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Circular Renovation of an Apartment Building with Prefabricated Additional Insulation Elements to Nearly Zero Energy Building

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Abstract

Construction and demolition waste constitute more than one-third of the total waste generated in the European Union. The pursuit of sustainable renovation must progress further to encompass elements that ensure reuse or recyclability. A fundamental transformation, involving extensive renovation and a transition to circular renovation practices, is indispensable in effectively addressing the pressing challenge of decarbonization for the entire building stock in Europe. In this study, we have developed a circular deep renovation solution using prefabricated modular external additional insulation elements to achieve a nearly Zero Energy Building (nZEB). Circular prefabricated modular external additional insulation elements were formulated, manufactured, and installed. The potential for disassembly and reutilization of materials was developed and demonstrated for both a prototype and the complete deep renovation. The analysed prefabricated modular solutions exhibited greater potential for circularity compared to the traditional External Thermal Insulation Composite System (ETICS) due to their superior demountability and reusability characteristics. The overall cost of the renovation, which included the installation of a new heating system, replacement of water and sewer pipes, addition of 50 kW photovoltaic (PV) panels on the roof, installation of new balconies, addition of a balanced ventilation system with heat recovery, and replacement of the electricity system in common areas, amounted to 505 €/m^2. Following the deep renovation, the Energy Performance Value was measured to be 92 kWh/(m^2·a), resulting in an EPC class of A. This implies that the building now meets the requirements for nZEB in accordance with Estonian legislation, with no performance gap.

Keywords: deep renovation; design for disassembly; nZEB; prefabricated insulation element; circular renovation.

Introduction

The European Union has set a significant goal of decarbonizing its building stock (EPBD recast, 2018) is a crucial and multifaceted undertaking, aimed at realizing a carbon-neutral European society. It has been recognized that the built environment accounts for 40% of final energy consumption and 36% of greenhouse gas emissions in the EU. Furthermore, the energy used in the construction phase makes up 50-60% of a building's overall life cycle energy, leading to a substantial burden of embodied CO_2 emissions (Rauf et al., 2015). The construction sector is responsible for over half of all extracted materials in the EU (EC COM 571, 2011), exacerbating the depletion of natural resources and the resulting environmental impacts. To address these challenges, it is

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crucial to adopt renewable energy technologies and promote the reuse and recycling of resources and materials. A comprehensive transformation, encompassing deep renovation and a shift towards circular renovation practices, is essential for tackling the urgent decarbonization challenge facing Europe's building stock (Daly, 2023; Pittau et al., 2019).

One of the most important lessons learned from the "first generation" prefabricated deep renovation pilot projects (Arnesano et al., 2018; Assimakopoulos et al., 2020; Pihelo et al., 2020) that the main barriers related to specific technical solutions (Targo Kalamees et al., 2016; Kuusk et al., 2015), hygrothermal performance (Pihelo et al., 2016; Pinotti et al., 2018), cost effectiveness (Kuusk & Kalamees, 2016; Padula et al., 2018), but deal with the deep renovation and nZEB knowledge, for both the building owners/users (Mjörnell et al., 2014) and for the designers (Kuusk, Kalamees, et al., 2016). Although the multiple benefits of increased energy performance through a holistic renovation approach, including indoor environmental quality, health, well-being, and moisture safety, are widely recognized (Barmparesos et al., 2019; Ilomets et al., 2017), these benefits have not yet been seamlessly integrated into consumer-centric business models. Such integration is crucial to stimulate higher renovation rates, helping to decarbonize the building stock and achieve long-term climate, environmental and energy goals.

Although the Construction Products Regulation (CPR EU 305, 2011) mandates the sustainable utilization of natural resources, including the requirement for the reuse or recyclability of construction works, materials, and components after demolition, the concept of circularity is still in its early stages in the construction industry (Almeida et al., 2022; Dams et al., 2021; Ghaffar et al., 2020; Ossio et al., 2023). Specifically, circularity in renovation is just beginning to gain traction. Therefore, the pursuit of sustainable renovation must progress further to encompass aspects related to ensuring reuse or recyclability. Moreover, upon completion of construction, it is imperative for designers, builders, and end-users to have access to comprehensive data regarding the actual overall performance of the building under practical, real-world conditions. This data should encompass various aspects, including material usage (Sagan et al., 2021; Stephan et al., 2018) , energy performance, indoor environmental quality, moisture safety, and, notably, the health and well-being of occupants within the renovated building. Without such information, the performance gap between the intended and actual targets for high-performance buildings may remain unacceptably wide (Cozza et al., 2019; Hamburg et al., 2020, 2019).

In Estonia, nearly 70% of the population resides in apartment buildings. The country has a total of approximately 22,000 apartment buildings, predominantly constructed between 1960 and 1990. Approximately 14,000 of these buildings require extensive renovation to align with the objective of achieving a carbon-neutral building stock by 2050 (LTRS, 2020). Most of these buildings struggle with common problems such as high energy consumption (Kuusk & Kalamees, 2016), low ventilation (Mikola et al., 2017), uneven indoor temperature (Arumägi et al., 2015) and insufficient thermal comfort, serious thermal bridges (Ilomets et al., 2016). This underscores the urgent need for meticulous and comprehensive deep renovations.

Construction and demolition waste accounts for more than one-third of the total waste generated in the European Union. As the volume of renovation projects increases, there is a potential for a corresponding increase in construction and demolition waste. The adoption of circular practices during renovation projects aims to minimize the amount of waste generated. To enhance the reusability of building materials and components, prefabrication and modularity play a crucial role. In recent years, various projects have comprehensively addressed these aspects, focusing on the development of technological solutions (achieving a Technology Readiness Level of 6 to 7) (Ferrante et al., 2019; Lupisek et al., 2019; Pihelo et al., 2017), as well as overcoming market barriers and devising strategies for engaging end-users (D'Oca et al., 2018). The next step towards sustainable renovation involves considering embodied aspects such as embodied energy and embodied CO_2 (Kertsmik et al., 2023). To guide apartment associations in adopting new solutions, it is crucial to raise awareness and provide effective demonstrations. This study focuses on the development of a circular deep renovation solution for achieving nearly Zero Energy Building (nZEB) standards in cold climates like Estonia. This is accomplished through the utilization of prefabricated modular external additional insulation elements, progressing from Technology Readiness Levels 6 to 9 (Fig. 1).

Fig. 1

Apartment building before (left) and after (right) the circular deep renovation with modular prefabricated additional insulation elements

Methodology

In this study we used different methods for research and development of circular modular prefabricated additional insulation elements.

Circular prefabricated modular external additional insulation elements were developed from levels TRL 6 to TRL 9. Hygrothermal performance was measured by temperature and humidity sensors (Onset HOBO UX100-023A). Thermal bridges' locations were measured with thermography by using FLIR E302 thermal camera. To model the hygrothermal performance of the external walls, simulations with Delphin software (based on (Nicolai, 2008)) were carried out. To calculate the risks of mould growth we used Finnish mould model (VTT et al., 2018). For the simulations, the climate conditions from the Estonian moisture reference year (Targo Kalamees et al., 2004) were applied.

Production and installation, potential for disassembly and reuse of materials were developed and demonstrated for a prototype (TRL 6) and for the full deep renovation (TRL 9). Design for disassembly of product level and system level is assessed using the Alba Concepts Building Circularity Index (Vliet et al., 2015).

Circularity renovation solutions were developed for different purpose:

- Reused or recycled materials added to renovated building;
- Reuse of existing materials from the renovated building in the renovated building;
- Reuse of existing materials from renovated building in other building;
- Recycling of existing materials from renovated building.

Indoor climate (temperature, humidity) was measured from 4 apartments before and after the renovation. Before and after the renovation energy performance (heat use for room heating, ventilation and heating domestic hot water (DHW), electricity use for lighting, appliances, and service systems, and electricity generation from renewable sources (PV panels)) was measured (normal meters installed to building) and modelled (IDA-ICE software).

The organisational structure and development responsibilities were following. TalTech: pre-renovation research of building envelope, indoor climate and energy performance, concept prototype design and measurement conceptual design, life cycle assessment. Timbeco: pre-renovation research of load bearing structures, laser scanning, prototype production and installation, detailed design, life cycle cost, budget management.

Results and discussion

Developing of circular prefabricated modular external additional insulation elements

We analysed the life-cycle cost of various façade insulation solutions (without the cost of the windows), considering the initial cost and maintenance expenses over a period of 50 years, Table 1. The initial cost includes production and installation costs per square meter of façade. Wooden façade cladding requires a new coat of paint every 10-15 years, while ETICS (External Thermal Insulation Composite System) requires a new plaster layer every 15-20 years. Although the initial cost for prefabricated solutions is higher, the total cost over a 50-year life cycle is similar for both prefabricated solutions and ETICS due to the lower maintenance cost of prefabricated solutions.

Table 1 presents Life Cycle Cost (LCC) values without factoring in the influence of inflation and capital costs. Those desiring the LCC result considering inflation and capital costs (which can vary widely) may independently calculate it, using the initial cost as a baseline.

Table 1
Life-cycle cost per facade m² of insulation solutions (including VAT)

	Initial cost, facade €/m²	Maintenance cost, €/m²	Maintenance per 50-year life cycle	Total cost, facade €/m²
Fibre cement wind barrier and fibre cement façade board	151	0	0	151
Fibre cement wind barrier and wooden façade cladding	128	18	3	182
Mineral wool wind barrier and fiber cement façade board	155	0	0	155
Mineral wool wind barrier and wooden façade cladding	132	18	3	186
ETICS – rock wool	86	36	2	158
ETICS – EPS	78	36	2	150

The product and technology research and development started from TRL 6 (Pihelo, 2020). Potential of drying out of the initial moisture from insulated AAC external wall and hygrothermal performance of prefabricated timber frame elements for the additional insulation were analysed and we find the appropriate sets for the major energy renovation of apartment. The best choice of material for a wind barrier based on hygrothermal performance was mineral wool. The mould growth risk was high if the installation starts in the cold and humid season or if vapour barrier layer has too high vapour resistance (e.g. PE-foil, $S_d \geq 50$ m).

We demonstrated the performance of prototype in operational environment (TRL 7) by installing it to the end wall or a 3-storey apartment building (Pihelo et al., 2023). The structure of the prefabricated additional thermal insulation element was based on timber frames (c/c 600 mm) with 195 mm of mineral wool (MW) insulation (layer 4 in Fig. 2, left), where the air and vapor tightness from the inner side was to guaranteed with an air and vapor barrier membrane (layer 5) and covered with a wind barrier layer (layer 3) from the external side. Ventilated air gap (layer 2) with vertical timber battens 28×70 mm contributes to the drying out of built-in moisture, and the facade boarding ensures the weatherproof protection of envelope structures (layer 1). To minimize convection between structures and to fill the gap between the uneven original wall surface and the prefabricated timber frame insulation element, a mineral wool buffer layer with density $\rho = 22$ kg/m³ is anticipated on the back of the prefabricated elements. The designed thermal transmittance of the AAC wall, insulated additionally with prefabricated timber frame insulation elements was $U_{external\ wall} = 0.12–0.14$ W/(m²·K) depending on insulation thickness.

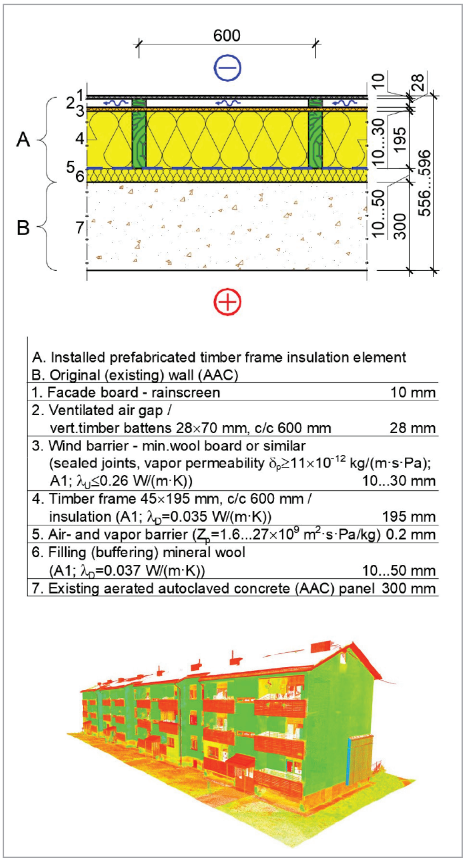


Fig. 2

Horizontal cross-section of existing wall with prefabricated facade insulation element (above). Extract from the point cloud model of the apartment building (below)

Based on field measurements or the wall prototype in operational environment we qualified hygrothermal model for the final stage of the design. As measurements and the modelling results were in good agreement, we may classify the model qualified (TRL 8).

Circularity renovation solutions

On a product level a medium degree of circularity has been achieved. Type and accessibility of connections, crossings and form containment showed high degree of circularity and material use showed low degree of circularity. Analysed prefabricated modular solutions had higher circularity potential than the traditional External Thermal Insulation Composite System (ETICS) due to the low demountability and reusability potential (Kuusk et al., 2022). Multifunctional use of building components and products helps to increase the potential for circularity. The facade elements were designed using circular principles, making it possible for them to be easily dismantled and reused in future renovation projects for similar buildings or in the construction of new apartment building or terraced house, (see Fig. 3 (TRL 2)).

Fig. 3

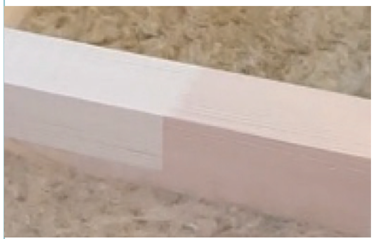
An apartment building (above) and a terraced house (below) solutions that can be built by using circular prefabricated modular external additional insulation elements

A year after installation the prototype insulation elements we demounted them, transported to factory and disassembled there. The target was to identify possible areas of concern to get material for reuse, to analyse what quality and quantity it is possible to get for later reuse. Reusable material was reused to product new insulation. Disassemble the insulation element lasted 70 minutes, while the most time-consuming was the removal of the wind barrier board. Mineral wool was divided according to their condition into three groups: full-size (60 % that can be reused as new product), half-size (35 % that could be used but some waste may be come and air cavities between insulation boards due to non-ideality may increase thermal transmittance of the element (Hallik et al., 2022), and pieces of wool to be recycled (5 % were damaged or too small to be used again) (Kullerkupp, 2022). Considering transportation and work time to demount and disassemble, the price of 45´195 mm wooden planks used in the wooden panel was 6.18 €/m. The price of new material was in 2020 2.83 €/m and in 2022 3.63€/m (Kullerkupp, 2022). In the current case, the element was small, but in the case of larger-scale work, the cost could be lower and become more competitive.

The construction demolition waste generated on the construction site was disposed of in a way that allowed recycling or reusing of the materials, see Table 2.

Table 2

Circular use of materials and components in pilot building renovation

Material	Circularity	Description	Illustration
The use of finger-joined timber for pro-duction of frame of insula-tion elements	Recycled materi-als added to reno-vated building	Finger joints are used to join short wood pieces to form longer units. The joint consists of several adjacent wooden wedges or "fingers" and is held together with glue.	
Old radiators	Reuse of existing components from the renovat-ed building in the renovated building	Old cast iron radiators from apartments were used in stairwells. The radiators were cleaned and sandblasted before being painted. Some of radiators started to leaks after reinstallation	
Plinth paving (concrete)	Recycling of existing materi-als/components from renovated building	Concrete with recycled filler was used to pour the plinth of the building.	
Roof's covering (metal sheets)	Reuse of existing materials from renovated building in other building	The roof sheet removed from the building was reused on the roof of a farmhouse in southern Estonia. About 20 % of the roof sheet was unsuitable for reuse (recycled).	
Old windows	Reuse of existing components from renovated building in other building	The old windows were partially reused in the cottages and garden houses. High thermal transmittance does not allow them in buildings with energy performance requirements	
Reuse of wall prototype's materials	Reuse of existing materials/com-ponents from the renovated build-ing in the reno-vated building	≈95 % of the materials were reusable to a greater or lesser extent	

Production and installation of prefabricated facade elements

Before commencing the renovation project, a pre-renovation study was conducted to examine the structural reinforcements' locations and fastening solutions' stability on the building. The building was laser-scanned, resulting in a point cloud of the apartment building's facade and surroundings (see Fig. 2 right). This data was then used to create a digital 3D baseline model of the building in Autodesk Revit software, providing a foundation for the facade element model's creation.

During the production of the façade elements, 66% of the timber frame and horizontal insulation slats were utilized by gluing together the production scraps using the finger jointing method. The elements were equipped with ventilation pipes, windows, and facade covering material made of mass-painted cement panels combined with hot-oiled wooden cladding.

An external wind barrier and an internal vapor barrier tape were used to install the window. The fastenings of element structures are designed so that these elements can be removed from the walls later and used either for the same purpose on another building or disassembled.

The facade elements were installed using a crane and telescopic boom lifts. The elements were delivered in the installation order and lifted into place Fig. 4 left. Scaffolding was not installed around the building. In the case of a traditional method of reconstruction, the use of scaffolding would have been around the building for 5-6 months.

Fig. 4

The windows were installed and sealed at the factory with vapor barrier tape (left). Ventilation ducts were installed in the facade elements at the factory (right)

Before the installation of the facade elements, the window openings of the living rooms on the south side of the building were made larger and a balcony door was also installed. By closing the balconies on the north side of the building, the surface of the kitchen was increased by 5.2 - 6.7 m², depending on the apartment. The net area of the entire building increased by 134.2 m². New balconies were built on the south side, working partly as sunshades to reduce excessive heat in the rooms (see Fig. 5).

Fig. 5

Milling the window openings larger to fit the window together with the balcony door (left). New balconies on the south side of the building (right)

Duration and cost of renovation

The contract for the deep renovation was initially signed for six months, but due to unforeseen events caused by the COVID-19 pandemic and disruptions in the supply chain, there was a delay of three months. For instance, the delivery of the ventilation unit was delayed by two months, and since the installation of the ventilation units was done through the roof, it was not possible to complete the roof works and PV panel installation.

The design phase for the prefabricated elements took 14 weeks, while the installation of load-bearing steel corners and base timber lasted for two weeks. The installation of timber frame elements, including demolition works and removing of old windows, took a total of eight weeks.

The total cost of the renovation, including the installation of a new heating system, replacement of water and sewer pipes, addition of 50 kW PV panels on the roof, installation of new balconies, addition of a balanced ventilation system with heat recovery, and replacement of the electricity system in common areas, amounted to 505 EUR/(net area m^2) (see Table 3).

The cost of prefabricated insulation elements with installation and new windows was 233 €/(facade m^2) or 166 €/(net area m^2). This cost includes laser scanning, fixing details, crane, boom lifts, removal of old windows, cutting of old balcony slabs, demolition of old kitchen external wall, drilling of new ventilation holes in the existing wall, and cutting in the new balcony doors.

Table 3

Cost of renovation work sections for net area the building (including VAT)

Name of work	Price (€/net area m^2)	Percentage
The cost of prefabricated insulation elements with installation and new windows	166	33%
New ventilation system	46	9%
Replacing heating system	25	5%
Replacing water and sewage system	18	4%
Replacing electricity in common areas	17	3%
New PV panels	18	4%
New balconies	17	3%
Water isolation and insulation of cellar external wall	19	4%
Interior finishing renovation works	48	10%
Replacing the roof covering and attic insulation	44	9%
New main doors	8	2%
Other costs in total: renting equipment, waste utilization etc.	78	15%
Total	505	100%

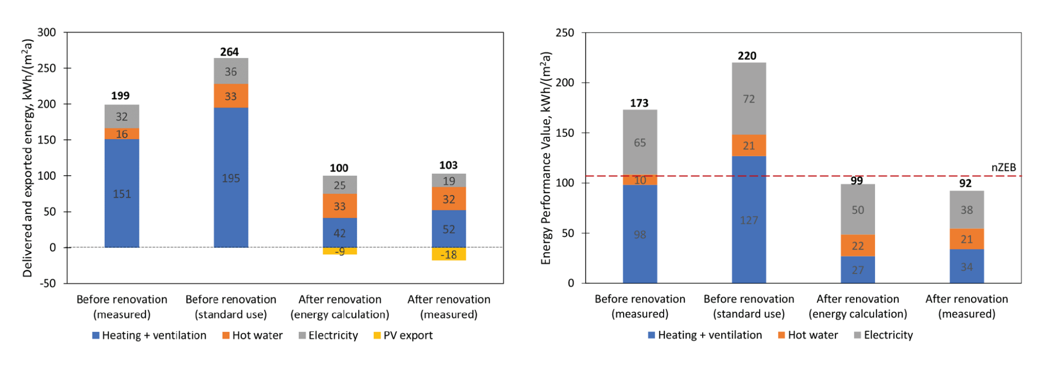
Energy performance and indoor climate

Prior to the renovation, the heating demand was 151 kWh/(m^{2}a) and electricity use was 32 kWh/(m^{2}a). However, due to the low ventilation airflow rate, the actual normalised heating energy usage was expected to be around 195 kWh/(m^{2}a). After the renovation, the heating energy use was significantly reduced to 52 kWh/(m^{2}a) and electricity use was reduced to 19 kWh/(m^{2}a). This translates to a 65% reduction in the measured energy used for room heating and a 42% decrease in electricity consumption (see Fig. 6 left).

The building had an Energy Performance Value (EPV) of 173 kWh/(m^{2}a) before the renovation, leading to an Energy Performance Certificate of class D. However, after undergoing a deep renovation, the Energy Performance Value was measured to be 92 kWh/(m^{2}a), resulting in an EPV class of A (see Fig. 6 right). This means that the building now meets the requirements for nZEB of new building according to Estonian legislation (RT I, 13.12.2018, 2018). In current case energy performance target was fulfilled without performance gap like it happened in the first prefabricated renovation pilot in Estonia (Hamburg et al., 2020).

Fig. 6

Delivered and exported energy (left) and corresponding Energy Performance Value (right)



During indoor climate measurement, which included temperature, humidity, and CO2 levels, it was found that the ventilation airflow in the apartment was lower than required. This is similar to other apartment buildings that have a natural ventilation system (Mikola et al., 2017). The average CO_2 level in the four measured apartments at night was 1050 ppm, with the maximum level reaching 2200 ppm. Before the renovation, the CO_2 levels in the building were measured. As a part of the renovation, a new mechanical supply-exhaust ventilation system with heat recovery was installed. The efficiency of the ventilation system was assessed by measuring the airflows. It was found that in the bedrooms, the intended design value of 10 l/s for supply airflow was achieved. The measurement results indicate that the temperature has become more stable after the renovation (see **Fig. 7**). After the deep renovation, which included the installation of a mechanical ventilation system, indoor moisture loads decreased significantly: moisture excess Dn from 2.5 g/m^3 to 1.4 g/m^3 (representing low indoor humidity loads (Ilomets et al., 2018)).

See taken on the case study building images and corresponding temperature factors (f_{Rsi}) in **Fig. 8**. After the renovation temperature factor was on the safe side $f_{Rsi} \geq 0.8$ (T Kalamees, 2006).

Fig. 7

Indoor temperature (left) and moisture excess (right) in apartments before and after the renovation

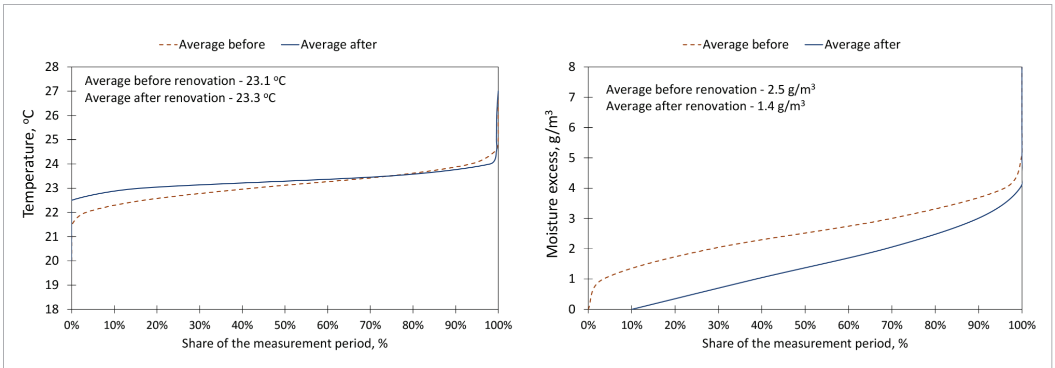
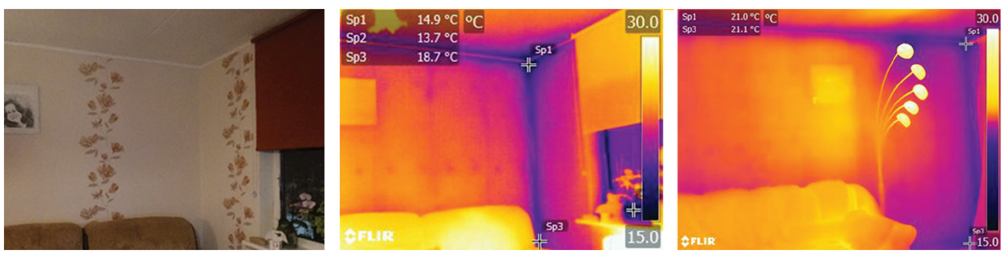


Fig. 8

Thermography images before (middle) and after (right) the renovation, and corresponding temperature factors (f_{Rsi})



$f_{Rsi\ (Sp1)} = 0.66$, $f_{Rsi\ (Sp3)} = 0.78$ $f_{Rsi\ (Sp1)} = 0.96$ $f_{Rsi\ (Sp3)} = 0.95$

Conclusions

Circular prefabricated modular external additional insulation elements ($U_{external\ wall}$ = 0.12–0.14 W/(m^2·K)) were developed, produced, and installed in a typical apartment building with minimal disruption to occupants due to the shorter construction time compared to traditional on-site renovation. The total cost of the renovation, inclusive of the installation of a new heating system, replacement of water and sewer pipes, addition of 50 kW PV panels on the roof, installation of new balconies, addition of a balanced ventilation system with heat recovery, and replacement of the electricity system in common areas, amounted to 505 €/(net area m^2).

On a product level, a medium degree of circularity was achieved. The analysed prefabricated modular solutions exhibited higher circularity potential than the traditional External Thermal Insulation Composite System (ETICS) due to their lower level of demountability and reusability. Construction demolition waste generated on the renovation site was disposed of in a manner that allowed for recycling or reusing of the materials. This included incorporating recycling or reusing materials into the renovated building, reusing existing materials from the renovated building in the same building, or reusing existing materials from the renovated building in other buildings.

Prior to the renovation, the building had an Energy Performance Value (EPV) of 173 kWh/(m^2a), resulting in an EPC class D. However, after undergoing deep circular renovation, the Energy Performance Value was measured to be 92 kWh/(m^2a), leading to an EPC class A. This achievement aligns with the requirements for nearly Zero-Energy Buildings (nZEB) for new buildings under Estonian legislation. Notably, there was no performance gap in meeting the energy performance target in this case. The improvement in indoor climate can be observed through the maintenance of a more stable room temperature, reduced indoor humidity load on the building envelope, and minimized thermal bridges following the renovation.

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