Decision-making case study for retrofit of high-rise concrete buildings based on life cycle assessment scenarios

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Abstract

The prefabricated reinforced concrete panel construction method was spreading throughout Europe during the reconstruction wave following the World War II in order to decrease the general housing shortage. Nowadays approximately 13.5% of the Hungarian people live in these high-rise buildings, therefore their refurbishment is inevitable. The problem this building stock presents is that the operational energy use is extremely high, due to design, constructional and structural errors.

During the research a methodology was developed for the analysis of the refurbishment possibilities of prefabricated concrete buildings in order to reduce the impact on the environment. The method is based on Life Cycle Assessment and in case of an existing building more scenarios proposed for the refurbishment are to be compared, providing a decision support tool for the architectural design process by identifying the largest environmental impacts and optimizing the design.

The methodology is demonstrated on a case study: the 10-storey high apartment building including 360 flats was built in 1968 according to the original Soviet technology, and it was one of the first prefabricated concrete buildings in Hungary.

The paper deals with the question 'What makes an existing high-rise reinforced concrete building sustainable throughout its remaining life-span?'

Keywords: Life Cycle Assessment (LCA), scenarios for refurbishment, life time, prefabricated concrete apartment building

1. INTRODUCTION

The European Union has recently confirmed its commitment towards a sustainable future by adopting the 20-20-20 target: reducing the greenhouse gas emissions at least 20% below 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 around 40% of the energy consumption in the EU providing a great potential for cost-effective energy savings. There are more options to reduce the energy consumption in case of new buildings but the **sustainable refurbishment of the existing building stock** is an urgent task.

The goal of sustainable rehabilitation is the modernization of the existing building stock meeting the demands of present times and focusing on technical and ecological aspects at the same time, as well as the lengthening of their life-span and the conservation of built heritage. Besides the aesthetical and economical questions, energy efficiency and environmental impacts are important factors of decision making about the retrofitting of an existing building. Life Cycle Assessment (LCA) provides a scientifically sound solution for optimising the environmental performance of building.

The **reinforced concrete precast large panel construction** method was spreading throughout Europe during the reconstruction wave following the World War II in order to decrease the general housing shortage. Today their overall refurbishment is inevitable and urgent. The main problem this building stock presents is that the operational energy use is extremely high, due to design, constructional and structural errors. This paper deals with the question ’What makes an existing reinforced concrete high-rise building sustainable in the long term?’ through a case study.

1.1 The existing building stock

In Hungary the first initiatives of the prefabricated reinforced concrete large-panel construction method were carried out in 1954, later in 1966, and the large-scale “production” of large wall panel blocks became possible. During the following decades, about 30-35,000 flats were built annually. Altogether 510,000 flats of this type were built throughout the country (nowadays appr. 13.5% of the people live in these high-rise buildings). Considering the economical requirements of that period, mainly four to ten storey-high blocks were built, in the form of housing estates.

1.2 The environmental evaluation of building refurbishment

During the research **a methodology was developed** for the analysis of the refurbishment options of prefabricated concrete buildings in order to reduce their impact on the environment. The method is based on **Life Cycle Assessment (LCA)** that studies the environmental aspects and potential impacts throughout a building’s life from raw material acquisition through production and operation to disposal. A comparative analysis was developed: different refurbishment options were studied in order to compare their relative environmental impacts. The methodology is demonstrated on a case study.

2. CASE STUDY

The case study building is a **ten-storey high apartment building including 360 flats** situated in Budapest. The building was retrofitted in 2007 to a high energy standard exceeding the requirements of the current regulations. The aim of our study is to evaluate whether the actual retrofit option was the most adequate for the refurbishment regarding the long term using the developed methodology.

2.1 Description of the building

The analysed apartment house was built in 1968 by the first Hungarian Construction Factory according to the original Soviet technology, and it was one of the first precast large-panel buildings in Hungary located in the Kelenföld housing estate, in Budapest.

Regarding **the building constructions and the building materials**: the one-storey high reinforced concrete wall or floor panels are welded on their edges and assembled by fixing and concreting on the site in order to realise their box-structure, therefore the weak points of the structure are mostly the **joints**. Considerable attention should be paid to both satisfactory joint sealing (heat-insulation and waterproofing) and the protection against corrosion of joining reinforcing bars.

Outside perimeter wall panels with built-in insulation are made of sandwich-structure: reinforced concrete elements with polystyrene thermal insulation. The thickness of the thermal insulation in the sandwich-panels decreased to 2 cm at the joints resulting in extreme thermal bridge losses on the façade (see Figure 1).

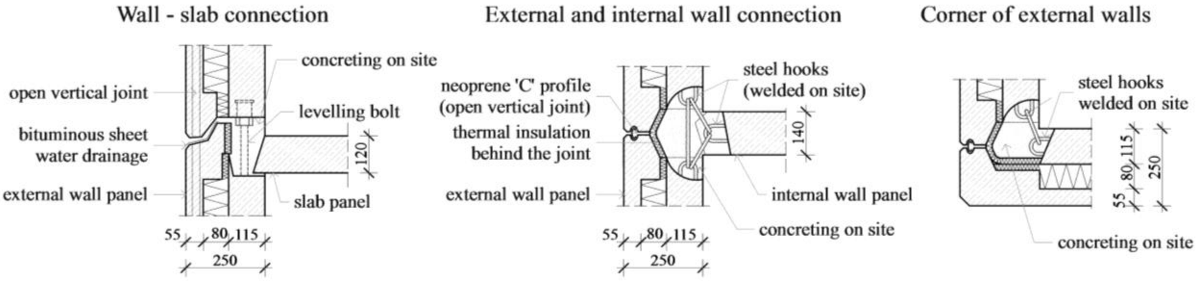

Figure 1: General details of the external panel connections (based on [1])

In the Kelenföld housing-estates a double-shell (ventilated) cold roof covered by bitumen membrane water proofing was generally applied with a low-insulation level, and lots of drainage problem nowadays.

The original wooden windows had obsolete construction, with very poor insulation capacity and high filtration rate. In most cases they were made with reveal shape and installed without any external shading devices.

Regarding **the building services** district heating systems with no possibility of local control were usual until the middle eighties. 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 The retrofit

The goal of the retrofit was to reduce energy consumption. According to the data of the district heating company the heating energy consumption of the building was 11,201.6 GJ/year (that is 140.26kWh/m^2,year), in 2006.

In 2007, the refurbishment process began with the thermal insulation of the building shell (facades, roof and the slab of the basement) and the installation of up-to-date windows and entrance doors.

Since the sandwich panels were originally insulated but the quality of the joints was poor, the **additional thermal insulation** was designed to minimize the thermal bridge losses. The insulation of the building envelope was completed by **the upgrading of the windows**: the old, extremely bad timber windows were exchanged for good quality double glazed PVC ones. Due to these steps the heating energy consumption of the building **decreased** to 7,336.6 GJ/year (that is 91.86kWh/m^2,year) in 2008. This means approximately 40% energy saving considering the different winter conditions (in 2008 the average temperature in winter was higher than two years before). The community of the inhabitants aims to renew the heating system as the next step to have an overall refurbishment of the block.

3. METHODOLOGY

This study focuses on the environmental optimisation of the retrofit of the existing precast large-panel building in Kelenföld housing estate. This method provides a **decision support tool** for the architectural design process by identifying the largest environmental impacts and optimizing the design of the refurbishment. The method of life cycle assessment (LCA) was applied, following the norms ISO 14040 [2] and ISO 14044 [3].

The main goal of the study was to evaluate the environmental impacts of the refurbishment of a typical existing high-rise large panel residential building in Hungary and the contribution of the different life cycle phases of refurbishment, maintenance, operation and disposal. Seven different scenarios are compared to support the decision making.

The **functional unit** was a high-rise prefabricated reinforced concrete apartment building with altogether 22,185 m2 heated area in Budapest (Hungary) to provide housing for 100 additional years. An **Excel-based tool** was developed for the analysis.

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 [4]. Since the sources of this database are mainly the Swiss and German industry the building materials produced in Hungary required certain modifications. The composition of the Swiss and the Hungarian electricity mix differs significantly; hence these modules were changed accordingly. 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. For products absent from the database new datasets were developed based on the material composition [5].

During the research the **non-renewable cumulative energy demand** method the **CML method** was used to assess the environmental impacts, both are internationally accepted and widely used.

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

During the production phase, the **construction** of the building requires energy and building materials transported to the site. In this study 15 MJ/m2 of diesel and 2 kWh/m2 of electricity were assumed for the construction based on the ecoinvent data. Based on the building geometry and composition of the building elements, the built-in weight and the embodied energy of the materials was calculated with an average 5% mass added to account for construction waste.

In the **operation phase**, the energy demand of the building service systems was assessed according to the Hungarian building energy calculation method [6] based on the Energy Performance of Buildings Directive [7]. The user-related components of the energy demand (e.g. the air change rate, internal gains and domestic hot water need) are defined in the Hungarian Government Decree on the energy performance of buildings. The annual energy demand for lighting was neglected, as it is allowed by the regulation in case of residential buildings. The **gross energy demand** including the efficiency and losses of the systems was calculated using the tabulated values of the Decree [6].

Maintenance activities involve small repairs and periodic replacement of building elements and service systems based on their expected life-span, this includes the production of the new elements. No modernisation, thermal performance upgrade or major rebuild, enlargement, conversion etc. were considered during the maintenance phase. For the maintenance works 1 kWh/m2 electricity was assumed. The values for the life-span of the building elements were estimated based on the literature sources [8][9][10].

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 life cycle 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. For the demolition process itself, 30 MJ/m2 of diesel was calculated based on the ecoinvent data.

According to the literature, **the physical lifetime of large-panel buildings** is assumed to be between 80-120 years in Eastern Europe [1]. The expected lifetime of the building constructions and building service systems are not fundamentally different from traditional building elements. In this study the expected life time of a large-panel building is 80 years.

The case study building was built in 1968, so in the analysed moment (the retrofit was taking place in 2007) it was 39 years old (rounding to 40 years), so the remaining life time is 40 years more.

It is assumed that the retrofit (especially the thermal insulation of the external walls) is expected **to increase the remaining life span of the building.** Due to the additional thermal insulation, the expansion of the external reinforced concrete layer of the sandwich panels' decreases, and the joints between the panel elements are completely hidden eliminating the possibility of moisture penetration. By 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 life time of the building increases** by 20 years (20%).

The scenarios proposed for the retrofit to be compared, in case of a 40 year-old large-panel building:

- *No overall renovation:* retaining the current building in its current state, only maintenance work is done. The demolition is due at the end of the expected life time, in 40 years, when a new building will be erected with lower energy consumption.
- *Retrofit:* undertaking a comprehensive refurbishment, therefore the operational energy need is reduced for the remaining lifetime, the renovation prolongs the life time of the building, hence the demolition and the erection of a new building is delayed. The different levels of possible refurbishment in point of the energy performance:
  - retrofit 1: the finished, actual retrofit work (see 4.2.);
  - retrofit 2: increased thermal insulation level of the building envelope;
  - retrofit 3: increased thermal insulation level with upgrading the existing heating system and installing heat recovery ventilation;

  - retrofit 4: retrofit 3 complemented by installing flat-plate solar collectors on the flat roof.

  After 60 years, 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 erected new one will have 40% 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, of the same size). Two different levels regarding the energy performance were considered:
  - new building 1: high-level thermal insulation and windows with gas heating system and heat recovery ventilation ('A' category)
  - new building 2: high-level thermal insulation and windows, heat recovery ventilation with solar energy use ('A++' category)

The long-term thinking suggests including **the embodied energy of every building component in the calculation,** not only the envelope. Those elements do not influence the operational energy consumption directly, but they account for a significant section of the embodied environmental impacts, especially in case of multi-storey buildings [5].

4. RESULTS

LCA professionals use different impact assessment methods, with several environmental indicators. In this study, beside the non-renewable cumulative energy demand the CML method was used to assess the environmental impacts. The used CML categories were: the global warming potential, 100 a (GWP), the acidification potential, average European (AP), the ozone depletion potential, steady state (ODP) and the eutrophication, generic (EP).

Normalization, an optional step of life cycle assessment was applied to understand the relative significance of the impact category results. In accordance with EN ISO 14044, normalisation is the calculation of the magnitude of the category indicator results relative to reference information. The obtained results of the impact categories are converted to common units, therefore the relative significance of the category results can be compared. In this study, the reference values (normalisation factors) given by Guinée were used referring to the intervention in Western Europe in 1995 [11].

Figure 2 shows the ratio of the normalised category results of the retrofit 1 scenario referring to 1 m2 floor area and 1 year per capita. The focus is to compare the relative values. All normalization figures (of the other retrofit scenarios) show that buildings have the most significant contribution in the category of global warming (GWP) and also the acidification potential (AP) is relevant, but the contribution is less than half of the GWP. The normalised ozone depletion and eutrophication caused by the retrofit are insignificant.

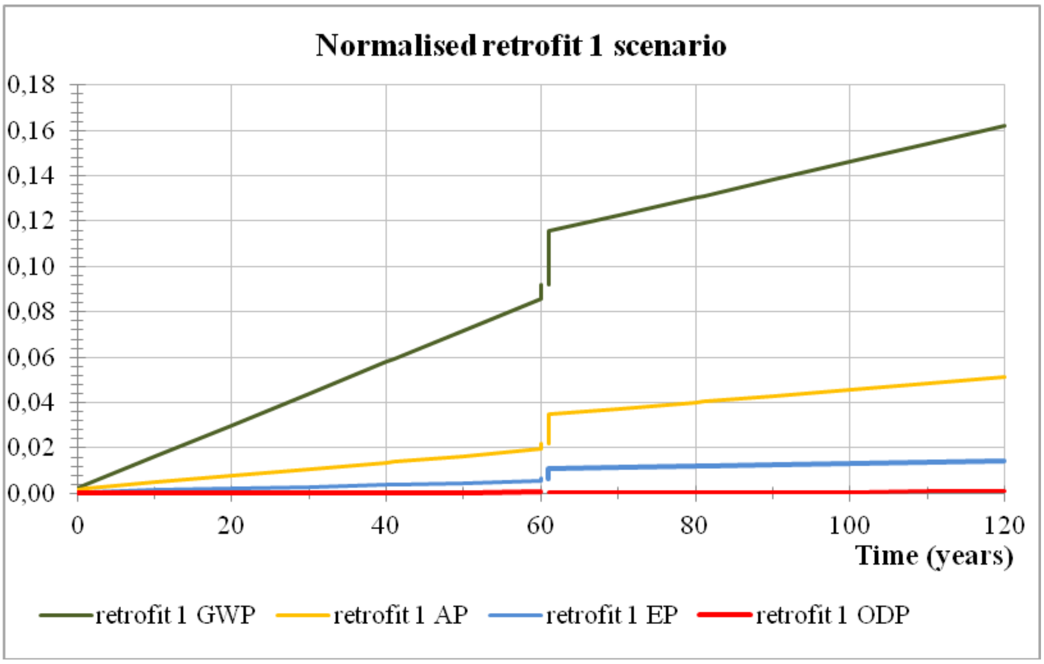

Figure 2: The normalised impact category results (of the retrofit 1 scenario)

Therefore in this paper the **global warming potential**, as the most significant environmental indicator is demonstrated in more detail. Figure 3 below shows the global warming potential of all the scenarios, referring to one year and to one square metre of floor area as a function of time.

Figure 3 shows that **for the first 2-3 years** after the decision point, the ‘no overall renovation’ scenario seems to be the best decision. However, after this time, all retrofit options have a lower environmental impact.

Until year 50 after the decision point, the ‘retrofit 4’ scenario has the lowest global warming potential, which is the high level retrofit of the existing large-panel building. At that moment the retrofitted building will be demolished and a new one will be erected but with a lower energy consumption and lower global warming impact, since many emissions are directly linked to the energy use.

The **steps of the designed ‘retrofit 4’ scenario are:** increased thermal insulation of the external building envelope (16 cm polystyrene on the external wall, 10 cm wood wool insulation on the basement floor and 24 cm polystyrene on the flat roof); the change of the existing wooden windows in the flats and the staircase for multi-chambered PVC thermally efficient windows with low-e glazing (u=1.1 W/m^{2}K) and the installation of new metal main entrance doors (u=1.1 W/m^{2}K). To avoid thermal bridge effects the insulation of the parapet walls of the loggias, balcony slabs, plinths, and the attic walls will be carried out. Finally in the course of the modernization of the building services thermostatic valves are fixed to the radiators in the flats in order to be able to control the heat flow and mechanical ventilation is implemented with heat recovery (70% efficiency) completed by flat plate solar collectors installed on the roof (app. 2,0m^2/apartment) and the necessary puffer water tanks in the basement.

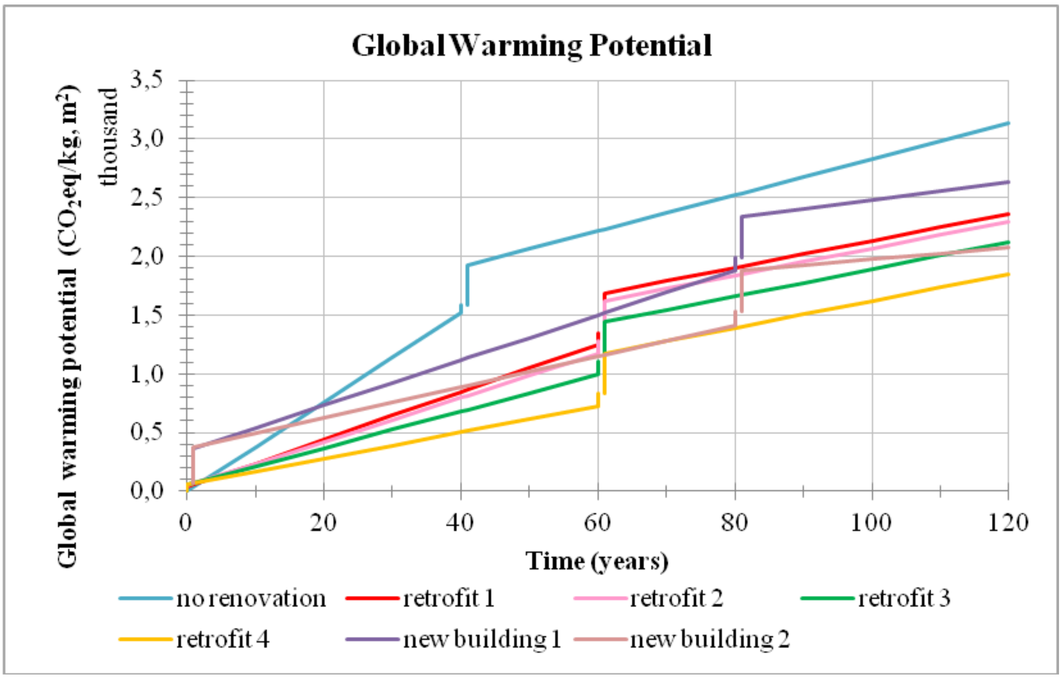

Figure 3: The global warming potential of all the alternatives

Analysing **the longer term – 60 to 80 years** – due to the high level of uncertainty in the energy mix and the future regulations about the energy performance of buildings it is difficult to decide whether the immediate demolition of the building and the construction of a new low-energy building (scenario: new building 2) or the retrofit 4 scenario has the lowest life cycle CO_2 eq emission.

The same tendencies can be observed in case of the **ozone depletion potential** of the alternatives, consequently the operation phase is dominant. The ‘retrofit 3’ and ‘retrofit 4’ scenarios have the lowest ozone depletion potential during the assessed period of time.

Regarding the **acidification potential**, the production phase is more significant than from the point of view of CED and GWP: the construction is around 24-26 % of the total emission. All retrofit scenarios have lower acidification impact than the new building scenarios.

Similarly to AP, the production phase of the new building scenarios is relatively dominant in the category of the **eutrophication potential**. Production is 25-29 % of the life cycle impacts. The relatively high significance of the end-of-life phase is remarkable, it is around 9% of the total.

The **cumulative energy demand** is suitable as a screening indicator in the environmental assessment of buildings. Since the burning of fossil fuels is dominant in greenhouse gas emissions, and the analysed buildings are heated by district heating based on natural gas in the Kelenföld housing estate, the CED and GWP values were highly correlated in this assessment also.

5. CONCLUSIONS

For energy efficient retrofit, the payback time is usually calculated on the basis of the investment and the savings. But when the question is whether a retrofit is worth doing or not, all relevant aspects have to be considered, not only the payback time.

The ‘no overall renovation’ scenario has the lowest life cycle CO_2 eq emission in the first 2-3 years, but after this time the retrofit options have a lower global warming potential: the energy and the environmental impact invested into the retrofit is quickly recouped. The **comprehensive retrofit is the most environmental friendly option until about 50 years**, when the renovated building reaches the end of its expected life time. In an even longer term (60-80 years), as it is difficult to predict the future regulations about the energy performance of buildings and the possible changes of the building materials in the long term, there is an increasing uncertainty involved in the assessment.

The analysed time period depends on the decision makers. Investors are generally interested in the very short term. The government or the local governments are able to think 10 to 15 years into the future in case of buildings, but their actions depend on the political decisions.

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