SUSTAINABLE SOLUTIONS FOR EXTENSIVE RETROFITTING OF RESIDENTIAL BUILDINGS

Doctoral thesis – Summary

for obtaining the Scientific Title of PhD in Engineering from Politehnica University Timișoara in the Field of Civil Engineering by

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The building environment has been the focus of energy and environmental debates and policies, and the need to reduce greenhouse gas emissions to meet targets by 2050 [1] and improve energy security has motivated a large body of studies on energy efficiency and environmental impacts associated with buildings. Improvement in energy and environmental performance requires innovative research, new policies and standard regulation, new materials and technologies, the integration of renewable energy sources, of increased awareness and outreach and people awareness (designers, practitioners, and end users). The operation of buildings has often been focused on the literature in conventional buildings, and this stage dominates energy demand and environmental impacts. Buildings have a long service life, during which end-user expectations should be met, including requirements for thermal comfort (TC) and indoor environmental quality (IEQ). As research and polices succeed in reducing the impacts of building's operation, the relative contribution of other life-cycle stages has increased, and integrated and holistic approaches are needed to avoid problem-shifting. Reducing the energy and environmental impacts associated with the built environment is a challenging task, which requires a comprehensive understanding of the dynamics and main drivers of energy demand and environmental impacts. In addition, a few topical questions are addressed for improving building energy performance: life cycle assessment (LCA), urban planning, district-scale nearly zero energy buildings (NZEBs), smart grid scenarios, IEQ and TC, assessment of retrofitting actions, generative building design methods and thermal storage with phase change materials (PCMs)[2], These follow two paths:

- the use of integrated and holistic approaches to assess and improve the energy and environmental performance of buildings, and
- the development of new solutions, technologies, materials, and dynamic methodologies

Currently, a significant part of the urban population in Romania lives in low-rise collective housing built by using large prefabricated reinforced concrete panels (LPRCP). Most of these units have not yet reached half of their intended lifespan and are over 30 years old. Furthermore, the materials that have been once used especially regarding thermal insulation are outdated or have degraded in time. Because of the constant changes in society, these building currently are failing to keep up with the current needs and regulations while consuming significant amounts of energy in the process. Because of this, it is necessary for a flexible and sustainable strategy to be devised in order to not only make them energy efficient but also considering social, economic and environmental benefits to lead to a reduction of GHG emissions and improvement of the quality of life.

Chapter two highlights current advances in the energy and environmental performance of buildings towards a more sustainable built environment.

Numerous studies focus on reducing overall operational energy demand and designing new low-energy buildings. However, if the operational energy is decreased, the embodied requirements are increased. The LCA methodology calculates potential environmental impacts that and associated with a material and its energy flows, through sequential life-cycle phases of a process (or product) from 'cradle to gate' or "cradle to grave". It is usually used in an industrial context and aims to improve the environmental performance of products. The LCA framework is defined by ISO14040 series [3] [4] and includes four iterative steps: definition of the goal and scope, inventory of the license cycle, of the life cycle, of the impact assessment and interpretation of results. Over the last 15 years, LCA has been used in the construction and building context to address trade-offs between different building life cycle and building components and to help identify the most effective opportunities to reduce impacts.

Buildings are complex systems. They incorporate multiple construction materials, processes, that come from different industries and producers. Although extensive international inventory data are available for energy production systems and construction materials (e.g., EcoInvent database [5] [6]), materials coming from local construction have a significant role in buildings. Natural materials (i.e., wood) have a lower impact than others (e.g., concrete or brick) however their embodied impact depends on the entire production chain which includes wood growth, wood harvesting, and forest regeneration. These vary from place to place and go beyond the building scale. In contrasts to standardized products, a building is usually one-of-a-kind product.

Design, location and local urban characteristics also affect the environmental performance of buildings, and focusing on the individual building alone might neglect potential interactions with the urban scale, shift impacts and overlook improvement opportunities for a more sustainable urban development [7] [8].

The NZEB concept [9] has been widely studied; however, slight attention has been given to groups of buildings in the urban context. District scale approaches aim to gather the study of buildings and urban characteristics that may influence their energy performance. It is important to better understand the interaction between buildings and urban context, and to consolidate the potential benefits of sharing resources and energy systems at this scale.

The control of energy resources in a smart grid scenario where the existence of dynamic tariffs (variable in amplitude and along the day) is a reality that can be done in an efficient way through the use of decision support systems, such as energy management systems endowed with adequate optimization algorithms[10]. Existing power systems are one of the main reasons for greenhouse or global warming effects which lead to environmental impacts by using fossil fuels, especially coal. In contrast to fossil fuels, renewable energy (RE) offers an alternative source of energy that is pollution free, from a technology perspective[11]. There is a high focus towards using RE, particularly solar and wind energy, in return for electricity without generating carbon dioxide emissions. However, most existing transmission and installed distribution networks are considered "dumb" or inefficient systems as they cannot return the smart data required for a modern grid operation. Smart grids bring centralized massive power plants and distributed power generators together, allowing a multidirectional power flow and information exchange. This two-way power communication system creates an advanced and energy-efficient advanced energy delivery network in contrast to traditional power systems where power flows only in one direction, i.e., from generators to customers through transmission and distribution relays[11]

Energy behaviours are an important underexploited resource in the context of promoting end-use energy efficiency in the residential sector, and the potential of energy savings can be as significant as those from technological solutions.

As people spend most of their time indoors, IEQ is a key issue on people's life. Besides human comfort in general, indoor conditions such as ventilation requirements strongly influence the energy consumption in buildings. More education is demanded on the energy subject to improve the energy performance and the IAQ of buildings[12].

When coupled with a performance assessment mechanism, generative design methods can contribute to the improvement of building's design by producing a number of alternative solutions to be compared by the building practitioner, by integrating different design aspects that otherwise would be assessed individually, and by creating large datasets of synthetic data to analyse the general buildings behaviour in specific contexts.

The methodologies for assisting decision making in the appraisal of retrofit actions according to multiple, generally conflicting evaluation aspects may be distinguished into two main approaches: first, approaches in which alternatives are explicitly known a priori and second, models in which alternatives are implicitly defined in the setting of an optimization model. More research has to be carried out to generalize the use of multi-objective methodologies for the assessment of building retrofit actions[13] [14].

Active and passive PCM-based TES (thermal energy storage) systems can be used in buildings to improve the use of renewables and to reduce the energy demand for heating and cooling. However, there is still a long way for the generalized use of PCM-based systems in design and retrofitting strategies, and more research has to be carried out in these research fields[15].

Chapter three analyses the existing collective housing stock in Romania compared to their European counterparts

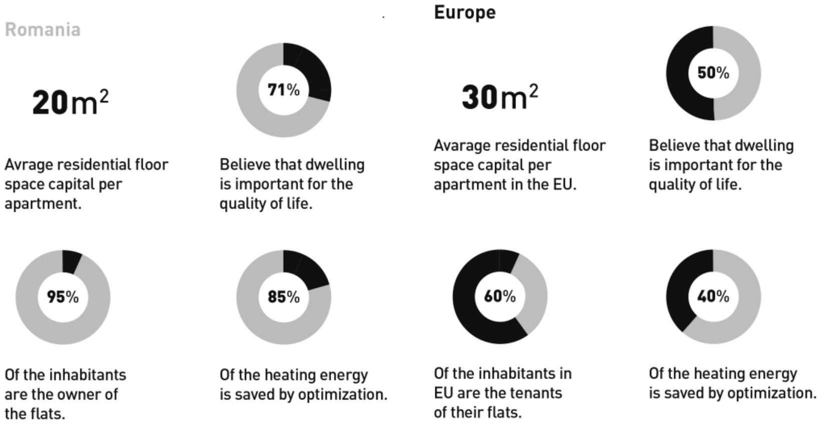
Large prefabricated reinforced concrete panels (LPRCP) collective housing units represent 1.8% of the entire building stock. According to the 2011 National Population and Housing Census, Romania had around 19 million people. More than half (52.8%) lives in urban areas, most of them in collective housing units built by using LPRCP. A total of 84000 blocks of flats were built, having 2.5 million apartments. Most of the built urban housings (around 71%) were the multi-dwelling type and cover 66% from the inhabitable area. A total of 57431 LPRCP units were erected, most of them between 1965 and 1989, 41540 in total, being low-rise[16] [17].

These buildings were built due to the heavy expansion of the industries near the cities, resulting in a massive migration from the nearby rural areas to the urban environment, doubling the urban population. Furthermore, the number of cities increased from 187 to 237. In order to rapidly meet the increased demands of the housing market, new housing units had to be built in a short amount of time and in a simple way on the site.


This phenomenon, using LPRCP, was a common feature of the cities in Eastern Europe in the 1970s and 1980s. Such technologies were used in the northern European countries as well, but unlike their counterparts from Eastern Europe, these have managed to improve their buildings towards sustainability[18].

In Romania, LPRCP buildings have used standardised project types, for a better use of land. The most common project type of these so-called “match boxes” was the T770 one.

With the constant change of the daily lifestyle, the initial conditions that these housing units offered became far from adequate, starting even by end 1980s. If one is to compare these units with the one from western Europe, in Romania only 20 m²/person of floor area is provided, while Southern countries allocate 31 m²/person and 36 m²/person is ensured in the Western countries [19].



Chapter four focuses on design and build. To test the performance of envelope components that could be used for retrofitting the above-mentioned blocks a modular laboratory has been built. This was supported by a grant of the Romanian Ministry of Research and Innovation, CCCDI - UEFISCDI, project number PN-III-P1-1.2-PCCDI-2017-0391 / CIA_CLIM - Smart buildings adaptable to the climate change effects, within PNCDI III. with two main research directions: (1) intelligent facade use, with low heat transfer that actively contributes to increasing indoor comfort, with passive control passive energy through the use of solar energy; (2) intelligent energy efficiency through automated systems and energy collectors. The building process was carried out in 4 stages.

The first stage involved simulating different facades configurations similar to those already existing on the market. It compared options with mineral wool and polyurethane core, for which thermal transfer analyses were carried out, including phase change, attenuation calculation amplitudes and temperature amplitude ratio. The study was completed by calculating the balance energy, for the model building, considering the option analysed.

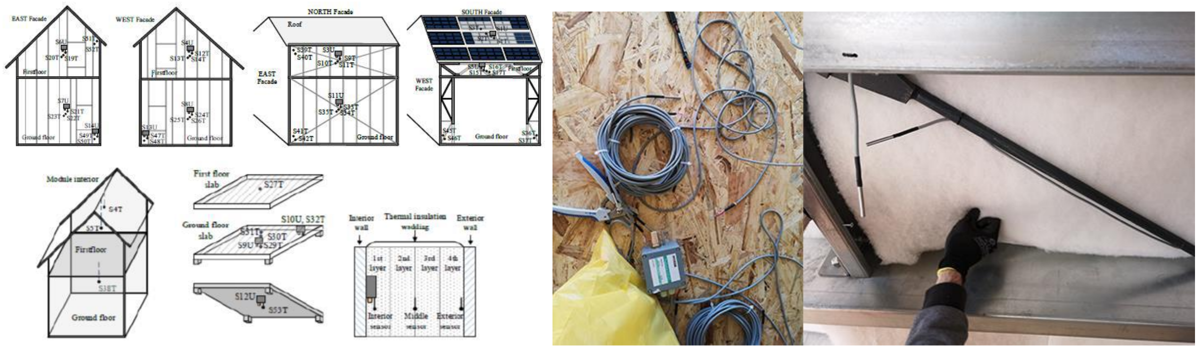
Facade System	Overall thermal resistance [m²K/W]	Lowest net heating energy balance [kWh/a]	Heat storage capacity [kJ/ m²K]	Thermal capacity of inner layers [kJ/ m²K]	Phase shift [hours]	Amplitude attenuation	TAV
MW 1	5,943	3624,8	47	19,7	6,7	7,9	0,126
MW 2	6,193	3597	47	19,8	6,7	8,3	0,120
PIR 1	5,850	3723,2	46	21	6,8	8,2	0,122
PIR 2	6,001	3658,2	46	21	7,2	8,5	0,117

The second stage of the project focused on construction of the test module and experimenting alternative insulation materials for building envelope systems. Recently, the environmental perspective of thermal insulation products is considered, and the use of secondary raw materials is increasingly in the spotlight. Thermal insulation wadding produced with polyester fibers made from the recycling of post-consumer PET bottles is one such insulation material developed in the last decade[20] [21]. The manufacture of polyester fibers begins with recycling post-consumer PET bottles from differentiated waste collection. After washing, grounded to flakes, these are used in fibre production. Next, the layers of raw material for thermal insulation wadding are obtained by guiding the polyester fibers mechanically in the same direction. Eventually, the thermal insulation wadding is obtained by overlapping and thermal bonding (ca. 180ºC) two or more layers of raw material wadding with the desired density and thickness [22].

Material	Thickness [mm]	Net weight [kg/sqm]	U [W/m2K]	Thermal resistance R [m2K/W]
MW 100	100	9	0.4	2.5
PET 150	150	3.597	0.36	2.77

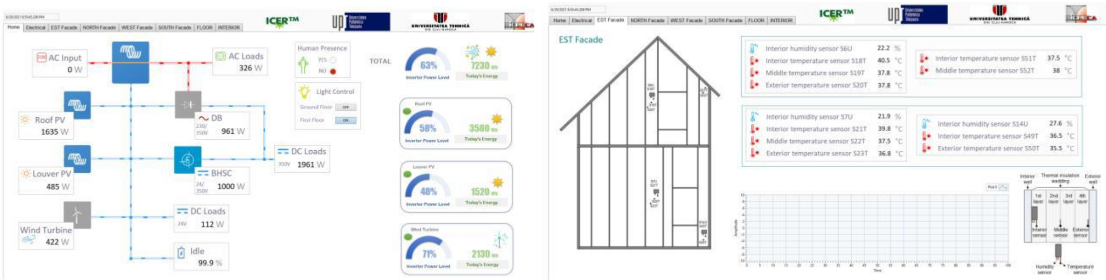
Mineral wool vs PET technical performance

The third phase focused on monitoring the model data. For monitoring the characteristics of facades under various atmospheric conditions, the module was equipped with 14 humidity sensors, 53 temperature sensors and 3 CO2 concentration monitoring sensors.



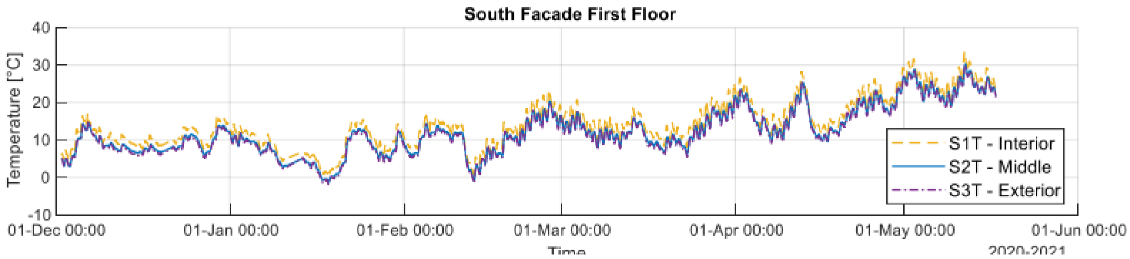
Sensor placement within the module

The final phase further detailed the prior with the following events: In stage, the assembly of the wind turbine and the supporting structure and the photovoltaic slats was carried out in the model. Monitoring of the experimental data was continued to follow the variations given by temperature, humidity, and CO2 concentration sensors. The production of energy was also monitored because of the production of photovoltaic panels on the roof. Once the systems have been coupled of the wind turbine and the photovoltaic blades it was be possible to monitor the energy production given by these systems.

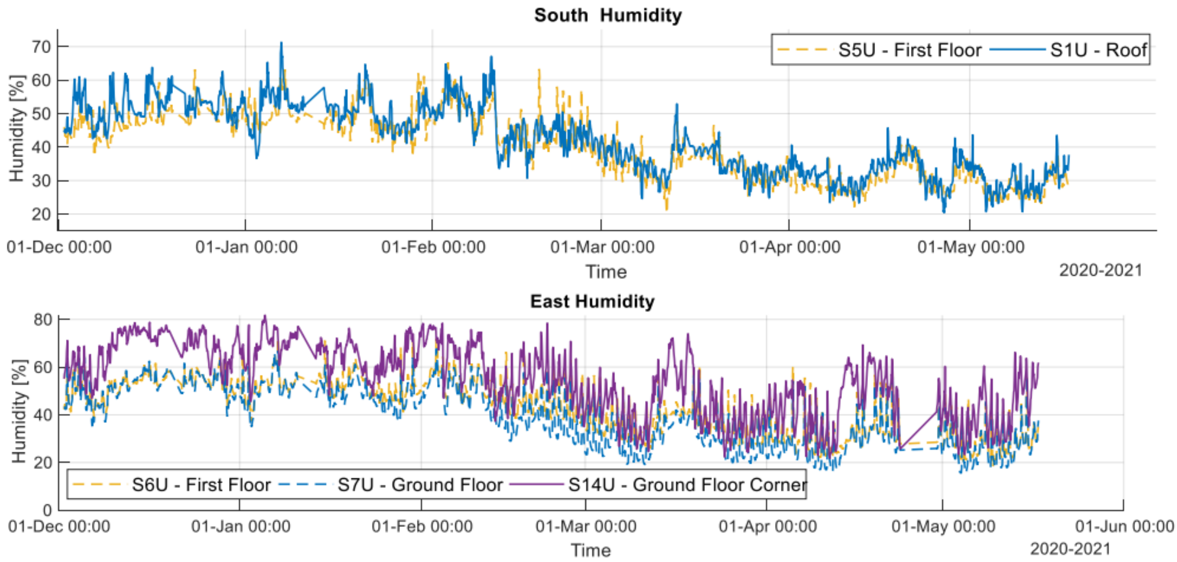


SCADA interface viewports

The recordings transferred by the sensors show the envelope behaviour of the experimental module and interior comfort conditions. At the time of the recordings the indoor temperature was influenced only by solar input, electrical devices and human interactions during interference by maintenance and observation, HVAC indoor comfort adjustment systems (heating-cooling, air conditioning) not being connected. Energy production was also monitored. The recorded data shows that there are load periods with energy of up to 10kWh / day, which compensates for cloudy or snowy days, in which the energy is provided by batteries. In the natural operating conditions of the module, the consumption is constant approximately 2.6 kWh/day.



Temperature information provided by sensors on the south facade



Humidity sensor data

To illustrate the environmental benefit of the thermal insulation system obtained from recycled PET batting, in this phase an additional LCA type analysis was carried out, comparing the results obtained with the results obtained for a classic mineral wool system. The results indicate that the total impact of the insulation system PET_150 (438.09 kg CO2eq) is less than the environmental impact given by MW_100 (864.86 kg CO2eq) by approximately 48%.

Chapter five takes the tested envelope components from the test module to the existing T770 building. Three scenarios for extensive retrofitting are presented, considering implementation difficulties and costs. As base, the load-bearing outer walls are made of reinforced prefabricated concrete panels, with an average total thickness of 27 cm. The 12.5 cm resistance layer, as well as the 5 cm protection layer, are made of reinforced concrete B250 (C16/20), having a 7.5 cm thermal insulation layer of aerated concrete and EPS granules.

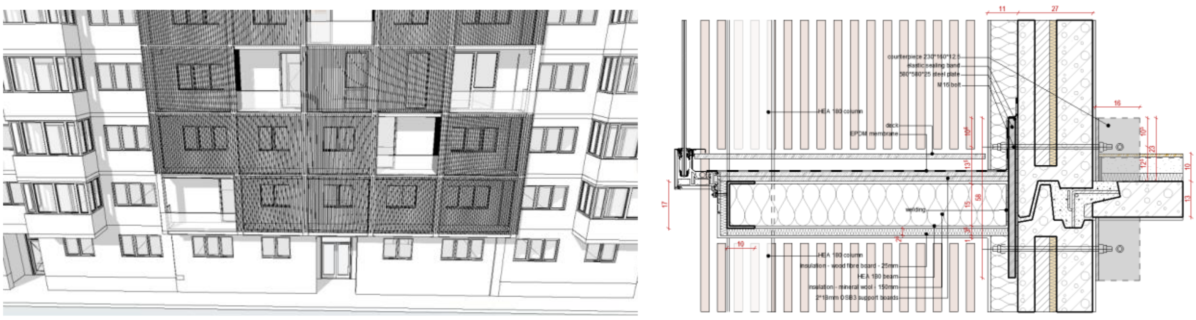
The thermal behaviour of the building's envelope (for the whole building), existing and new, is studied using the online U-calculation platform Ubakus [23]. The platform is easy to use and it allows generation of building components using either existing embedded materials or creation of new ones for further use. The energy simulations are carried out with ArchiCAD's Energy Evaluation[24] option only consider the required energy for heating and cooling with no additional consumption sources (f.e appliances).

The first scenario and the most accessible consist of an upgrade to the existing building envelope with new insulation materials and more efficient window elements.

Envelope	Total net energy [kWh/m²year]	Net Heating [kWh/m²year]	Net Cooling [kWh/m²year]	R [m²K/W]
Existing panel	35.42	21.52	13.90	1.52
XPS 8 cm	30.51	19.72	10.79	3.64
Mineral wool 10cm	27.82	19.63	8.19	4.21
PET insulation 15cm	27.86	19.65	8.21	4.13

Energy performance of building envelope systems

In addition to a new thermal envelope, the second option offers a secondary building façade made out of lightweight steel structure. The structure is fastened to the existing reinforced prefabricated concrete panels and provides support a possible horizontal extension of the apartments. The new main structural elements are HEA 180 beam and column profiles which are, welded to steel endplates and connected to the existing prefabricated panels of the building. The structure is fastened to the existing reinforced prefabricated concrete panels and provides support a possible horizontal extension of the apartments. The connection is done in pairs by one M16 threaded rod that crosses the internal diaphragm, having the role of preventing axial forces that could cause tearing of the panels in the monolithic area.



Structure detail

The final scenario, and the most challenging is the redesign of the current staircase and the addition of an elevator to solve accessibility issues. Due to the significant implications of the solution the terrace roof is also transformed into a public space with different functions. These functions also serve as support for installing renewable energy systems.

Model 770 initial floor plan (left) ; new floor plan (right)

Finally, **the sixth chapter** is presenting a summary of the results, the conclusions of the thesis, main personal contributions and a complete presentation of the research dissemination in conference and journal papers and their citations. At the same time, the chapter also presents an outline of possible future studies towards building energy efficiency solutions.

It again highlights that the construction sector generates a considerable volume of waste every year, which can reach up to 40% in industrialized countries, almost all of which comes from the rehabilitation or demolition of buildings. Therefore, this waste is a key issue and changing the way we manage the use of construction materials is crucial.

This is where the circular economy comes in, a system that aims to make resource use more efficient and reduce environmental impact, while not neglecting people's well-being. In short, when thinking about a product, we need to consider its entire life cycle, from the design phase to the moment it can no longer be used. According to the linear model, at the end of a life cycle products were usually thrown away, but the circular economy proposes a new approach, in 3 steps: reduce-reuse-recycle. Therefore, the famous motto "Nothing is lost, everything is transformed" valid in science can easily be applied in the circular economy as well. All over Europe, architects consider the reuse of materials by other users and the recycling of waste as the main qualities of a circular building economy. A third of them even expect to achieve a fully circular construction economy by 2030.

The main achievements and personal contributions are:

- Design of the experimental model as part of the “CIA_CLIM - Smart buildings adaptable climate change effects” research program;
- Construction and monitoring of the experimental module;
- Analysis and interpretation of recorded results;
- Calibration and numerical validation of the experimental model;
- Extending the results obtained experimentally at a building block level.

As a result of the research work carried out, the following research directions, not explored within this thesis, must be specified:

- a complex assessment of energy consumption on an entire block extended to the neighbourhood level, rehabilitated in an integrated manner, according to the proposed measures;
- Life cycle assessment of the integrated rehabilitation method with regards of circular economy;
- Further applied experimental study using modular test models;
- Based on the model design strategies, a second participation in the Solar Decathlon Competition, involving students from different fields of study.

The research outcomes presented in this thesis have been published conference proceedings and research projects.

- 7 papers in Web of Science indexed proceedings;
- 4 papers in international database proceedings
- 3 papers in international proceedings;
- 2 research projects

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