

Article

# Development and Performance Assessment of Prefabricated Insulation Elements for Deep Energy Renovation of Apartment Buildings

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**Abstract:** A need for the refurbishment and renewal of the existing building stock has been in focus for many decades, principally because of excessive global energy consumption and pollution. This paper presents a methodology and the results of analysis of choices of realizable sets of timber frame prefabricated insulation elements for major renovation of apartment buildings. Numerous combinations of elements with different characteristics were analyzed by applying measurements, interviews, and building performance simulation software, and thereupon their performance, installation eligibility, and concurrent cost levels were compared. Mineral wool board with a special wind barrier facing was found to be the best material as a wind barrier from the perspective of hygrothermal performance. An air and vapor barrier should have sufficient vapor permeability to allow dry-out of constructional moisture. It is possible to renovate apartment buildings to meet the nZEB energy performance requirements and their moisture safety can be guaranteed without paying high relative difference cost. Calculations showed that the global cost was lower for solutions with some mold growth risk. Great care is needed when decreasing costs without simultaneous hygrothermal analyses. The facade cladding was found to have the highest influence on the initial cost of the prefabricated insulation element.

**Keywords:** hygrothermal performance of buildings; nZEB renovation; deep energy renovation; moisture safety; prefabricated timber frame insulation elements; quality assessment

## 1. Introduction

If the building materials and structural elements are nearing the end of their service life and the energy performance of the building needs to be improved, the owner of the building has to take measures required to ensure that the relevant criteria are met. As in Europe, more than 70% of the residential buildings are over 30 years old and about 35% are more than 50 years old, complete technical improvement of their condition has been receiving increasing attention [1,2]. Energy performance of building directive (EPBD) [3] requires all new buildings to be nearly Zero Energy Buildings (nZEB) as of the year 2020 and to renovate almost all buildings by the year 2050. Due to the reduction of energy use during the lifetime of buildings, renovation resulted in a reduction of global warming potential [4]. Case studies have shown the viability of the nZEB renovation measures to improve the condition of residential building stock in Croatia [5], Spain [6,7], Poland [8], and the Mediterranean climate [9]. The outcomes show huge potential energy and economic savings and support deep energy renovation needs [10,11].

In the cold climate, additional thermal insulation is always needed to radically improve the energy performance of buildings. To fulfill future nZEB requirements, the building envelope should be more

highly insulated than buildings designed some years ago [12]. A highly insulated building envelope is an inevitable prerequisite for nZEB renovation in all climates. López-Ochoa [13] analyzed the energy, environmental, and economic impacts of the energy renovation of thermal envelopes and optimized the insulation thickness to be added to the walls, roofs, and first floor.

A highly insulated building envelope requires thoroughgoing hygrothermal analysis to avoid moisture damage [14,15]. Therefore, in the design of nZEB renovation, hygrothermal performance of the building envelope and sustainability should also be analyzed [16] and considered as an important selection criteria. On the other hand, too many selection criteria makes analysis difficult [17] for practitioners and consultants. Qi [18] showed that quality control during the renovation preparation stage is critical to ensure that quality failures are reduced in numbers and severity. In the changing climate conditions, it means that the market participants must find efficient ways to improve the quality of design and installation to meet increasing requirements of energy and hygrothermal performance of new and existing buildings.

La Fleur et al. [19] showed that the cost of the demolition and construction of a new building is higher compared to energy renovation to the same energy performance. This makes renovation the first choice, when there exists need for residences in that region. The cost of renovation is an important criteria for decision making and determining renovation solutions. Gustafsson [20] analyzed energy renovation measures in Sweden and showed that all renovation measures resulted in an increased life cycle cost (LCC), compared to the reference building. Firląg et al. [8] analyzed nZEB solutions for heating dominated climate and showed that nZEB renovation is not yet cost optimal in Poland. Patiño-Cambeiro et al. [7] analyzed nZEB renovation solutions for Spanish building stock and showed that more active financial support, together with the dissemination of the technical requirements and the benefits obtained from energy renovations are needed. Hu [21] indicated that in the optimum scenario, investing in energy-efficient retrofitting and renewable energy, when combined, produced close to a 90% reduction in the life cycle cost compared to the pre-renovation state. Kuusk [22] showed that for a concrete large panel apartment building in Estonia, additional insulation of 200–300 mm to the external wall leads to the greatest reduction in the global cost and primary energy use and that to reach the nZEB level, thermal transmittance of the external wall should be  $U \leq 0.15 \text{ W}/(\text{m}^2 \cdot \text{K})$  [23]. Hirvonen et al. [24] showed that improving the building envelope is an effective way to reduce emissions of detached houses in Finland.

Fotiou [25] showed that the achievement of ambitious energy-efficiency targets in the long-term heavily depends on pursuing a fast and extensive renovation of existing buildings. External thermal insulation composite systems (ETICS) have been used for decades on masonry, concrete, and other substrates. ETICS primarily fulfill the functions of thermal insulation and protect the building against the influences of weather. Many authors [26–28] have pointed out that as to ETICS, durability issues, including the degradation of the surface and aging of the materials, are the most urgent ones. Installation of timber (or other similar) frames, filled in between with insulation layers and covered by wind and weather protective facade layers, to the external envelope manually on the building site is another common method for energy refurbishment as well as for building extensions. Both methods are based on onsite field work, accompanied by long-lasting manual labor, low efficiency, and use of scaffolding on the external envelope. Because of unpredictable weather conditions and varying quality of installation the results obtained are not always in agreement with expectations [29]. Therefore, the building owners, construction companies, and other market participants are in search of alternatives to improve the quality of the existing building stock by means of prefabrication and by lesser disturbance to a building's occupants.

An innovative method of renovation is the application of prefabricated renovation elements, which has the potential to reduce costs and renovation time, lower disturbance for inhabitants, and enhance quality and performance in terms of energy efficiency and indoor climate [30–32]. The recent research on technical, financial and social barriers and challenges in deep renovation of buildings points out that the main barriers are not related to specific technical problems but are due to insufficient deep renovation and nZEB knowledge, in the case of both building owners (i.e., awareness and commitment)

and designers (i.e., managing properly the design and construction process in order to guarantee the expected performance and targets set) [33,34].

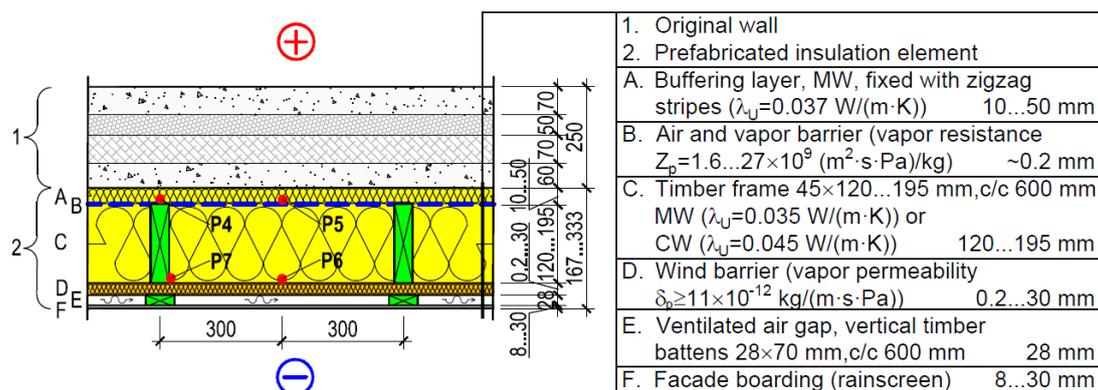
The literature review and described hereinbefore projects reveal that many development programs have focused primarily on energy and cost-effectiveness with a commitment to develop state-of-the-art implementation of prefabricated insulation elements for deep energy renovation. However, most of them have not analyzed (or reported the results of) the hygrothermal performance associated with the original building envelope and its condition. The current study combines hygrothermal and energy performance analysis with cost-efficiency calculations to find a suitable solution for nZEB renovation of apartment buildings with prefabricated wall insulation elements.

## 2. Methods

### 2.1. Analyzed Building Envelope Construction Types

In total, 1620 dimensional, conditional, and material combinations of prefabricated timber frame insulation elements were analyzed (see Figure 1 and Table 1). The cost (including production, installation, maintenance, and energy use), hygrothermal performance, and handling on installation were evaluated by considering the interaction of various parameters:

- Initial moisture content (IMC) of original concrete facade by volume:  $w = 85 \text{ kg/m}^3$ ,  $95 \text{ kg/m}^3$ ,  $110 \text{ kg/m}^3$  (i.e., IMC by mass (kg/kg):  $u = 3.7\%$ ,  $4.1\%$ ,  $4.7\%$ );
- Air and vapor barriers (see Figure 1, layer B): vapor barrier with varying water vapor resistance, original wall without vapor barrier layer, polyethylene (PE) foil;
- Timber framing (see Figure 1, layer C):  $45 \text{ mm} \times 120 \text{ mm}$ ,  $45 \text{ mm} \times 145 \text{ mm}$ ,  $45 \text{ mm} \times 195 \text{ mm}$ ;
- Types of insulation in prefabricated timber frame element (see Figure 1, layer C): mineral wool (MW), cellulose wool (CW); thickness of insulation with 50 mm MW buffering layer (see Figure 1, layer A): 170 mm, 195 mm, 245 mm;
- Wind barriers (see Figure 1, layer D): sheathing membrane, gypsum board + sheathing membrane, fiber cement board, wood fiberboard, MW board with special wind barrier facing;
- Ventilated air gap with vertical timber battens (see Figure 1, layer E)  $28 \text{ mm} \times 70 \text{ mm}$ ;
- Facade systems (see Figure 1, layer F): wooden boarding, plastic boarding/siding, metal profile sheets, cement fiberboards, facade stones cladding, plastered facade weatherboard.



**Figure 1.** Horizontal cross-section of the original wall with installed prefabricated timber frame insulation element and analyzed critical points.

The materials of the designed and studied structures are described in Figure 1 and in Table 1. Thermal transmittances of the studied structures are shown in Table 2. Analyzed in prefabricated elements layers of materials are marked with letters A to F. Alternatives of the air and vapor barrier layer are marked with B1 to B3. Alternatives of the insulation layer are marked with C1 and C2.

Alternatives of the wind barrier layer are marked with D1 to D5. Alternatives of the facade materials are marked with F1 to F6.

**Table 1.** Description of materials (see Figure 1) in sets of analyzed structures. \*.

Material Layer		Frame Thickness, See Figure 1, Layer C		
		120 mm	145 mm	195 mm
A	Buffering layer	Mineral wool (MW) 50 mm (thermal conductivity $\lambda_U = 0.037$ W/(m·K))		
B1	Air and vapor barrier	Product ~0.2 mm (with varying water vapor resistance, depending on RH, 0.2 m at RH 85% $\leq S_d \leq 5$ m at RH 20%)		
B2		Without vapor barrier layer, air tightness is guaranteed by other means		
B3		PE-foil ~0.2 mm ( $S_d \geq 50$ m)		
C1	Timber frame, insulation type, thickness, thermal conductivity	45 mm $\times$ 120 mm MW 120 mm $\lambda_U = 0.035$ W/(m·K)	45 mm $\times$ 145 mm MW 145 mm $\lambda_U = 0.035$ W/(m·K)	45 mm $\times$ 195 mm MW 195 mm $\lambda_U = 0.035$ W/(m·K)
C2		CW 120 mm $\lambda_U = 0.045$ W/(m·K)	CW 145 mm $\lambda_U = 0.045$ W/(m·K)	CW 195 mm $\lambda_U = 0.045$ W/(m·K)
D1	Wind barrier	Sheathing membrane ~0.2 mm ( $S_d \leq 0.015$ m at RH 85%)		
D2		Gypsum board 9 mm (vapor permeability $\delta_p \geq 25 \times 10^{-12}$ kg/(m·s·Pa), $\lambda_D = 0.19$ W/(m·K)) + sheathing membrane (see position D1)		
D3		Fiber cement board 9 mm ( $\delta_p \geq 11 \times 10^{-12}$ kg/(m·s·Pa), $\lambda_D = 0.26$ W/(m·K))		
D4		Wood fiberboard 22 mm ( $\delta_p \geq 40 \times 10^{-12}$ kg/(m·s·Pa), $\lambda_D = 0.050$ W/(m·K))		
D5		MW board 30 mm with special wind barrier facing ( $\delta_p \geq 110 \times 10^{-12}$ kg/(m·s·Pa), $\lambda_D = 0.031$ W/(m·K))		
E	Ventilated air gap	Vertical timber battens 28 mm $\times$ 70 mm, c/c 600 mm		
F1	Facade system	Wooden boarding		
F2		Plastic boarding/siding		
F3		Metal profile sheets		
F4		Cement fiberboard		
F5		Facade stones (cladding system)		
F6		Facade weatherboard with plaster		

\* Materials' data are from the database of the calculation program Delphin [35,36] and the properties are adjusted with lab tests and/or literature data.

The structure of the prefabricated insulation element is based on timber frames (c/c 600 mm) with different thicknesses (see Figure 1, layer C, 120–195 mm), where air and vapor tightness from the inner side has to be guaranteed with an air and vapor barrier layer (see Figure 1, layer B) or by other means with original wall treatment and from the external side covered with a wind barrier layer (see Figure 1, layer D). The main insulation layer (see Figure 1, layer C) of the element consists of MW with density  $\rho = 22$  kg/m<sup>3</sup> or CW with density  $\rho = 70$  kg/m<sup>3</sup>. To minimize convection in between the structures and to compensate the roughness of the original wall, 50 mm MW ( $\rho = 20$  kg/m<sup>3</sup>) as the buffer layer was added onto the back side of the prefabricated element (see Figure 1, layer A). The buffering layer is fixed in zigzag with strings, which are released after the element is installed. The buffering layer and all other layers of insulation are installed in the factory and are protected with plastic foil against

weather damage during transport and on the building site. In hygrothermal analysis all sets installed are considered to be airtight and the wall elements covered with weatherproof facade boarding, thus not affected by wind-driven rain.

**Table 2.** Thermal transmittance  $U_c$  ( $W/(m^2 \cdot K)$ ) \* of analyzed sets with different insulation materials (mineral wool (MW) and cellulose wool (CW)) and wind barrier layers. See Table 1 for description of layers D1–D5.

Wind Barrier Layer	Thermal Transmittance $U_c$ , $W/(m^2 \cdot K)$ * (Frame Thickness, Layer C1 or C2)					
	120 mm		145 mm		195 mm	
	MW	CW	MW	CW	MW	CW
D1	0.20	0.22	0.18	0.20	0.15	0.17
D2	0.20	0.22	0.18	0.20	0.15	0.17
D3	0.20	0.22	0.18	0.20	0.15	0.17
D4	0.18	0.20	0.17	0.18	0.14	0.16
D5	0.17	0.18	0.15	0.17	0.13	0.15

\* Thermal transmittance is calculated with the existing original wall construction ( $R_{\text{exist.wall}} = 1 \text{ m}^2 \cdot \text{K}/\text{W}$ ).

## 2.2. Reference Building

A typical five-story apartment building with a total heated area of 2968  $\text{m}^2$ , constructed of prefabricated concrete large panel elements in 1966 (serial project 1–464), was selected for the reference building (see Figure 2). Prefabricated concrete large panel apartment buildings were typical and built in Eastern Europe during the 1960–1990s. For example, 2 million  $\text{m}^2$  of prefabricated concrete large panel apartment buildings was built during that period in Estonia and 4.7 million  $\text{m}^2$  in Vilnius, Lithuania [37]. This building type needs deep energy renovation because of serious thermal bridges [38], high thermal transmittance of the external walls ( $U_{\text{wall}} = 0.8\text{--}1.5 \text{ W}/(\text{m}^2 \cdot \text{K})$ ), insufficient performance of ventilation [39], high indoor humidity loads [40], and corrosion damages of concrete facades [41].



**Figure 2.** Overview of the reference building in 2014 before (left) and in 2015 after (right) the renovation.

## 2.3. Hygrothermal Performance of Exterior Wall: Measurements and Simulations

Hygrothermal simulations with the software Delphin [35,36] were conducted to analyze the performance of the external walls on the basis of values of temperature and relative humidity in critical points (see Figure 1, points P4, P5, P6, P7). Delphin is a simulation program for coupled heat, moisture and matter transport in porous building materials and it is used for different applications, e.g., calculation of mold growth risks with consideration of climate impacts, structure conditions and materials modelling. The moisture mass balance is expressed according to Equation (1):

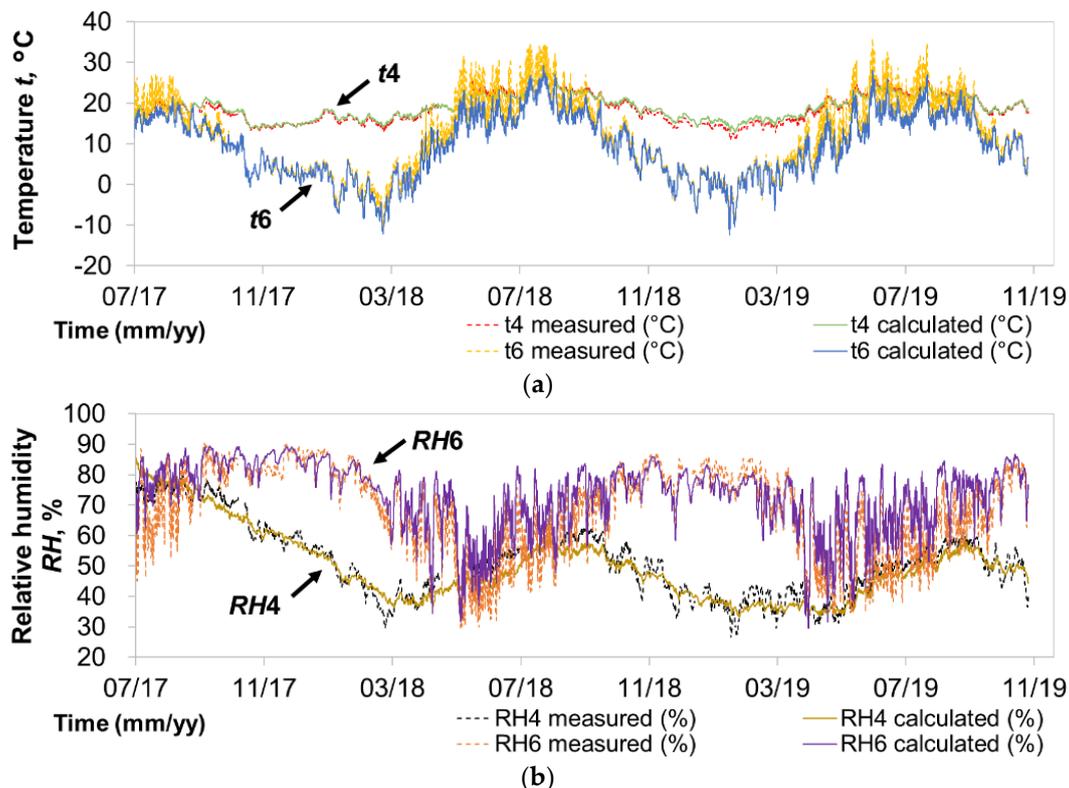
$$\frac{\partial}{\partial t} \rho_{\text{REV}}^{m_{w+v+i}} = - \frac{\partial}{\partial x} [j_{\text{conv}}^{m_w} + j_{\text{conv}}^{m_v} + j_{\text{diff}}^{m_v}] + \sigma_{\text{REV}}^{m_{w+v+i}} \quad (1)$$

where  $\rho_{\text{REV}}^{m_{w+v+i}}$  is moisture density in reference volume (liquid water + vapor + ice) ( $\text{kg}/\text{m}^3$ ),  $\sigma_{\text{REV}}^{m_{w+v+i}}$  is moisture sources/sinks in reference volume ( $\text{kg}/\text{m}^3 \cdot \text{s}$ ),  $j_{\text{conv}}$  is convective flux ( $\text{kg}/\text{m}^2 \cdot \text{s}$ ),  $j_{\text{diff}}$  is diffusive flux ( $\text{kg}/\text{m}^2 \cdot \text{s}$ ),  $m$  is mass,  $v$  is vapor,  $w$  is water, and  $i$  is ice. The energy balance is expressed according to Equation (2):

$$\frac{\partial}{\partial t} \rho_{\text{REV}}^U = -\frac{\partial}{\partial x} [j_{\text{diff}}^Q + u_l \cdot j_{\text{conv}}^m + u_g \cdot j_{\text{conv}}^m + h_v \cdot j_{\text{diff}}^m + h_{\text{voc,g}} \cdot j_{\text{diff}}^m] + \sigma_{\text{REV}}^U \quad (2)$$

where  $\rho_{\text{REV}}^U$  is the internal energy density in reference volume ( $\text{J}/\text{m}^3$ ),  $\sigma_{\text{REV}}^U$  is energy sources and sinks in reference volume ( $\text{W}/\text{m}^3$ ),  $j_{\text{diff}}^Q$  is heat conduction ( $\text{W}/\text{m}^2$ ),  $j_{\text{conv}}$  is convective flux ( $\text{kg}/\text{m}^2 \cdot \text{s}$ ),  $j_{\text{diff}}$  is diffusive flux ( $\text{kg}/\text{m}^2 \cdot \text{s}$ ),  $m$  is mass,  $g$  is gas,  $v$  is vapor,  $l$  is liquid,  $u$  is specific internal energy ( $\text{J}/\text{kg}$ ),  $h_v$  is the specific enthalpy of water vapor ( $\text{J}/\text{kg}$ ),  $h_{\text{voc,g}}$  is the specific enthalpy of gaseous volatile organic compounds ( $\text{J}/\text{kg}$ ).

To calibrate the calculation model in Delphin software program, field measurements were conducted in a concrete large panel apartment building renovated in 2017 by using prefabricated timber frame insulation elements [42,43]. Temperature and relative humidity were measured at one-hour intervals before, during and after the renovation at different points of the external envelope with temperature and relative humidity sensors Rotronic HygroClip SC05:  $\emptyset 5 \times 51 \text{ mm}$ , measurement range  $-40$  to  $+100 \text{ }^\circ\text{C}$  and  $0$ – $100\%$ , accuracy  $\pm 0.3 \text{ }^\circ\text{C}$  and  $\pm 2\%$ . Air and surface temperatures were measured with HOBO TMC6-HD temperature/relative humidity/2 external channel data loggers U12-013: measurement range from  $-20$  to  $+70 \text{ }^\circ\text{C}$ , accuracy  $\pm 0.35 \text{ }^\circ\text{C}$ . A good agreement between the measured data and the calculated values was achieved (see Figure 3).



**Figure 3.** Measured and calculated temperature  $t$  (a) and relative humidity  $RH$  (b) in the timber frame insulation element, in points 4 and 6. See Figure 1 for the measurement points P4 and P6.

#### 2.4. Assessment of Hygrothermal Performance

To assess the hygrothermal performance of the building envelope, the risk of mold growth as criterion was used. A mathematical model for the calculation of mold growth and decline and the mold index in varying conditions [44,45] was used in this research.

According to this model, under fluctuating humidity conditions, the total exposure time for the response of growth of mold fungi is affected by the time periods of high and low humidity conditions, as well as the humidity and temperature levels. In the simulation of mold growth, it is crucial to know the lowest (threshold) levels at which fungal growth is possible on different materials. The importance of the duration of such conditions is also significant. There are certain minimum and maximum levels for the moisture content of material, water activity or temperature between which fungi can grow in wood. Under these favorable conditions, mold growth may start and continue at different rates. The time period needed for the onset of mold growth and growth intensity are mainly dependent on water activity, temperature, exposure time and surface quality of the substrate [44,45]. The boundary curve for the risk of mold growth in the range of temperature between 5 and 40 °C on a material can be described by a polynomial function, see Equation (3):

$$RH_{\text{crit}} = \begin{cases} -0.00267 \cdot t^3 + 0.16 \cdot t^2 - 3.13 \cdot t + 100 & \text{when } t \leq 20 \text{ }^\circ\text{C} \\ RH_{\text{min}} & \text{when } t > 20 \text{ }^\circ\text{C} \end{cases} \quad (3)$$

where  $t$  is temperature (°C) on the investigated material surface and  $RH_{\text{min}}$  represents the minimum level of relative humidity (%) at which mold growth is possible (varies according to the sensitivity of the material, see Table 3) [45].

**Table 3.** Mold growth sensitivity classes, some corresponding materials and  $RH_{\text{min}}$  values [45].

Sensitivity Class	Materials	$RH_{\text{min}}$
Very sensitive	Untreated wood, sapwood	80%
Sensitive	Glued wooden boards, polyurethane (PUR) with paper surface, planed pine and planed spruce	80%
Medium resistant	Concrete, aerated and cellular concrete, glass wool, polyester wool	85%
Resistant	PUR polished surface	85%

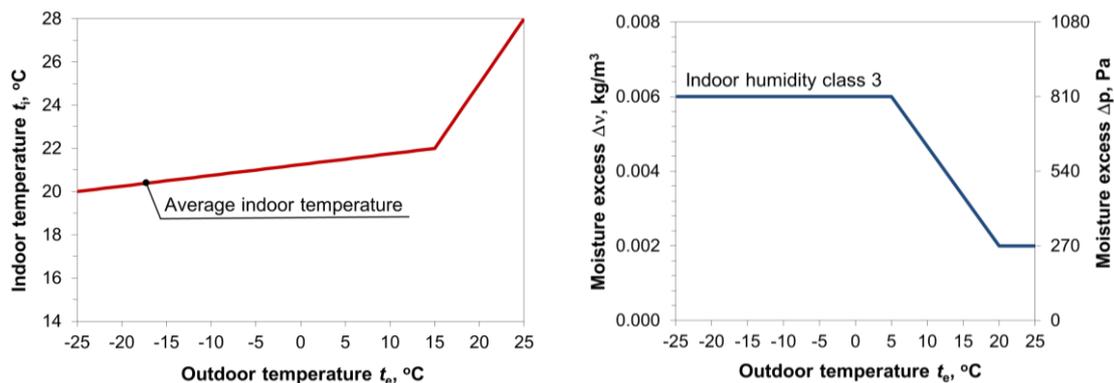
The safe value of the mold index ( $M$ ) was set in the current study at  $M < 1$  (no mold growth) and the critical value at  $M = 2$  (several local mold growth colonies on surface) according to the mold index model (see Table 4). Therefore, the mold index  $1 \leq M < 2$  is considered as a low risk of mold growth (small amounts of mold on surface, initial stage of growth) [46]. The mold growth sensitivity class (see Table 4) ‘sensitive’ for the used timber, timber-based materials and gypsum board with paper in the installed prefabricated insulation elements and in the existing envelope was assigned for calculations. For the other materials, the class ‘medium resistant’ was set.

**Table 4.** Description of mold indexes [45].

Mold Index ( $M$ )	Description of Mold Growth
0	No growth
1	Small amounts of mold on surface (microscope), initial stage of local growth
2	Several local mold growth colonies on surface (microscope)
3	<10% coverage, or <50% coverage of mold (microscope)
4	10–50% coverage, or >50% coverage of mold (microscope)
5	Plenty of growth on surface, >50% coverage (visual)
6	Heavy and tight growth, coverage about 100%

## 2.5. Climate Conditions

According to the Köppen-Geiger climate classification [47], Estonia belongs to cold (continental) humid climate with warm summers (Dfb). In the assessment of hygrothermal risks, the hourly data of the moisture reference year (MRY), critical to mold growth and water vapor condensation in Estonia, was applied to outdoor climate [48]. Indoor climate measurements from Estonian dwellings [49,50] were used to determine critical indoor hygrothermal conditions. For simulations, the following conditions were used: average indoor temperature, which is dependent on the outdoor temperature and indoor humidity class 3 (moisture excess  $2 \leq \Delta v \leq 6 \text{ g/m}^3$  depending on outdoor temperature), representing dwellings with a high humidity load and high occupancy according to the national annex of standard [51], see Figure 4.



**Figure 4.** Dependence of indoor temperature (left) and design value of moisture excess (right) on the outdoor temperature.

As the hygrothermal performance of constructions is highly dependent on their moisture content [14,52], calculations of mold index with different initial moisture content levels of the original wall ( $w = 85 \text{ kg/m}^3$ ,  $w = 95 \text{ kg/m}^3$ ,  $w = 110 \text{ kg/m}^3$ ) were performed to represent the critical conditions of various periods of the start of installation works of the prefabricated timber frame insulation elements onto the existing envelope at the building site.

## 2.6. Energy Performance

As in many countries, including Estonia, the energy performance of buildings is defined as an indicator, expressed as energy performance value (EPV) ( $\text{kWh}/(\text{m}^2 \cdot \text{a})$ ), of the total energy delivered into the building (i.e., heating, ventilation and air conditioning (HVAC) auxiliary, cooling, ventilation, domestic hot water (DHW), lighting and appliances), multiplied with conversion factors (CF) taking into account the primary energy content and the environmental impact involved (e.g.,  $CF_{\text{electricity}} = 2.0$ ,  $CF_{\text{district heating}} = 0.9$ , and  $CF_{\text{efficient district heating}} = 0.65$ ). It is mandatory to fulfill the local decrees requirements of energy performance [53,54] for new and reconstructed by major renovation buildings. The energy performance criterion for a nZEB renovation ( $\text{EPV} \leq 150 \text{ kWh}/(\text{m}^2 \cdot \text{a})$ ) and for new buildings ( $\text{EPV} \leq 125 \text{ kWh}/(\text{m}^2 \cdot \text{a})$ ) without local electricity production) was taken as the basis for evaluating energy efficiency of the studied solutions. In addition to general energy performance of buildings, the Estonian renovation grant scheme [55] sets the following criteria for renovation of apartment buildings:

- Thermal transmittance of building envelope:
  - $U_{\text{external wall}} \leq 0.20 \text{ W}/(\text{m}^2 \cdot \text{K})$ ;
  - $U_{\text{roof}} \leq 0.12 \text{ W}/(\text{m}^2 \cdot \text{K})$ ;
  - $U_{\text{window}} \leq 1.10 \text{ W}/(\text{m}^2 \cdot \text{K})$ ;

- Installation of mechanical ventilation with heat recovery (MVHR). It means centralized plate heat exchanger or apartment based (plate or rotary thermal wheels heat exchanger) balanced ventilation (efficiency  $\geq 80\%$ ) or exhaust ventilation with heat pump (efficiency  $\geq 60\%$ ). In simulations, MVHR with an efficiency of 75% was used;
- Full renovation of heating system. It means new insulated pipework and hydronic radiators with thermostats, DHW system and heating unit.

Energy performance of potential renovation solutions was modeled using the energy and indoor climate simulation program IDA Indoor Climate and Energy [56]. This software allows the modeling of a multi-zone building, internal and solar loads, outdoor climate, heating and ventilation systems, and dynamic simulation of heat transfer and airflows. It is validated and the building model is calibrated against field measurements [57]. Input parameters to energy performance simulation were selected according to standard use condition from the Estonian regulations [54]:

- Indoor temperature heating set point 21 °C;
- Air flow rate for apartments with apartment-based air handling units (AHU) 0.42 l/(s·m<sup>2</sup>) and apartments with central AHU 0.5 l/(s·m<sup>2</sup>). Supply air temperature 18 °C;
- Standard use of DHW: 30 kWh/(m<sup>2</sup>·a), i.e., 516 l/(m<sup>2</sup>·a) at  $\Delta T$  50 K;
- Standard use of electricity: for appliances and lighting 29.5 kWh/(m<sup>2</sup>·a); for circulation pumps 0.5 kWh/(m<sup>2</sup>·a);
- Internal heat gains: occupants 15.8 kWh/(m<sup>2</sup>·a) with a usage rate 0.6 (representing average occupancy 28.3 m<sup>2</sup> per person); appliances and equipment: 15.8 kWh/(m<sup>2</sup>·a) with usage rate 0.6; lighting 7.0 kWh/(m<sup>2</sup>·a) with a usage rate 0.1.

### 2.7. Cost Efficiency

The global cost calculations were applied to assess the cost effectiveness of the renovation measures [58]. The renovation cost was calculated considering financing with loan in the amount of 85% and with self-financing of 15%, which is a common practice required by banks and the renovation grant organization in Estonia for renovation projects of apartment buildings. The typical interest rate of 3% for apartment owners' associations was applied and the escalation of the delivered energy and maintenance prices was considered 1% in a year as an average [59]. The energy prices used in calculations were 0.12 €/kWh for electricity and 0.06 €/kWh for district heating, as an average market level in 2019 in Estonia. The discount period 20 years as the longest loan period for apartment owners' associations in Estonia was applied. Global cost was calculated according to Equation (4):

$$C_g(\tau) = \frac{C_i + \sum_{i=1}^{20} C_{a,i}(j) \times R_d(i)}{A_{\text{floor}}} - \frac{C_g^{\text{ref}}}{A_{\text{floor}}} \quad (\text{€/m}^2) \quad (4)$$

where  $C_g(\tau)$  is the global cost referred to the starting year (€/m<sup>2</sup>),  $C_i$  is the initial investment cost, self-financing of a renovation loan (€),  $C_{a,i}(j)$  is the annual cost of year  $i$  for the component  $j$ , energy and loan payback cost (€),  $R_d(i)$  is the discount rate for year  $i$ ,  $C_g^{\text{ref}}$  is the global cost of the reference building (€), and  $A_{\text{floor}}$  is the net floor area (m<sup>2</sup>).

To obtain the realistic costs for construction, installation and maintenance, the comprehensive cost estimations were taken as basis from three companies producing and installing prefabricated timber frame elements. The average initial cost of their offers was used in cost efficiency calculations.

## 3. Results

### 3.1. Hygrothermal Performance of Prefabricated Insulation Elements

Mold index  $M$  was calculated in critical points (see Figure 1) for all sets studied. Results are shown in Tables 5 and 6 where the mold index  $M$  is given at the most critical points at different initial moisture content (IMC) levels of the existing original wall with installed prefabricated insulation elements.

**Table 5.** Results of calculation of mold index  $M$  of wall constructions with MW. IMC of existing concrete wall  $w = 85 \text{ kg/m}^3$  ( $u = 3.7\%$ ),  $w = 95 \text{ kg/m}^3$  ( $u = 4.1\%$ ),  $w = 110 \text{ kg/m}^3$  ( $u = 4.7\%$ ). See Table 1 for description of layers D1–D5.

Wind Barrier Layer	Frame Thickness (Layer C1) IMC ( $\text{kg/m}^3$ )	Mold Index $M$ (Green, Yellow, Red) at the Most Critical Points (4 or 6)								
		C1 = 120 mm			C1 = 145 mm			C1 = 195 mm		
		85	95	110	85	95	110	85	95	110
D1	With air and vapor barrier B1 (0.2 m at RH 85% $\leq S_d \leq$ 5 m at RH 20%)	4	4	4	4	4	4	4	4	4
D2		4	4	4	4	4	4	4	4	4
D3		4	4	4	4	4	4	4	4	4
D4		4	4	4	4	4	4	4	4	4
D5		4	4	4	4	4	4	4	4	4
D1	Without vapor barrier B2	6	6	6	6	6	6	6	6	6
D2		6	6	6	6	6	6	6	6	6
D3		4	4	4	4	4	4	4	4	4
D4		6	6	6	6	6	6	6	6	6
D5		4	4	4	4	4	4	4	4	4
D1	With air and vapor barrier B3 ( $S_d \geq 50 \text{ m}$ )	4	4	4	4	4	4	4	4	4
D2		4	4	4	4	4	4	4	4	4
D3		4	4	4	4	4	4	4	4	4
D4		4	4	4	4	4	4	4	4	4
D5		4	4	4	4	4	4	4	4	4

**Table 6.** Results of calculation of mold index  $M$  of wall constructions with CW. IMC of existing concrete wall  $w = 85 \text{ kg/m}^3$  ( $u = 3.7\%$ ),  $w = 95 \text{ kg/m}^3$  ( $u = 4.1\%$ ),  $w = 110 \text{ kg/m}^3$  ( $u = 4.7\%$ ). See Table 1 for description of layers D1 ... D5.

Wind Barrier Layer	Frame Thickness (Layer C2) IMC ( $\text{kg/m}^3$ )	Mold Index $M$ (Green, Yellow, and Red) at the Most Critical Points (4 or 6)								
		C2 = 120 mm			C2 = 145 mm			C2 = 195 mm		
		85	95	110	85	95	110	85	95	110
D1	With air and vapor barrier B1 (0.2 m at RH 85% $\leq S_d \leq$ 5 m at RH 20%)	4	4	4	4	4	4	4	4	4
D2		4	4	4	4	4	4	4	4	4
D3		4	4	4	4	4	4	4	4	4
D4		4	4	4	4	4	4	4	4	4
D5		4	4	4	4	4	4	4	4	4
D1	Without vapor barrier B2	6	6	6	6	6	6	6	6	6
D2		6	6	6	6	6	6	6	6	6
D3		4	4	4	4	4	4	4	4	4
D4		6	6	6	6	6	6	6	6	6
D5		4	4	4	4	4	4	4	4	4
D1	With air and vapor barrier B3 ( $S_d \geq 50 \text{ m}$ )	4	4	4	4	4	4	4	4	4
D2		4	4	4	4	4	4	4	4	4
D3		4	4	4	4	4	4	4	4	4
D4		4	4	4	4	4	4	4	4	4
D5		4	4	4	4	4	4	4	4	4

- Numbers 4 and 6 indicate the most critical points (see Figure 1):
  - Point 4 – between original wall and air and vapor barrier layer;
  - Point 6 – between wind barrier and insulation layer of prefabricated element;
- Mold index is categorized by colors:
  - Green – no mold growth risk,  $M < 1$ ;
  - Yellow – minor mold growth risk,  $1 \leq M < 2$ , i.e., small amounts of mold on surface (microscope), initial stage of local growth;

- o Red – high mold growth risk,  $M \geq 2$ , i.e., several local mold growth colonies on surface (microscope).

Results of calculations of mold indexes show that all analyzed combinations with vapor barrier with varying vapor resistance (see Table 1, position B1) or without air and vapor barrier layer (position B2) are below the critical limit ( $M = 2$ ) of mold growth risk. Minor mold growth risk ( $1 \leq M < 2$ ) is in constructions insulated with MW when a sheathing membrane (position D1) or gypsum board with a sheathing membrane (position. D2) as the wind barrier layer was applied. Also, with fiber cement board (position D3) and wood fiberboard (position D4) as wind barrier layers on higher insulation thicknesses and with the initial moisture content of the original concrete wall  $w \geq 95 \text{ kg/m}^3$  minor mold growth risk was determined. With CW some mold growth risks are noticeable with wind barriers positions D1, D2, and D3 when the initial moisture content of the original concrete wall  $w \geq 95 \text{ kg/m}^3$  and in case of higher thicknesses of insulation without an air and vapor barrier layer (position B2). All analyzed combinations with PE-foil (position B3) are beyond the critical limit of mold growth risk ( $M \geq 2$ ) and therefore cannot be used in these structures. From the perspective of hygrothermal performance, MW board of  $\geq 30 \text{ mm}$  thickness with a special wind barrier facing is the best choice for wind barrier.

### 3.2. Energy Performance

The annual energy use of the reference apartment building with a total heated area of  $2968 \text{ m}^2$  was calculated with different sets of the external wall insulation elements following criteria for renovation measures of the grant scheme [55]. The calculations were based on the IDA Indoor Climate and Energy [56] simulation program results for the reference building. The variation of total delivered energy to the renovated building with well insulated external walls is up to  $\pm 2\%$ , see Table 7. The variation is relatively small because the building envelope is already well insulated and thus, energy for space heating is one of the smallest components of energy use.

**Table 7.** Influence of thermal transmittance of external walls on the use of delivered energy by the apartment building.

Thermal Transmittance of the External Walls $U_e$ , $\text{W}/(\text{m}^2 \cdot \text{K})$	Delivered Energy, $\text{kWh}/(\text{m}^2 \cdot \text{a})$						Total
	Space Heating	Heat		Equipment	Electricity		
		MVHR	DHW			Fans, Pumps	Lighting
0.22	14.0	16.9	33.3	22.5	10.5	7.0	104
0.21	13.7	16.9	33.3	22.5	10.5	7.0	104
0.20	13.4	16.8	33.3	22.5	10.5	7.0	104
0.19	13.1	16.8	33.3	22.5	10.5	7.0	103
0.18	12.8	16.7	33.3	22.5	10.5	7.0	103
0.17	12.5	16.6	33.3	22.5	10.5	7.0	103
0.16	12.2	16.6	33.3	22.5	10.5	7.0	102
0.15	11.9	16.5	33.3	22.5	10.5	7.0	102
0.14	11.7	16.5	33.3	22.5	10.5	7.0	101
0.13	11.4	16.4	33.3	22.5	10.5	7.0	101

The primary energy use depends mostly on the efficiency of district heating (the most typical heat source for apartment buildings in Estonia). After the renovation and with efficient district heating (i.e.,  $CF_{\text{efficient district heating}} = 0.65$ ) the apartment building fulfills the nZEB requirements for the new buildings [53] and with the common district heating (i.e.,  $CF_{\text{district heating}} = 0.9$ ) the nZEB requirements for major renovation. The results obtained contain a reasonable reserve for unforeseen energy use (e.g., user's influence), see Table 8.

**Table 8.** Influence of the heat source on the use of primary energy by the apartment building.

Thermal Transmittance of the External Wall $U_c$ , $W/(m^2 \cdot K)$	Primary Energy Use, kWh/(m <sup>2</sup> ·a)					
	Efficient District Heating			Common District Heating		
	Heat (CF = 0.65)	Electricity (CF = 2.0)	Total	Heat (CF = 0.9)	Electricity (CF = 2.0)	Total
0.22	41.8	80.1	122	57.8	80.1	138
0.21	41.5	80.1	122	57.5	80.1	138
0.20	41.3	80.1	121	57.2	80.1	137
0.19	41.1	80.1	121	56.9	80.1	137
0.18	40.8	80.1	121	56.5	80.1	137
0.17	40.6	80.1	121	56.2	80.1	136
0.16	40.4	80.1	120	55.9	80.1	136
0.15	40.2	80.1	120	55.6	80.1	136
0.14	39.9	80.1	120	55.3	80.1	135
0.13	39.7	80.1	120	55.0	80.1	135

### 3.3. Cost Analysis

The unit prices of prefabricated insulation elements include production, transport, and installation costs are seen in Table 9. The unit prices of elements with different wind barrier layers (see Table 9, positions D1–D5) are given without the prices of facade system materials. The cost of facade systems (see Table 10, positions F1–F6) is given separately with maintenance cost and maintenance interval for each facade material type (per 1 m<sup>2</sup> of facade).

**Table 9.** Unit prices of prefabricated timber frame insulation elements with different insulation (MW, CW) and wind barrier materials (D1–D5) without facade materials. See Table 1 for description of layers D1 ... D5.

Wind Barrier Layer	Unit Price of Element, €/m <sup>2</sup> (Frame Thickness, Layer C1 or C2)					
	120 mm		145 mm		195 mm	
	MW	CW	MW	CW	MW	CW
D1	88	85	90	87	96	93
D2	93	90	95	92	101	98
D3	96	93	98	95	105	102
D4	98	95	100	97	107	104
D5	100	97	102	99	108	105

**Table 10.** Unit prices, maintenance cost and intervals of maintenance of facade systems of the prefabricated elements. See Table 1 for description of layers F1–6.

Facade System	Unit Price of Facade, €/m <sup>2</sup>	Maintenance Cost, €/m <sup>2</sup>	Maintenance Interval, Years
F1	18	15	15
F2	22	5	15
F3	35	15	15
F4	54	5	25
F5	55	5	25
F6	56	15	20

The total initial cost (production, transport, installation) of insulation elements varies between 101 and 164 €/m<sup>2</sup>. The selection of the facade system has the highest influence on the total initial cost: ±13%–15%. The selection of the wind barrier influences the total initial cost by ±5%–6% and the insulation material by ±1%.

Table 11 presents the change of global cost (initial cost + energy saving + annual average maintenance during 20 years after renovation (i.e., during renovation loan payback period) divided by the building's net heated area). As the influence of insulation materials cost was very small, Table 11

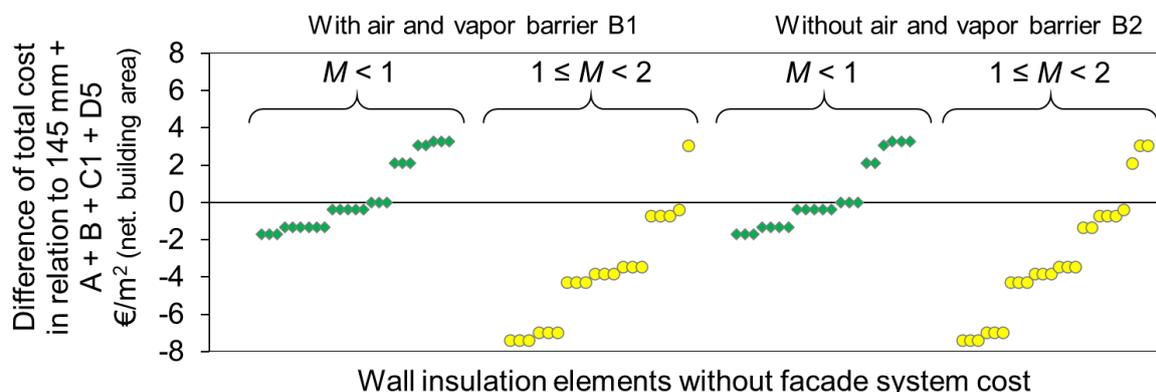
presents the results of sets with MW insulation only. Results are presented as the cost difference compared to the insulation element with 145 mm framing with 50 mm buffering insulation layer (see Table 1, position A) + air and vapor barrier (position B1) + MW insulation (position C1) + 30 mm MW wind barrier (position D5) + wooden boarding as facade system (positions E + F1). By combining moisture safety (Table 5) and total cost (Table 11) we can see that decreasing the total cost increases the risk of mold growth. Insulation elements with some mold growth risk ( $1 \leq M < 2$ ) were cheaper than solutions without mold growth ( $M < 1$ ) ( $p < 0.0001$  according to T-Test).

**Table 11.** Difference between the cost of insulation elements in relation to the set: framing 145 mm + A + B1 + C1 + D5 + E + F1. See Table 1 for description of layers A–F.

Wind Barrier Layer	Difference of Total Cost, €/m <sup>2</sup> (Net Building Area)																	
	Frame Thickness 120 mm						Frame Thickness 145 mm						Frame Thickness 195 mm					
	F1	F2	F3	F4	F5	F6	F1	F2	F3	F4	F5	F6	F1	F2	F3	F4	F5	F6
D1	-7	-11	5	10	11	17	-7	-11	5	10	11	17	-4	-8	8	13	14	20
D2	-4	-8	8	13	14	21	-3	-7	9	14	15	21	-1	-5	11	17	17	24
D3	-2	-6	10	16	16	23	-1	-5	11	16	17	23	2	-2	14	19	20	27
D4	-1	-5	11	16	17	23	0	-4	12	17	18	24	3	-1	15	20	21	27
D5	0	-4	12	17	18	24	0	-4	12	17	18	24	3	-1	15	21	21	28

- Mold index is categorized by colors:
  - o Green—no mold growth risk,  $M < 1$ ;
  - o Yellow—minor mold growth risk,  $1 \leq M < 2$ , i.e., small amounts of mold on surface (microscope), initial stage of local growth.

As the facade cladding does not essentially influence the mold growth risk in the critical points, at the same time having a noticeable contribution to the total cost, the cost difference was compared without the facade system in the same way as shown in Table 11. The results in Figure 5 indicate that combinations with lower cost pose relatively higher mold growth risk.



**Figure 5.** Influence of changing the total cost on the risk of mold growth without the contribution of facade systems to the cost of prefabricated element.

### 3.4. Installation and Handling Analysis

Ideas of energy renovation of old apartment buildings to the nZEB level [42,43] and answers to interviews with production companies, installation contractors, as well observations of analysis of renovation prospects with prefabricated elements, point out the most relevant problems and give guidelines for future research and development.

Accuracy of predesign and pre-installation measurements (e.g., geodesy, point-cloud, and 3D model) are crucial for a streamlined production and installation of elements because these reveal all possible deviations of openings and roughness of the original wall surface in all directions. The design

of and construction works at the pilot building verified the importance of precise data about envelope roughness because the surface deviations both in vertical and horizontal directions were up to  $\pm 50$  mm. Therefore, designed hanging brackets for elements should have an adjustable clearance allowing regulation of the elements in all directions during the installation to minimize the risk of time-consuming remounting of brackets in case of measurement inaccuracies.

The buffering layer has to be a light and compressible (flexible) material (e.g., MW,  $\rho < 20$  kg/m<sup>3</sup>) allowing the element to be safely pressed towards the uneven original surface and to be fixed to the load-bearing brackets while it hangs on the crane hooks and workers are standing in the high forklift basket. On the pilot building it was clearly seen that in some places the installers had quite some difficulties with pressing the element tightly to the original surface because of the variations of the surface level. Lighter MW as the buffering layer and brackets with greater adjustment clearance could help out.

Water and air tightness of horizontal joists between the elements was difficult and time-consuming to achieve as the elements are supported on a wall by each intermediate floor. Fastening of elements in the vertical direction is safer and allows designing and finishing larger gaps between elements. However, in this case, the mistakes from construction tolerances are transmitted and large differences in sizes can occur because of the existing wall roughness and irregularity.

Use of a traverse for lifting long and heavy elements by crane helps to avoid bending out or breaking an element but it can be impeded if the building has roof eaves stepping out of the wall perimeter. In that case, a forklift with a special lifting and supporting frame could be a solution. Or else, the solution could be to remove part of the roof and eaves temporarily. However, this is again an additional risk of rainwater overflow and moisture damage during construction works and needs an extra investment to prepare and remount the roofing.

Use of continual protective tarpaulins or tents on the existing envelope is obstructed because the crane or forklift must have access to wall surfaces to lift and fix the elements. Prefabricated elements must be packed to a protective foil firmly already at the factory so as to ensure their safe transport and installation without moisture impairments. The protective foil has to be removed only after the element is installed.

These are the important aspects of moisture safety and building technology that have to be analyzed, explained, and agreed upon in the contracting phase and controlled by a moisture safety expert and the owner's surveillance engineer during the installation works.

#### 4. Discussion

The research task was to find among results obtained combinations that are most consistent with requirements of the nZEB renovation (new buildings and major renovation), considering possible hygrothermal risks and costs. Earlier studies [60–62] confirm that for deep renovation of existing external envelopes the most proper solutions are with insulation layers with low water vapor resistance (both for main insulation and wind barrier layers) and vapor barriers/retarders with varying vapor resistance capability. Solutions where the vapor resistance of the outer layer is higher and with a lower thermal resistance (e.g., sheathing membrane, strand board, or gypsum board) compared to MW or CW may cause excess humidity accumulation, which in turn might cause a higher mold growth risk with envelope degradation. It was concluded hereinbefore that in addition to energy performance it is necessary to pay special attention to moisture safety measures in the design and building processes of highly insulated buildings.

High thermal resistance and water vapor permeability of the wind barrier are key components of a well-functioning building envelope. This is validated by the results of calculations of mold index indicating a rise of mold growth risk with increasing vapor resistance of the outer layer of elements (e.g., sheathing membrane vs. MW board) and with greater insulation thickness (i.e., with the decrease of temperature and the corresponding increase of *RH* in external layers of the structure). Nevertheless, cement fiberboard gave better results in some cases compared to wood fiberboard wind barrier (although it has lower water vapor permeability and thermal resistance) because of its larger

mold tolerant surface. Comparison of the use of MW and CW showed that owing to the relatively high moisture buffering capacity of CW, constructions insulated with it can withstand much higher moisture loads without substantial mold growth risk. It has been verified by other research as well [63]. Nevertheless, in case of greater thicknesses of insulation and lower water vapor permeability of surface layers, the risk of mold growth may rise with CW insulation as well.

In the renovation of the existing buildings with prefabricated insulation elements it is very important to take into consideration that the use of a vapor barrier layer with very high vapor resistance (e.g., PE-foil) may cause accumulation of built-in moisture between the original wall and the installed vapor-tight layer of the insulation element and lead to the condensate state there for a very long time (according to our studies, even up to 4–5 years) [52]. On the other hand, the decision to give up the use of a vapor control layer between the existing envelope and the installed element may result in moisture damage and mold growth related problems, particularly in the case of the moisture content of the original wall is close to saturation level (e.g., rainy periods in late summer or in autumn may cause the original wall's external layer to become very wet, up to  $RH = 100\%$  because of wind-driven rain) and/or when the water vapor resistance of the outer layer of an element (e.g., wind barrier) is too high to let the built-in moisture dry out as fast as necessary for satisfactory hygrothermal performance of the whole system [64]. This can be seen in Tables 5 and 6, where combinations without a vapor barrier layer show a higher mold growth risk compared to solutions with a vapor barrier layer, particularly in the area behind the wind barrier layer. The reason here is the higher  $RH$  in critical points due to the moisture flux, which is more intensive in the structure without a vapor control layer between the original (and usually with a high content of built-in moisture) wall and the installed insulation elements.

It is very important to point out that the differences in calculated mold indexes presented are caused also by the different mold growth sensitivity classes applied for materials. Furthermore, the considered critical points were different when solutions with and without air and vapor barrier layers were compared. With air and vapor barriers (see Table 1, positions B1 and B3) the highest moisture load is in points P4 and P5 but with alternative without vapor barrier layer (see Table 1, position B2) the highest loads are in points P6 and P7 (see Figure 1 for analyzed points).

Therefore, if there are technological obstacles or other justified reasons for not to use a vapor barrier (control) layer between the original wall and the prefabricated timber frame insulation elements, it is crucial to reconsider the mold growth sensitivity class of wood or wood-/cellulose-based products with a high content of nutrients favorable for fungal growth. Because of the higher moisture flow in the absence of a vapor control layer in the direction from the original wall towards the prefabricated timber frame element, in the case of the use of untreated wood (e.g., not planed, pine or spruce sapwood) the mold growth sensitivity class 'very sensitive' should be assigned to the surfaces of timber details. In a cold and humid climate this will lead to a mold index  $M \geq 2$ , i.e., mold formation risks are considerably high. A strict recommendation is that a vapor control layer with varying vapor permeability (e.g., 0.2 m at  $RH 85\% \leq S_d \leq 5$  m at  $RH 20\%$ ) should be used while the use of vapor barrier products with high vapor resistance (e.g., PE-foil,  $S_d \geq 50$  m) should be avoided to keep the moisture flow controlled when additional insulation elements are installed on top of the existing moist external envelope. It is in a good agreement with and was well studied and described in our past research as well [14,52,65].

Our results showed that mold growth is avoidable and MW wind barrier board, wood fiberboard, or cement fiberboard are the preferred materials. From the production perspective, a rigid wind barrier (wood fiberboard and cement fiberboard) is preferable due to easier and quicker installation procedures. Nevertheless, these wind barriers might not be suitable if the moisture content of the original facade is high. Construction practice has shown that it is impossible to wait for better weather and to dry out the facade. Therefore, the insulation element should include a safety factor, and MW wind barrier board is the best solution because of its high water vapor permeability and thermal resistance.

Blowing in loose-fill cellulose wool (CW) is a typical method of insulation. To prevent the settling of the insulation layer of CW, the density of loose-fill insulation in walls should be much higher than commonly assumed for attics. Rasmussen [66] argued that to prevent settling the density of loose-fill

CW insulation in the wall should be  $\rho \geq 65\text{--}75 \text{ kg/m}^3$  to compensate for any humidity cycling and creep. However, he did not consider the vibration due to transportation (which is unavoidable for prefabricated insulation elements). Therefore, the density of loose-fill insulation for prefabricated insulation elements should be much higher than for attics. Higher density requires more material, resulting in higher cost and heavier elements.

Building contractors and producers of insulation elements have given critical feedback about the design and installation of insulation elements. The most objective and practical of them stress indispensable need for a pre-installation phase: well-prepared measurement of the existing situation and translation of the results into detailed and precise design documentation. Clients and moisture safety experts point out the importance of how materials are handled during transportation to the building site and especially during the ongoing works under changing and challenging weather conditions. The use of protective foils, pallets, and well-planned precautionary actions before precipitation is a must to avoid later problems with moisture damage, degradation of structures, and unsatisfactory indoor climate.

Facade cladding choices (e.g., wooden or plastic boarding/siding, metal profile sheets, cement fiberboards, facade stone cladding, etc.) are rather made by personal preferences of each customer. The preferred materials are dissimilar in unit price as well as mounting and maintenance costs. However, these costs may account for a large proportion of the total renovation budget. Therefore, circular use of materials could be one way of reducing the cost of facade cladding.

In comparison of the energy performance on the basis of variation of total delivered energy we can see that differences were relatively small because the energy for space heating was one of the smallest components of total energy use. However, it is important to see that in calculations indoor temperature set point was  $21 \text{ }^\circ\text{C}$ . It was shown by preceding studies [67–69] that indoor temperature set point used is higher, typically  $22 \text{ }^\circ\text{C}$  for post-renovation situation. That a  $1 \text{ }^\circ\text{C}$  rise will affect the amount of delivered energy for space heating in average +33%, EPV for +1.2–+1.4% and the global cost for +1.0–+1.3%.

Compared to conventional solutions of energy refurbishment (e.g., ETICS or analogues), the cost level of the analyzed prefabricated elements for the end-user is still slightly higher (about  $101\text{--}164 \text{ €/m}^2$ ). The current market prices of the ETICS with expanded polystyrene (EPS) insulation are around  $90\text{--}100 \text{ €/m}^2$  and with rendered MW around  $100\text{--}120 \text{ €/m}^2$ . This cost difference together with some shortage of expertise of participants is described also by other researchers as the main reason why prefabricated insulation elements are not yet in a competitive market position [70,71]. Renovation activity must be increased to a very large extent to fulfill EU decarbonization targets. Estonian practice has shown [72] that increased renovation volumes create new problems such as shortage of contactors, construction workers, and construction materials, which results in increased renovation costs. The ETICS and other rendering methods have been on the market already for many decades without moving forward towards industrialized production. The main way to increase the efficiency and reduce the cost is to raise the automation level and to find means of unification of products for faster design, mass production and installation. Other industries have shown that industrialization and mass production decrease the costs. Therefore, the prefabricated elements will obviously have cost advantages in the future.

## 5. Conclusions

A complex method of analysis and selection to find the most appropriate set of prefabricated insulation elements for major renovation of apartment buildings was introduced in this research. The most consistent sets, based on hygrothermal performance, handling and production characteristics and reasonable cost, were presented.

Mineral wool board with special wind barrier facing is the best material for wind barriers from the perspective of hygrothermal performance. In cold and humid climates PE-foil cannot be used as an air and vapor barrier layer in prefabricated insulation elements as it does not allow constructional

moisture to dry out and causes condensation and mold growth. Compared to mineral wool, cellulose insulation has advantages concerning hygrothermal performance, but its installation density should be high ( $\rho \geq 65 \text{ kg/m}^3$ ) to avoid settling due to humidity cycling, creep, and vibration on transportation from the production facilities to the building site.

The variation of thermal transmittance of a well-insulated external wall has minor influence on the energy performance of the building. It is possible to renovate an apartment building to correspond to the new building nZEB level with efficient district heating and to fulfill the nZEB requirements for renovation in the case of common district heating being used.

Cost analyses showed that materials affecting moisture safety and energy performance do not influence the total cost too much. Therefore, it is possible to select the best materials from the perspective of hygrothermal and energy performance without increasing the renovation price noticeably. The facade cladding had the highest influence on the initial cost of the insulation element ( $\pm 13\%$ – $15\%$ ). This means that the materials having the greatest effect on the hygrothermal performance of the building envelope have smaller influence on the initial cost. It is possible to guarantee moisture safety without paying a high relative difference cost. Decreasing the global cost of elements would increase the mold growth risk.

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