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ENVIRONMENTAL ASSESSMENT OF A PRECAST CONCRETE BUILDING STOCK IN A TIME PERSPECTIVE

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Abstract

The sustainable refurbishment of the existing building stock is a key issue in achieving the ambitious long-term energy and environmental goals of the European Union. Europe has a vast building stock built with prefabricated reinforced concrete large-panel construction technology after World War II to decrease the general housing shortage, mostly in the Eastern-European countries and East Germany.

This study focuses on the environmental evaluation of the retrofitting of the existing precast large-panel building stock in Hungary and provides a decision support tool for the architectural design process by identifying the largest environmental impacts. Different scenarios, including demolition/new construction and various refurbishment levels, were analyzed through life cycle assessment and considering the potential impacts throughout the building's lifetime. The effect of building lifetime and calculation period on the environmental performance was evaluated in detail.

The typology of the precast large-panel building stock was set up by grouping buildings according to their age, architecture and technical parameters. The methodology is demonstrated on a case study area: the Kelenföld housing estate in Budapest (Hungary) built in 1965-75 was chosen for the analysis. After assessing the environmental performance of the determined types, the mitigation potential of the housing estate was estimated.

Key words: building typology, concrete building, life cycle assessment, life time, precautionary principle, refurbishment scenarios

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1. Introduction

The European Union has recently confirmed its commitment toward a sustainable future by adopting the 20-20-20 target: reducing greenhouse gas emissions by at least 20% below the 1990 levels, reducing energy consumption by 20% and increasing the share of energy from renewable resources to 20% by 2020. The energy consumption of the building sector is significant all over Europe, accounting for approximately 40% of the energy consumption in the EU and thus providing a great potential for cost-effective energy savings. There are more options to reduce the energy consumption in the case of new buildings, but the sustainable refurbishment of the existing building stock is an urgent task.

The reinforced concrete precast large-panel construction method was spreading throughout Europe during the reconstruction wave following World War II to decrease the general housing shortage. Such buildings are widespread in Hungary and other Eastern-European countries, as well as in the former East-Germany, but there are also several examples in Denmark and France. Today, their overall refurbishment is inevitable and urgent. The main problem presented by this building stock is that the operational energy use is extremely high due to design, construction and structural errors.

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The goal of sustainable rehabilitation is the modernization of the existing building stock to meet the demands of present times and simultaneously focus on technical and ecological aspects as well as lengthening the life-span and conserving the building's heritage. In addition to aesthetic and economic questions, energy efficiency and environmental impacts are important factors in the decision-making process regarding the retrofitting of an existing building.

Life cycle assessment (LCA) provides a scientifically sound solution for optimizing the environmental performance of buildings. Several case studies have analyzed the retrofitting of existing buildings from a life cycle perspective. Erlandsson and Levin (2005) evaluated a multi-family building that was representative of a large building stock built during a construction program in the 1960s and 1970s in Sweden. It was shown that rebuilding was a better choice than the construction of a new building from an environmental perspective. Power (2008) described the social, environmental and economic aspects of demolition vs. refurbishment and argued in favor of refurbishment. Rønning et al., (2009) applied a hybrid LCA for the analysis of the headquarters of a Norwegian bank from the early 1970s and concluded that the replacement of the building with a new construction was more advantageous from an environmental point of view. An important new question was highlighted by Mequignon et al. (2013) regarding the relative importance of building lifetime in LCA studies. In their literature review, these researchers summarized that most LCA studies use a fixed building lifetime of 40-100 years and do not evaluate the influence of this factor on the results. There are only a few studies that address variable lifetimes. Based on the assessment of different wall structures, the study concluded that the lifetime of an element affects its environmental performance as much as the choice of the product itself.

The goal of this paper was to find the environmentally favorable measures for existing panel buildings with a special focus on the expected lifetime of the building. The analysis was based on the newly developed building typology of Hungarian panel buildings.

2. The typology of the existing precast large-panel buildings

In Hungary, the first initiatives of the prefabricated reinforced concrete large-panel construction method were carried out in 1954, and later in 1966, the large-scale "production" of large wall panel blocks became possible. During the following decades, approximately 30,000-35,000 flats were built annually. Altogether, 510,000 flats of this type were built throughout the country, and approximately 13.5% of the people currently live in these high-rise buildings (Birghoffer and Hikisch, 1994). Because the primary aspect of designing these so-called 'panel buildings' was their large production, many uniform features can therefore be recognized concerning the geometry and the construction. The typical height of the large-panels is 2.80-2.85 m (resulting in 2.65 m of headroom), and the width of the panels was changed during the construction period, with 2.70 m and 3.6 m being representative in the beginning and 5.4 m being used later; however, several types of panels were typically applied in a single building. In addition, the construction of balconies and loggias was similar, but their frequency on the façade may vary.

Considering the economic requirements of that period, four- and ten-story-high blocks were mainly built in the form of housing estates. Although the size of the panels is uniform, they were combined optionally; therefore, a variety of floor plans was composed. The most frequent basic types are freestanding high-rise blocks with only one staircase and terraced buildings consisting of several staircases. There are two subtypes of terraced buildings depending on the number of flats on a story: 'narrow blocks' (generally with 3 apartments in the staircase) and 'wide blocks' (with 6-10 flats per story). The fourth main type is the H-shaped so-called 'eared' building, which is relatively fragmented according to the other types. Generally, in housing estates, these basic types were settled individually or connected in different ways.

2.1. General description of the building constructions and building services

Regarding the building constructions and building materials, the one-story-high reinforced concrete wall or floor panels are welded on their edges and assembled by fixing and concreting on the site to realize their box-structure; therefore, the weak points of the structure are mostly the joints.

The outside perimeter wall panels with built-in insulation were composed of a sandwich structure: reinforced concrete elements with rockwool or polystyrene thermal insulation. The configuration of the joints was developed during this construction period considering the connection and the level of thermal insulation: at the early stage, the thermal insulation was not continuous, causing extreme thermal bridge losses on the façade, and the joint was closed with flexible sealing that was damaged due to UV radiation, causing leakage problems. Since the end of the 1960s, the thermal insulation in the sandwich panels was 7-8 cm, but this width decreased to 2 cm at the joints. In the beginning of the 1980s, a higher thermal insulation level was used for the joints (Fig. 1). Instead of closed joints, neoprene 'C' profiles were installed between two precast panels, forming an open joint.

Because of these features mentioned above, considerable attention should be paid to both satisfactory joint sealing (heat-insulation and waterproofing) and protection against the corrosion of the joining reinforcing bars.

In the beginning of this industrialized construction period, the double-shell (ventilated) cold roof covered by bitumen membrane waterproofing was typical, but after a while, the warm roof was generally applied with a low-insulation level. During the fourth period, several buildings with pitched roofs were erected. Until the 1980s, wooden windows were installed with very poor insulation capacities and high filtration rates. In most cases, they were made with a reveal shape and installed without any external shading devices. After 1982, wooden or PVC structures were used with better thermal insulation and air-tightness capacity.

Regarding the building services, district heating systems with no possibility of local control were typical until the mid-1980s. The heating systems are often unbalanced, resulting in overheating and under-heating in different flats of the same building at the same time.

2.2. Development of a building typology

A typology of the precast large-panel building stock was set up by grouping buildings according to their age, architecture and technical parameters (Table 1). According to the differences in the used materials, the building construction and the building services, four main building periods can be defined (1960-1967, 1967-1974, 1974-1982 and 1982-1992), and the determined types represent these different building periods well (Csoknyai et al., 2011; Talamon and Csoknyai, 2011). Because approximately 50% of the precast large-panel buildings were built between 1974 and 1982 (Birghoffer and Hikisch, 1994), half of the defined types were erected during this 3rd period. There is one building from the early 1960s representing concrete buildings with extreme thermal bridges ('3FOG-old') and three with better thermal insulation capacities. The last building ('1301') was built in 1985 with better energy performance.

In Hungary, all Housing Factories followed the original Soviet technology, but one of them bought the Danish license; therefore, one of the types represents this factory ('KF10'). The typology includes every typical floor plan and number of stories with different surface-to-volume ratios: two of the types have 5 heated stories, and the other buildings are 10-11-stories high.

Finally, another important aspect was that all of the selected types were built in large quantities in the country. The established eleven types of buildings represent the precast large-panel building stock in Hungary well.

3. The environmental evaluation of building refurbishment

During this research study, a bottom-up methodology was developed for the analysis of the refurbishment options of prefabricated concrete building stock to reduce their impact on the environment, which is demonstrated here on a case study area. The method is based on life cycle assessment (LCA), which studies the environmental aspects and potential impacts throughout a building's lifetime from raw material acquisition through production and operation to disposal.

A comparative analysis was developed: different refurbishment options were studied to compare their relative environmental impacts. This method can be the basis of a decision support tool for the architectural design process to select the most advantageous strategy. The methodology and the assumptions are described in more detail by Hrabovszky et al. (2013). In this paper, our previous results have been recalculated, and the scope of the analysis has been extended.

3.1. Case study area: Kelenföld housing estate

The Kelenföld housing estate in Budapest can be considered one of the first realized results of prefabricated panel construction in Hungary, which was developed in the capital from 1965 to 1975. Mainly 10-story and multi-story blocks among 15-story high-rise buildings and 1- or 2-story-high service buildings were attached to the blocks.

One of the largest housing estates in Budapest consists of 37 construction blocks with approximately 8,500 flats, which means that it is the home of approximately 20,000-25,000 citizens. In this study, the Kelenföld housing estate in Budapest was chosen for the analysis, and after assessing the environmental performance of the determined types, the mitigation potential of the housing estate was estimated.

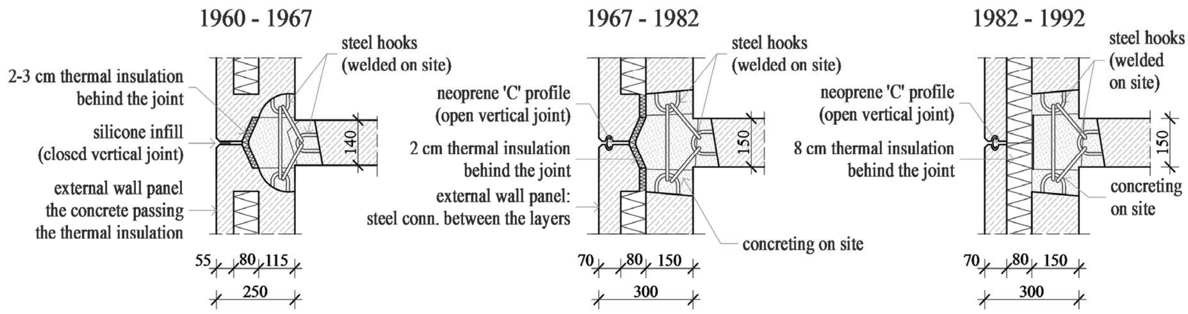
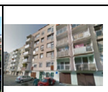
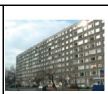
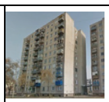
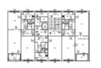
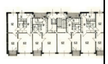
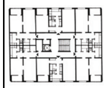
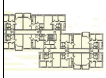
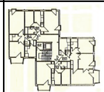
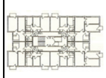
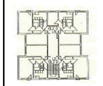
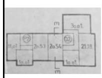


Fig. 1. The improvement of the general details (external and the internal panel connections) of the first Hungarian Construction Factory (based on Birhgoffer and Hikisch, 1994)

Table 1. Typology of the precast large-panel building stock in Hungary

picture											
floorplan (1 staircase)											
code of building	**3 FOG-old**	**3 FOG**	**KY**	**TB 51**	**6 FOG**	**A10**	**KB-512**	**KF10**	**C3**	**GYŐR 6/73**	**1301**
year of construction	1965	1970	1970	1980	1970	1975	1980	1980	1980	1975	1985
number of heated storeys	10	10	11	5	10	10	10	11	11	5	10
floor area	**13812.7 m^2**	**25574.4 m^2**	**12114.5 m^2**	**4528.9 m^2**	**19292.0 m^2**	**6770.8 m^2**	**5040.6 m^2**	**4083.6 m^2**	**6202.3 m^2**	**4211.2 m^2**	**8974.9 m^2**
number of flats	180	360	176	30	300	100	80	66	88	60	120
wall panels: thermal ins	8 cm rockwool	7-8 cm PS	7-8 cm PS	7-8 cm PS	7-8 cm PS	7-8 cm PS	7-8 cm PS	7-8 cm PS	7-8 cm PS	7-8 cm PS	7-8 cm PS
wall panels: insul. at joints	no insulation	2-3 cm	2-3 cm	2-3 cm	2-3 cm	2-3 cm	2-3 cm	2-3 cm	2-3 cm	2-3 cm	7-8 cm
windows: material	wooden	wooden	wooden	wooden	wooden	wooden	wooden	wooden	wooden	wooden	PVC
windows: infiltration rate	high	high	high	high	high	high	high	high	high	high	moderate
shape of roof	flat roof, ventilated	flat roof, ventilated	flat roof	flat roof	flat roof, ventilated	flat roof, ventilated	flat roof	flat roof	flat roof	flat roof, ventilated	pitched roof
heating system	double pipe system	double pipe system	double pipe system	single pipe system, flow-through	double pipe system	single pipe system, flow-through	single pipe system, flow-through	single pipe system, flow-through	single pipe system, cross conn.	single pipe system, cross conn.	single pipe system, cross conn.

Five types of buildings can be found in the case study area; therefore, the analyzed buildings are three different types of terraced panel buildings (the '3FOG-old' with extreme thermal bridges, the '3FOG' and the '6FOG'), the H-shaped 'eared-building' with 6 flats per story ('Kf10') and the detached so-called 'A10' building with 10 flats per story.

All of these buildings are 10-11 stories high and widely distributed not only in the analyzed housing estate but also in the whole country. The analyzed apartment houses were built by the first Hungarian Construction Factory according to the original Soviet technology.

3.2. Main assumptions

The whole remaining lifecycle of the buildings was considered. The lifecycle was divided into five phases: production, operation, maintenance, retrofit and disposal.

During the production phase, the construction of the building requires energy and the building materials to be transported to the site. Based on the building geometry and composition of the building elements, the built-in weight and the embodied energy of the materials were calculated with an average 5% mass added to account for construction waste. The reference inventory database used for the assessment in this study was the Ecoinvent v2.0 database by the Swiss Ecoinvent Centre, which contains high-quality inventory data of more than 2,500 products and services. This database was adapted for Hungarian circumstances (Szalay, 2008).

In the operation phase, the energy demand of the building service systems was assessed according to the Hungarian building energy calculation method (TNM, 2006) based on the Energy Performance of Buildings Directive (EPBD, 2002). The buildings erected by industrialized technology in Hungary are supplied particularly with district heating, and based on the data given by FŐTÁV (the district heating company of Budapest), the district heating mix of the assessed area was composed. The annual energy demand for lighting was neglected, as is allowed by the regulation in the case of residential buildings.

Maintenance activities involve small repairs and periodic replacement of building elements and service systems based on their expected lifespan and includes the production of the new elements. No modernization, thermal performance upgrade or major rebuild, enlargement, conversion etc. was considered during the maintenance phase.

The retrofit phase includes a comprehensive refurbishment, reducing the operational energy need for the remaining prolonged lifetime. The phase includes the transport of the new building materials to the site (e.g., the new windows) and the transport of the replaced old elements to final disposal (e.g., the old windows), the production and installation of the new materials and the disposal of the exchanged building structures. The last lifecycle phase includes the disposal of the replaced building materials in the maintenance phase and the demolition of the building at the end of the effective life, separation, transport and processing of materials according to their end of life scenario and re-cultivation of the deposit site. An Excel-based tool was developed for the analysis, and the calculations are based on real building documentations.

3.3. The expected lifetime of the building

According to the literature, the expected physical lifetime of large-panel buildings is assumed to be between 80 and 120 years in Eastern Europe (Birghoffer and Hikisch, 1994). The expected lifetime of the building construction and the building service systems are not fundamentally different from that of the traditional building elements. In this study, the expected lifetime of a large-panel building was assumed to be 80 years.

As a new parameter, which is usually not considered in LCA studies, we assumed that the retrofit (particularly the thermal insulation of the external walls) is expected to increase the remaining lifespan of the building. Due to the additional thermal insulation, the expansion of the external reinforced concrete layer of the sandwich panels decreased, and the joints between the panel elements are completely hidden, eliminating the possibility of moisture penetration. Due to the new thermal insulation boards on the façade, the thermal bridge effect caused by the lower thickness of thermal insulation in the external panel joints is eliminated. Therefore, the risk of internal condensation is reduced. Thus, due to the retrofit, we assumed that the expected lifetime of the building increases by 20 years (20%).

Seven scenarios proposed for the retrofit in the case of the analyzed large-panel building:

- *No overall renovation (NR):* retaining the current building in its current state; only maintenance work is performed. The demolition is due at the end of the expected lifetime, when a new building will be erected with lower energy consumption. This is our baseline scenario.
- *Retrofit:* undertaking a comprehensive refurbishment; therefore, the operational energy need is reduced for the remaining lifetime, and the renovation prolongs the lifetime of the building. Hence, the demolition and the erection of a new building are delayed. The different levels of possible refurbishment in terms of the energy performance are the following:
- retrofit 1 (R1): achieve the current energy performance regulations in Hungary;
- retrofit 2 (R2): increase thermal insulation level of the building envelope to fulfill the requirements for the energy performance (the future regulation of 2015);
- retrofit 3 (R3): increase the thermal insulation level by upgrading the existing heating system and installing heat recovery ventilation;
- retrofit 4 (R4): retrofit 3 complemented by installing flat-plate solar collectors on the flat roof, reaching the Nearly Zero Energy Building requirement.

After 55-65 years (depending on the types) at the end of life, the renovated building will be demolished and a new one will be erected. Due to the increasingly stringent international regulations on energy performance, it is assumed that the newly erected building will have 30% lower energy consumption than the 'new building 2' scenario.

- *Demolition followed by the erection of a new building:* demolishing and constructing a new building (of the same shape and same size). Two different levels regarding the energy performance were considered:
- new building 1 (NB1): high-level thermal insulation and windows with gas heating system and heat recovery ventilation ('A' category).
- new building 2 (NB2): high-level thermal insulation and windows, heat recovery ventilation and solar energy use ('A++' category).

The long-term thinking suggests the inclusion of the embodied energy of every building component in the calculation, not only the envelope. These elements do not influence the operational energy consumption directly but account for a significant section of the embodied environmental impacts, especially in the case of multi-story buildings (König et al., 2010).

3.4. Results

LCA professionals use different impact assessment methods with several environmental indicators. In this study, along with the non-renewable cumulative energy demand, the CML method was used to assess the environmental impacts. The CML categories that were used included the global warming potential (GWP), the average European acidification potential (AP), the steady-state ozone depletion potential (ODP) and the generic eutrophication (EP).

Normalization was applied to understand the relative significance of the impact category results. In this study, the normalization factors given by Guinée in reference to the intervention in Western Europe in 1995 were used (Guinée et al., 2001).

All of the normalization figures of the analyzed building types show that buildings have the most significant contribution in the category of global warming, and the acidification potential was also found to be relevant although its contribution is less than half of the global warming potential. The normalized ozone depletion and eutrophication caused by the retrofit are insignificant. According to the results of normalization found in this study, the global warming potential, as the most significant environmental indicator, is demonstrated in more detail. Because the results for each building type are similar, the results of building 'A10' will be reviewed in more detail.

Fig. 2 shows the global warming potential for all of the scenarios of the 'A10' building, based on one year and to one square meter of floor area as a function of time. According to these results, for the first 2-3 years after the decision point (year 0), the 'no overall renovation' scenario seems to be the best decision. However, after this time, all of the retrofit options have a lower environmental impact. Until 60 years after the decision point, the 'retrofit 4' scenario, which is the high-level retrofit of the existing large-panel building, has the lowest global warming potential. At that moment, the retrofitted building will be demolished, and a new one will be erected with lower energy consumption and lower global warming impact because many emissions are directly linked to energy use. When analyzing a longer term, i.e., 60 to 100 years, there is a high level of uncertainty in the results due to the unforeseen changes in the future energy mix and regulations on the energy performance of buildings.

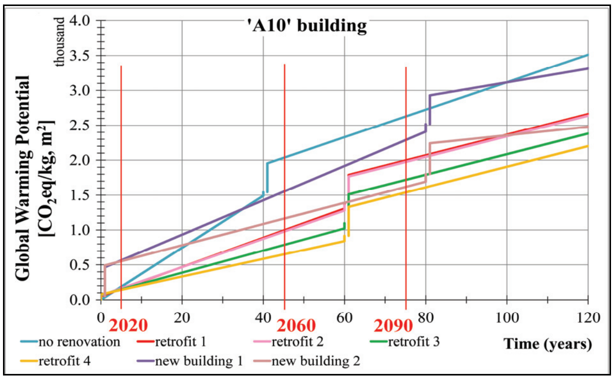


Fig. 2. The global warming potential of all of the alternatives in the case of the ‘A10’ building

The Kelenföld housing estate includes 37 precast panel buildings with a floor area of approximately 554,155 m^2. From the results for the individual buildings, the total energy saving and the mitigation potential of the housing estate can be calculated by taking into account the number of buildings per building type (Table 2).

According to the developed methodology, because of the different remaining lifetimes for the different scenarios and because the results are a function of time, the mitigation potential depends on the analyzed date. In this study, we chose to analyze three different dates: 5 years after the decision point (i.e., 2020), 40 years later (i.e., 2060) and 2090 (indicated with red lines on Fig. 2). In 2020, five years after the decision point, all of the demolition, construction and retrofit work is already finished, and considering the retrofit scenarios, the decrease in the cumulated GWP is between 17.39 and 29.95% compared to that obtained with the ‘no renovation’ scenario. Depending on the level of refurbishment, the operation phase becomes less significant as the energy performance of the retrofitted building increases (Fig. 3).

In the case of new buildings, because 2020 is only five years after their erection, the GWP is 200-212% higher than that obtained for the baseline scenario, and the construction phase is the most significant with 70.2-77.89% of the total emissions (Fig. 3).

In the case of the acidification potential the construction phase is more significant therefore the cumulative impact is increasing in almost all scenarios 5 years after the decision point (Fig.4.)

The next analyzed date was 2060, which is 45 years after the decision point. In the case of the ‘no renovation scenario’, the original building is supposed to be demolished after its estimated lifetime, and a new building will be erected; therefore, in 2060, the ‘no renovation’ scenario includes a demolition and a new building construction phase.

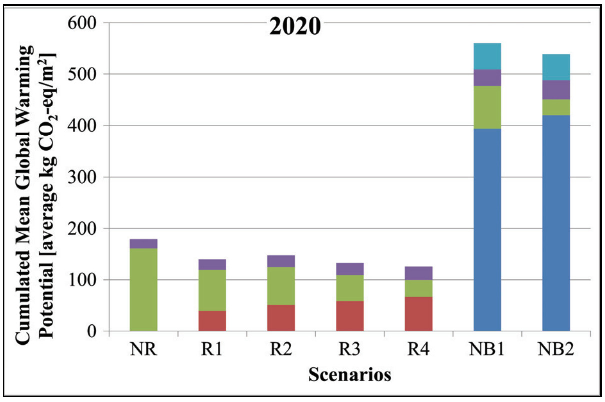
Table 2. Global warming potential of the building types from year 0 to 2020, 2060 and 2090

Building type	***Scenarios***	***Number of buildings***	***Floor area of one building (m^2)***	***Global warming potential (kg CO_2-eq/m^2)***		
				2020	***2060***	***2090***
A10	no renovation	12	6 770.8	186.29	2 051.70	2 465.82
	retrofit 1	12	6 770.8	154.67	992.59	1 995.89
	retrofit 4	12	6 770.8	142.20	650.57	1 530.30
	new building 2	12	6 770.8	568.33	1 175.78	1 631.37
6FOG	no renovation	5	19 292.0	178.69	1 825.49	2 157.02
	retrofit 1	5	19 292.0	128.68	928.79	1 803,11
	retrofit 4	5	19 292.0	112.19	577.79	1 368.47
	new building 2	5	19 292.0	524.82	1 010.34	1 374.48
KF10	no renovation	3	4 083.6	188.13	2 149.45	2 516.07
	retrofit 1	3	4 083.6	142.29	967.18	1 951.98
	retrofit 4	3	4 083.6	129.25	618.89	1 436.07
	new building 2	3	4 083.6	523.55	1 061.52	1 465.01
3FOG-old	no renovation	6	13 812.7	180.03	1 732.44	2 094.02
	retrofit 1	6	13 812.7	133.20	881.37	1 732.78
	retrofit 4	6	13 812.7	117.94	535.10	1 345.13
	new building 2	6	13 812.7	537.72	1 067.57	1 464.95
3FOG	no renovation	11	25 574.4	175.22	1 818.58	2 199.87
	retrofit 1	11	25 574.4	142.74	954.48	1 863.81
	retrofit 4	11	25 574.4	128.65	606.85	1 432.79
	new building 2	11	25 574.4	534.86	1 094.22	1 513.74

Hence, this scenario has the highest lifecycle CO_2-eq emissions (Fig. 5). The maintenance phase becomes increasingly significant in all of the scenarios, and in the case of the 'retrofit 4' scenario, it is 39.04% of the total emissions.

Regarding the acidification potential, the construction phase is more significant from the point of view of GWP, and because the maintenance phase also contains many construction works, these two phases of the lifecycle have the highest acidification impact. In 2090, the SO_2-eq emissions found for all of the scenarios are relatively close.

Summarizing the results for all of the buildings in Kelenföld (Table 3), in the long-term, the high-level retrofit scenario has the lowest impact: if all of the 37 buildings were upgraded according to the Nearly Zero Energy Building standard ('retrofit 4' scenario), a 67.3% decrease in the global warming potential could be achieved by 2060 compared with that obtained with the baseline scenario. Hence, this scenario has the highest lifecycle CO_2-eq emissions (Fig. 5). The maintenance phase becomes increasingly significant in all of the scenarios, and in the case of the 'retrofit 4' scenario, it is 39.04% of the total emissions.



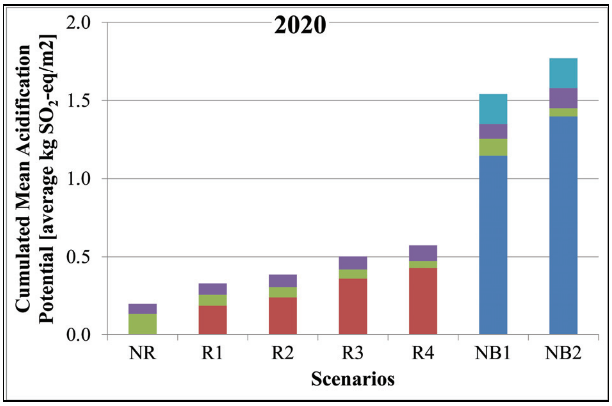
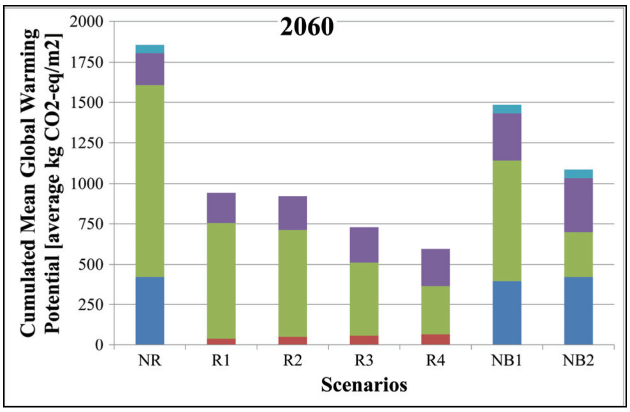


Fig. 3. Cumulated mean global warming potential of Kelenföld housing estate under the different scenarios from year 2015 to 2020

Fig. 4. Cumulated mean acidification potential of Kelenföld housing estate under the different scenarios from year 2015 to 2020



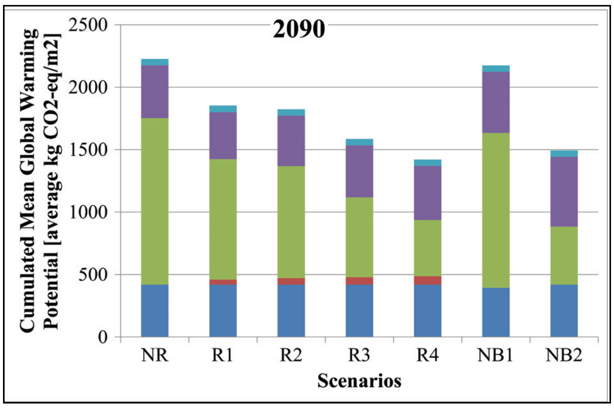


Fig. 5. Cumulated mean global warming potential of the housing estate under the different scenarios from 2015 to 2060

Fig. 6. Cumulated mean global warming potential of the housing estate under the different scenarios from 2015 to 2090

Table 3. The possible decrease in the global warming potential achieved by the different scenarios in the case study area

Area	*Scenarios*	*Total number of buildings*	*Total floor area (m^2)*	*Global warming potential as a ratio of the NR scenario*		
				2020	**2060**	**2090**
Kelenföld	no renovation	37	554 155.3	100.00%	100.00%	100.00%
	retrofit 1	37	554 155.3	**78.79%**	51.12%	83.46%
	retrofit 4	37	554 155.3	**70.71%**	**32.34%**	**64.02%**
	new building 2	37	554 155.3	301.59%	58.80%	67.42%

Hence, this scenario has the highest lifecycle CO_2-eq emissions (Fig. 5). The maintenance phase becomes increasingly significant in all of the scenarios, and in the case of the 'retrofit 4' scenario, it is 39.04% of the total emissions.

4. Conclusions

According to the findings presented in this paper, the comprehensive refurbishment of prefabricated concrete panel building stock is worthwhile from an environmental point of view in both the short and the long terms.

In this paper, we considered that refurbishment is expected to prolong the remaining lifetime of a building, which is a relevant factor that is usually neglected when evaluating demolition vs. refurbishment scenarios.

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