Development of a Modular Retrofitting System for Residential Buildings and Experience from Pilot Installation

P Hejtmánek, K Sojková, M Volf and A Lupíšek
Czech Technical University in Prague, University Centre for Energy Efficient buildings, Trinecká 1024, 273 43 Bustehrad, Czech Republic
antonin.lupisek@fsv.cvut.cz

Abstract. In order to significantly reduce energy consumption of its building stock, Europe has to focus on energy retrofitting of existing buildings. A usual building retrofitting process is very labour intensive and time consuming. It usually takes several weeks or even months to replace old windows by new, install new thermal insulation layers on the external walls and roofs of buildings and renew the heat distribution systems or to attach renewable energy sources on the building’s envelope. To make refurbishment more efficient and allow its scaling up, a European project Development and Advanced Prefabrication of Innovative, Multifunctional Building Envelope Elements for Modular Retrofitting and Connections (MORE-CONNECT) has been initiated under H2020 program. This project developed a system of prefabricated retrofitting modules, that enable to cut primary energy consumption of a typical residential building by 80 %, reduce on-site installation time bellow two weeks and improve the indoor environmental quality. At the same moment, the project aimed on implementation of systemic quality control over the whole design, pre-production, production and installation process in order to significantly reduce the number of warranty claims by the clients. The paper describes the design process of the modular retrofitting system and a pilot installation made on a mock-up building to test the concept, and presents the experience made.

1. Introduction
Renovation of buildings is a key to meet the EU’s energy efficiency targets [1]. In order to significantly reduce energy consumption of EU building stock, Europe has to focus on making the process of energy retrofitting of existing buildings more efficient. Commonly, energy retrofitting is made step-by-step. The traditional building retrofitting process is very labour intensive and time consuming. Usually, it takes several weeks or even months to replace old windows by new, install new thermal insulation layers on the external walls and roofs of buildings, and renew the heat distribution systems or to attach renewable energy sources on the building envelope. Nevertheless, there is a potential for change: Massive industrialisation can be used to scale up the retrofitting processes from single cases to large-scale renovations at district level [2].

1.1. Objectives
The objective of this paper is to present design process and assembly of a modular retrofitting system for residential buildings in Central Europe. The solution was developed within the European project MORE-CONNECT [3,4] and verified on a pilot building in Buštěhrad, the Czech Republic.
The European project “Development and Advanced Prefabrication of Innovative, Multifunctional Building Envelope Elements for Modular Retrofitting and Connections” (MORE-CONNECT) has been initiated under H2020 programme. The project partners aimed to develop a system of prefabricated retrofitting modules, that would cut primary energy consumption of a typical residential building by 80%, reduce on-site installation time below two weeks, and improve the indoor environment for the tenants.

The project started with general overview of boundary conditions for the development: identification of typical problems of the existing residential buildings; description of climatic conditions in EU countries and comparison of the boundary conditions and legal definitions; selection of suitable materials and technologies; and identification of similarities in building stock among the participating countries.

Based on these boundary conditions, a general modular retrofitting system [5] flexible enough to be accommodated to various country-specific variants of the retrofitting systems was designed. The system is composed of:

- Prefabricated wall and roof modules that improve thermal resistance of the building envelope;
- Aesthetic and functional upgrades that include changes in layouts and their extensions by new balconies or new flat units built in attic spaces;
- Integrated mechanical ventilation system secured by an air-handling unit with heat recovery;
- Additionally installed control system including sensors of indoor air quality;
- Energy systems upgrade/replacement including integration of renewable energy sources;
- Optionally, new heat distribution system and new electric installations.

The system should be open to configure on the basis of desired extent of renovation and a level of energy savings. All desired technical appliances should be integrated into the system modules (i.e. wall, roof or technological ones) and installed to the building in one step altogether. As a default option, the wall modules are to be mounted on an existing wall as an additional layer using steel anchors. The panels are mounted on the building by a crane, the last corrections and connections are done by workers from assembly platforms, so there is no need for scaffolding.

In the next step, country-specific variants were developed considering optimum cost, energy performance and environmental parameters and user comfort levels.

2. Development of country-specific retrofitting system

2.1. The reference building

The development of an optimized solution for the Czech Republic was focused on multi-family residential buildings that were massively built in the country in the period 1946–1960. Many of those buildings are still waiting for renovation. These buildings are typical by longitudinal wall structural system made of full bricks. Ceilings are made of reinforced concrete. The buildings have up to four floors, a gable roof, and basement partially or completely underground.

As a reference, the residential block located in Milevsko, South Bohemian Region from 1958 was selected (Figure 6a). It has three main stories. A basement floor is half of its height under ground level. It is used as social housing with 24 studios (living room, kitchen, bathroom), each with net floor area 31 m². Each flat has two windows oriented either to the east or to the west. Technical and housing facilities and cellars are placed in the basement, including the heat exchanger connected to the local heat distribution network that provides heat for heating and preparation of hot water.

2.2. Design process

The reference building with its features and problems was taken as a starting point for the development of the modular retrofitting system. Design process started with the simulation of its actual energy performance and with setting the maximum target primary energy consumption. Then, the general design was accommodated with use of multi-step multi-criteria optimization process that considered
primary energy, embodied and operational emissions of greenhouse gases and costs. Several variants of the system composition were considered. Moreover, the MORE-CONNECT solution has been compared with common-practice solutions. Optimization resulted in a set of compositions, configurable based on the desired level of energy efficiency and characteristics of technical systems.

3. Testing the solution and the design updates

Over the course of the development process, a set of tests was needed to verify the solution. The performed tests consisted of assembly test of two modules with HVAC, data and piping connectors, simulation of air-tightening process, and reaction-to-fire test. As a subsequent step, a small mock-up building had been built up, on which the complete system with all details was verified: module mounting with all types of connections, HVAC and BIPV installation and operation. During the following years, overall long-term performance of the system will be monitored.

3.1. Assembly tests: Module equipment and connections

Except the physical assembly test, i.e. whether two modules can be attached together (Figure 2), the assembly tests followed the two crucial goals. First, the tests aimed to prove a workability and labour intensity of the connections (whether connections are well reachable and mountable for the workers). Secondly, an air-tight layer workability had to be verified. The experiments were performed at the UCEEB testing hall and followed these steps:

- At the beginning, a mock-up of future window lining was created (Figure 1a) to verify the air-tightness of module itself, especially connection of a window frame to the module structure and sealing of wires and pipe penetrations. Results were incorporated into the final design.
- Then, a pilot module was produced according to findings of the previous step. This module was made by project partner in his factory and workers’ feedback lead to further improvement.
- Finally, a mock-up of an original wall of the retrofitted building was added to the pilot module (here in the opposite order for the testing purposes, Figure 2b). Connection of existing wall and panel was proven with all its specifics such as sealing of electrical switchbox and entering wiring, wiring of the sunblinds, and heating pipes leading in the window lining.

![Figure 1](image_url)  
**Figure 1.** Assembly tests: (a) mock-up of future window lining; (b) mock-up of an original wall of the retrofitted building added to the pilot module.
The final test proved the general correctness of the design. However minor changes were needed:

- The integrated electrical switchbox (see Figure 4) was designed from scratch again. Originally, there was a possibility of leading the air-tight layer through cover of the switchbox, leaving the number of present wires in the outer zone. The detail was simple, however, compactness of the air-tight layer depended on the user who sometimes needs to inspect or service the device inside the box. This could lead to damaging of the air-tight layer. Therefore, more complicated way was chosen where the switchbox laid inside the inner zone and its envelope formed an air-tight layer. Change of switchbox material, special screws, special wire plugs, and optimized electrical design with reduced number of wires were needed for this solution.

- Window dimensions in the module structural frame had to be adjusted by centimetres, due to tolerances of production, tolerances of building measurement, and need of manoeuvring space to finish the sealing.

- Mounting of the air ducts to the module structure turned out to be quite difficult because of number of individual elements, i.e. ducts and thermal insulation between them. Therefore, a special frame was developed to connect all pipes and insulation together (Figure 3). This adjustment first simplified duct installation on the panel. Second, it minimized the number of module-to-module connections because all air ducts behave as one unit.

- Modules and the building are connected with tailor-made anchors (Figure 5); lower and upper edge of the module have oval holes milled for anchor pins. The anchor enabled rectification in two directions: vertical and depth. Longitudinal position of the module was adjusted with movement of anchor pin inside the module hole, present range was ±2 cm. The pilot installation showed a need of holes redesign/enlargement, not due to rectification (production tolerances) but to speed up the installation. Moreover, since the modules are stabilized to the accurate position together consecutively, the longitudinal rectification could be much freer and one continual milled groove instead of series of oval holes might be optimal.
3.2. Fire tests
Since the wall modules combined both incombustible and combustible materials, various fire risks arose and had to be identified and classified. One of those risks was a possible fire spread through the façade and it was verified by medium-scale fire test according to ČSN ISO 13785-1 [6]. The Czech National Annex determines as the only compliance criterion the average temperature of three surface thermocouples at a specific height. This average value shall not exceed 350 °C (ignition point of most combustible materials). Passing only the medium-scale test however limits the MORE-CONNECT application on the buildings with fire height lower than 12.0 m, i.e. 4- or 5-storey buildings.

The average surface temperatures did not exceed 250 °C and the system thus passed the National Annex requirements. Furthermore, also the temperatures inside the specimen were measured: At the combustible material closest to the surface temperatures did not exceed 160 °C, inside the HVAC duct, temperatures did not rise at all.
3.3. Experimental mock-up building and installation of the whole system

The test mentioned above proved sufficient feasibility of the concept. The next goal was to integrate gained knowledge to the next version of modular system and test it in real scale. The originally planned experiment was changed from partial façade mock-up installation to a complete small experimental house. Such a house provides all representative details and connections that can be found on a typical residential building. The main aim of the change was to test all the possible system elements and the control system of the complete solution. This helps to get the real information on feasibility of the system.

The experimental building was designed based on the reference building described in Chapter 2.1. All the main details of the original pilot building were transformed into experimental mock-up building (Figure 6b and 6a) – masonry load-bearing walls with thickness of 45 cm; typical window dimensions; pitched roof with 30° slope; cellar with small windows; and interior and exterior plasters.

The building has a simple rectangular shape with external dimensions of 7.18 x 3.89 m. There is one room in the cellar used as a technical room for testing the connections of the HVAC system. Single room in the first floor simulates the apartment room in a residential building. An opening for the ventilation ducts were created in the gable wall.

The mock-up building was built up to the stage of the real building before refurbishment (e.g. after removal of windows and parapet walls – see Figure 6b). The next step was a creation of the 3D digital point cloud for the production of the modules and installation of the anchors. The refurbishment modules were prepared in the factory of project partner RD Rýmařov [8] and equipped with ventilation ducts, external window blinds with electrical control, and hydronic heating pipes. Already in the factory, the wall panels were completed up with the final layer of the plaster. The modules were then transported from the production factory to the construction site.

![Figure 6](image-url)

**Figure 6.** (a) Original pilot building. (b) The mock-up house (positions of the main details are referred by lines to the original pilot building on the left). (c) The house after installation of the modules with revealed inter-modular connections (chimneys do not belong to the house).
The installation of modules was done during one working day when all the walls (e.g. foundation wall modules; standard wall modules; and gable pitched modules) and roof modules were mounted to pre-prepared anchors. Interior, surfaces and other finishings were finished in one further week.

The building is operated as a demonstration building for occasional visits or meetings. The permanent housing was neither planned nor technically possible under the general conditions of the project. However, the visitors and other users of the building can be questioned about their sense of thermal comfort etc. Therefore, a questionnaire was prepared and the collection of the data from the users is planned.

The monitoring system [7] for timber structures originally developed by UCEEB was installed in the wall modules. The system was further adjusted for the application within MORE-CONNECT project, especially within the connections. The monitoring is fully autonomous and a web interface provides the real-time overview of the measured data. The following parameters are measured in the experimental building: temperature and relative humidity of exterior air; relative humidity, moisture content and resistance of timber elements; roof irradiance parameters and average temperature above the roof; electrical measurement (voltages, power); and indoor air quality (air temperature; humidity; pressure and VOC index). All the measurements started with finishing the experimental building (10/2018) so the outcomes will be presented later in a separate paper.

4. Lessons learned from the installation

Lessons the team learned from the installation:

• The system is workable in full-scale, in total the process is sufficiently fast. The real installation revealed heat bridges in specific positions (around the steel anchors, around HVAC starting connection etc.) These details have to be improved.
• The system is very complex which should not mean complicated. The integration of all necessary structural layers and all the technologies brought new requirements to the factory staff. The production of the system showed the need of incorporating more professionals with specific experience to be able to obtain sufficient quality on-site. This touches electrical and HVAC installations as well as final interior coverings. Interior finishings could be prepared in a different way so that even construction workers without any special qualification are able to create indoor lining of sufficient quality.
• Ventilation system is working, connections of the elements was fast and solid. After starting the ventilation system operation, the noise from interior exhaust appeared. This shall be improved by integration of a silencer before releasing the system to the market.
• Pipes of the hydronic heating systems were connected easily. However, this type of heating is considered rather risky and vulnerable due to uncomfortable access to the connections.
• The installation of the metal anchors on the external walls was very time-consuming. There were four main montage holes needed to be drilled for each anchor; drilling one hole took more than 90 seconds. Even with the small dimensions of the mock-up building, the installation of the anchors took 2 days.
• Although the finished external plaster survived the transportation successfully, the connections had to be done in-situ that took additional time after installation. The under-roof covers were not transported mounted to the modules; their installation also took additional time.

5. Conclusions

The MORE–CONNECT modular retrofitting system developed for the conditions of Czech post-war multifamily residential building was tested in both small- and full-scale tests.

The workability test had identified some weak points of the system and these were further solved and the system upgraded. During the fire test, the average surface temperatures did not exceed 250 °C, the system thus passed the National Annex requirements and can be used at the market. Despite that, the
A large-scale fire test should be performed in the future to get permission for use of the system for buildings taller than 12 m.

The full-scale installation on a mock-up building revealed some other tasks for further development. Some of them can be solved by adjusted design of important elements, some – e.g. plastering the intermodular connection or time-demanding fixation of the anchors – can be solved in the future by robotizing of those processes. The monitoring of operation will be performed and evaluation will follow.

The project partners are now focusing on significant improvement of pre-production and production process. Among others, the MORE-CONNECT project aims on implementation of systemic quality control over the whole design, pre-production, production and installation process in order to significantly reduce the number of warranty claims by the clients.

Final step before entering the market will be finding a real demonstration building and providing the full building refurbishment to it to gain the complete knowledge of the MORE–CONNECT system behaviour in real life.

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