boards. Horizontal joints will be equipped with slits (drip molds) to prevent rain penetration to the insulation. All internal intersections between modules will be sealed and filled with expansive PUR foam. To avoid having to tighten the existing envelope, it is planned to ensure the airtightness of the building with prefabricated highly-insulated modules.

5. Hygrothermal performance of prefabricated wall panels

Longer constructional moisture dry-out periods and obstacles to its capability weaken the hygrothermal condition of the whole building envelope. Therefore, it is necessary to pay special attention to the hygrothermal performance and moisture safety of the design and building processes of highly-insulated buildings. It was previously shown [21] that in highly-insulated buildings, high thermal resistance and vapor permeability of the wind barrier layer are the key components of a well-functioning building envelope and a longer constructional moisture dry-out period is detrimental to the hygrothermal condition. In the common timber-frame wall the PE-foil, as the air and vapor barrier, does not cause any serious problems to the hygrothermal performance [22,23]. In solutions with highly-insulated modular panels, installed onto the existing concrete wall, it prevents the moisture dry-out and could pose a higher risk of mold growth.

One of the most critical hygrothermal design tasks was the selection of a vapor barrier for the wall module [24]. The most influential parameters here are a built-in moisture dry-out after the installation of the insulation modules (requires a relatively permeable vapor barrier) and the long-term performance where a vapor tightening barrier is required because the joints of the original wall would not be air- and vapor tight. We did not find any previous studies about this matter from our literature review.

It was confirmed by our former studies that a concrete building envelope is affected by weather conditions (temperature, relative humidity, wind driven rain (WDR), radiation, orientation) in such substantial amounts that they cannot be ignored in the further design process of renovation with modular panels [25]. Cracks and openings in the walls contribute to the uncontrolled moisture flux into the structure. With hygrothermal analysis it was found that in our region the south-west oriented wall has about 20% higher moisture content than other sides of the building envelope and with the consideration of impact of WDR, the wall has almost 50% higher moisture content. Analysis showed that the moisture content in the whole external concrete slab is about $w=110$ kg/m$^3$ in the most critical periods, at the last quarter and the first months of the year (see Figure 3).

![Figure 3](image.png)

**Figure 3.** Example of dynamic simulation results (left) of monthly distribution of moisture content for external concrete slab in south-western orientation with WDR in points A, B and C and schematic layout of zones and calculation points A, B and C (right) in studied external concrete slab section of wall.
Figure 4. Example of dynamic simulation in the critical point in wall cross-section with the different vapor control layers and different initial moisture content (MC) of concrete large element throughout a 5-year period.

Required hygrothermal performance of studied solutions was ascertained with a smart vapor retarder (see Figure 4) with changing vapor tightness $0.2m < S_d < 5m$ when the initial moisture content of existing concrete large panel was $w \leq 110kg/m^3$ or with 22mm OSB as vapor control layer when the initial moisture content of the existing concrete large panel was $w \leq 75kg/m^3$ or with PE-foil as air and vapor barrier when the initial moisture content of the existing concrete large panel was $w \leq 55kg/m^3$. For future research, we plan to investigate the hygrothermal performance of insulation panels and connections by field measurements after the whole renovation process of the current pilot in autumn 2017.

6. Conclusions
A pilot nZEB renovation of a typical concrete large panel apartment building is planned to be 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.

The hygrothermal performance of the building envelope, constructed of concrete large panels and covered with prefabricated modular elements was analyzed in this research. Thermal transmittance of the developed solution with prefabricated modular panels is $U \approx 0.10W/(m^2\cdot K)$. 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 is 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 is 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 analysis, design and other preparation activities of the integrated nZEB design process gave us a unique experience, showing weak links in the chain and helping to prevent major faults in the construction of the pilot and in the further processes of design.

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