Buildings Sustainability on a Life Cycle Basis: Comparative evaluation between new construction and refurbishment of an existing building

KONDILI M. EMILIA[1,*], KALDELLIS K. JOHN[2], ANGELOS ENTMONS[3], NATALIS PETROVITS[3]

[1]Optimisation of Production Systems Lab, University of West Attica
[2]Sost Energy Applications and Environmental Protection Lab., University of West Attica
[3]PIRAEUS TOWER SA

*corresponding author:
e-mail: ekondili@uniwa.gr

Abstract On a global basis, buildings consume about 60% of raw materials per weight and almost 1/3 of the global energy consumption quantities. For many years the most important issue determining the sustainability of a building has been the energy consumed during its operation. However, recently a trend has emerged towards the consideration of the building's energy use on a life cycle basis rather than only in their operation; thus, including the construction, operation and end of life phases.

The objective of the present work is to describe the development and the implementation of a methodology for the comparative environmental performance of a building between two alternative solutions; namely its new construction versus its refurbishment. The comparative evaluation is based on detailed estimation of two important magnitudes, that of the embodied energy and the embodied carbon.

The methodology has been implemented in one of the most emblematic buildings in Attica Region, the Piraeus Tower that is undergoing a total refurbishment. The methodology may be applied in other buildings of various types and uses and provide a useful decision support tool for the selection between re-construction or refurbishment, leading to more sustainable in environmental terms as well as more financially efficient developments.

Keywords: embodied energy, embodied carbon, refurbishment, comparative evaluation

1. Introduction

For a number of years, in the building sector attention has been directed towards reducing energy consumption as much as possible during the building's operation phase (lighting, heating, cooling, hot water, appliance operation). However, the total energy utilised by a building includes also another interesting quantity that should be used in the environmental assessment of buildings with much greater reliability and accuracy. This remarkable energy quantity is still under investigation (Kaldellis et al.), namely the embodied energy and the embodied carbon (hereafter referred to as terminology embodied carbon - embodied energy, EC, EE respectively).

2. Embedded Energy and Embedded Carbon

The embodied energy, one of the most basic indicators of the environmental behaviour of buildings, refers to the sum of the primary energy coming from renewable or conventional energy sources required (Figure 1):

- ✓ for the mining
- ✓ the transfer of materials
- ✓ the production process, and
- ✓ the final deposition of the materials.

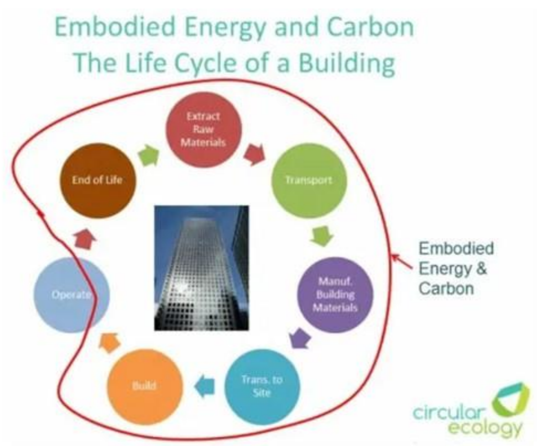

Figure 1. Embedded Energy and Embedded Carbon representation ([6]

Accordingly, the embodied carbon of a building is equal to the sum of:

- ✓ The carbon footprint of the materials themselves
- ✓ The carbon footprint of transporting the materials to the construction site of the building, and
- ✓ The carbon footprint of the on-site works in the building itself.

The total utilization of energy in a building throughout its lifetime is the sum of the Embedded Energy and the Energy during the Operation of the Building.

The EE in a building varies significantly from building to building and from location to location. It is determined by the materials and products themselves, the production systems and technologies, the primary energy mix for the production of final energy, the modes of transportation,

the suppliers, etc. For the above reasons, upper and lower limits are given to values of embodied energy and not necessarily absolute values.
In Figure 2 the correlation between EE (Embedded Energy) and energy during operation (OE) in various cases of energy management of buildings is indicatively shown.

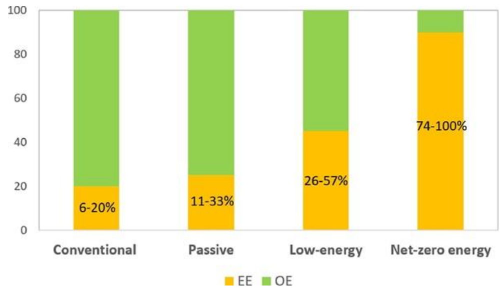

Figure 2: Relative importance of EE and OE energy of different types of building energy management [1].

In most cases there appears to be a linear relationship between embodied energy and embodied carbon, assuming a constant primary energy mix.

3. Best practices – Case Study

One of the most effective construction techniques to reduce the total energy footprint of a building is to choose the refurbishment instead of new construction whenever this is possible. The assessment at the level of Life Cycle Analysis of the renovation of a building and especially the comparative evaluation between the renovation and the new construction has several methodological difficulties. That prevents the possibility of fully quantifying the comparative advantages of renovation.

It is worth mentioning at this point the results of an interesting work including a comprehensive comparative evaluation, made by Hasik et al (2019).

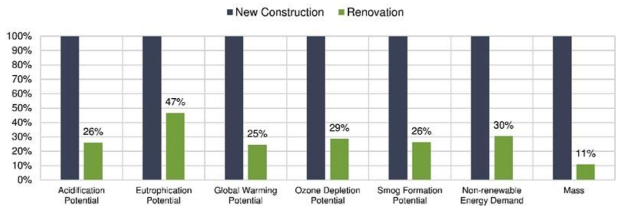

Figure 3: Comparison of environmental impacts between new construction and renovation [2]

In this study, a comparative assessment of a set of environmental impacts was made between renovation and new construction. The Case Study showed a reduction of 53–75% in six different environmental impact categories (Figure 3) in the comparison between renovation and rebuild. The utilization of the already existing foundation is a very important element of reducing this impact.

4. The PIRAEUS TOWER Case

Piraeus Tower (PT) was the most ambitious construction project in Greece in the 1970s. Located in the heart of Piraeus, the biggest passenger port in Europe, it was originally built in 1972 with the ambition to become a landmark in a port which was, at that time, rapidly changing and developing into an international hub for shipping and transportation.

The building frame was completed in 1974, some shops and offices were operating, however in the years that followed the project was abandoned and the Tower remained uncompleted and empty until 2020. In 2020, DIMAND in collaboration with EBRD and PRODEA Investments undertook the 99-year concession of the Piraeus Tower from the Municipality of Piraeus. (Fig 4).

Figure 4: Piraeus Tower [7]

Sustainability is in the hard core of PT missions and underlying philosophy. Therefore, Piraeus Tower will be the first high - rise building in Greece aiming at the highest level, Platinum of the leadership in Energy and Environmental Design (LEED), the most widely known green building rating system used worldwide. In this context, Piraeus Tower shareholders have shown a very high interest in analysing its integrated energy and environmental characteristics. Therefore, the present detailed study has taken place trying to assess the embedded energy and the carbon footprint of the building on a Life Cycle basis.

Table 1. Main axes of the comparative evaluation

Scenario I	Hypothetical Scenario, demolition and new construction
Scenario II	Real Scenario, Refurbishment
Stage A	Materials Embodied Energy
Stage B	Transportation to and from PT
Stage C	On site works

Table 2. Baseline of the comparative evaluation

HYPOTHETICAL SCENARIO I: Demolition and new construction	**REAL SCENARIO II:** RENOVATION
The foundation is maintained	The foundation is maintained
Complete demolition except foundations	Removal of worn out materials
Construction of the floors from the ground floor upwards	Renovation of the existing structure
Rebuilding materials	Renovation materials
Concrete	Concrete
Steel	Steel
	Saving quantities of glass for recycling
	Carbon fabrics Resins
NON-DIFFERENTIATED SCENARIO ELEMENTS	
Insulating material (same)	
Masonry (same)	
Openings (same)	
Energy consumption during operation (the same)	

For the comparative evaluation of the construction alternatives for Piraeus Tower, two scenarios have been considered and analysed; namely, Scenario I: Hypothetical Scenario – Demolition and re-construction and Scenario II: Actual project – Renovation analysis, which are clearly recorded in Table 1. The comparative evaluation refers to the magnitudes of embedded energy and embedded carbon for the three aforementioned stages (Table 1 and Figure 5).

The analysis as mentioned before compares two construction solutions based on the EE and EC magnitudes. Various assumptions have been made for the reliable comparison of these two construction solutions, indicated in Table 2.

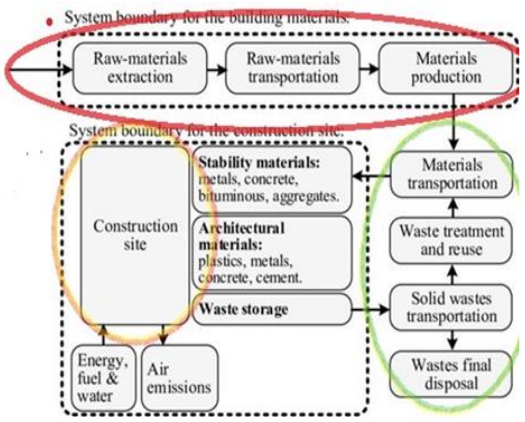

Figure 5: Schematic representation of A, B, C stages for the calculation of EE (based on Rodrigues et al, 2018)

It should be stressed that its added value is that the methodology may be used for the comparison of various construction solutions based on various and different performance measures. In our case only EC and Carbon Footprint have been considered; in its prospects the work may include also various other environmental impacts and indices. The main data of the EE and EC measures have been taken from various sources and most of them ae indicated in Table 3.

Table 3. Main data of the comparative evaluation (Minnuno et al. and other sources)

Material	Embedded Energy (MJ/kg)	Carbon Footprint (kg CO_2 eq/kg)
Concrete	1,0-3,0	0,14-0,28
Structural steel	21,9-35,3	1,7-2,8
Glass	18-35	
Carbon Fibers	240	
Reinforcement Resins	80	
Repair mortar	1,1	
Carbon fiber resir	80	
Diesel	38,6 MJ/lt	2,63 kg CO_2 eq/lt

5. Calculations and Final results

The differential quantities between the two Scenario have been calculated and then, exploiting data of Table 3 the Benefit or Loss of EE and EC have been estimated. The analytical results for Stage A are shown in Table 4.

Table 4: Results of the comparative evaluation, Stage A.

Material	Embedded Energy (GJ)	*Benefit or Loss*
Concrete	77800	Benefit
Structural Steel	71300	Benefit
Glass	3850	Benefit
Reinforcement Resins	-360	Loss
Repair mortar	-14	Loss
Carbon fiber resins	-440	Loss
Carbon Fibers	-785	Loss
TOTAL	***151350***	***Benefit***

Accordingly, detailed calculations have been made for Stages B and C. Detailed and reliable data have been provided by the engineering team of the project owner. Other required data have been extracted and validated from various scientific and commercial data bases.

The overall result in terms of EE of the materials (Stage A) gives a benefit for Scenario II of 151350 GJ or 42 GWh. This size corresponds to the annual electricity consumption of almost 10,000 families or 30,000 people, considering that the annual domestic electricity consumption in Greece is 1500 kWh per person.

The basic results that have been described in the previous chapters are summarized in Table 5. More specifically, in Table 5 the results of the comparative evaluation between the two construction solutions for Stages A, B and C are presented based in the Embodied Energy and Embodied Carbon magnitudes.

Table 5. Main results of the comparative evaluation

Analysis Phase	Embodied Energy Diff	Carbon Footprint	Benefit /Loss
A. Materials Embodied Energy	42 **GWh** (Savings for Scenario II)	*21.000 tn CO_2* (Savings for Scenario II)	Benefit
B. Transportation to and from PT	8,45 **GWh** (Savings for Scenario II)	*2130 tn CO_2* (Savings for Scenario II)	Benefit
C. On site works		*21 tn CO_2*	Loss

The amount of carbon dioxide saved from this energy, if it is considered that on average each kWh of energy releases about 0.5 ton of CO_2, is 21,000 tons. Also, considering an interesting fact about forests and their corresponding CO_2 emissions, the amount of carbon dioxide saved is 21,000 tons. If it is considered that one hectare of forest absorbs more than 400 kg of carbon dioxide per year [8]), the amount of CO_2 saved due to the renovation option releases a total of 58,000 forest hectares per year, or for a period of ten years it releases about 5,800 forest hectares each year.

6. Additional Environmental Benefits

In addition to the above results, there are various other important issues that need to be stressed, relevant to the selection of the refurbishment solution. The first one is related to additional environmental benefits incurred from the selected solution. Certainly, a detailed environmental assessment is required that will quantify more indices and will provide more detailed results. Indicatively we may refer to

- ✓ The noise and traffic congestion that would exist in the case of new construction that would also cause serious CO_2 emissions that should also be estimated in the carbon footprint.
- ✓ Avoidance of the foundations that will be the heaviest in terms of embedded energy process increasing it in orders of magnitude. In our current study the foundations are completely avoided.
- ✓ Water savings - water footprint reduction. In case of demolition there is continuous wetting resulting in big water quantities consumption. Detailed assessment should be made; however, it is believed that an amount of 5,500 tons of water are saved corresponding to the consumption of an area of 130 inhabitants for one year.
- ✓ The location of PT -independently of the construction solution- has one more serious sustainability advantage, the avoidance of the transportation burden because of the nearby train and metro stations.
- ✓ Parking positions -following the latest trends- are getting less since they absorb very big quantities of materials. In any case charging stations for EV have been planned for Piraeus Tower.

7. Conclusions and Prospects

In recent years there has been a particularly intense construction activity in the building sector with the aim of housing the population, the creation of tourist infrastructure and the development of large buildings as workplaces and business activities.

An important goal is the construction of buildings with minimized or even controllably reduced environmental impact. These building impacts include a large set of issues and parameters within which energy and carbon footprint play a very important and critical role. In this research work a comparative evaluation was made between two construction alternatives of the Piraeus Tower Utilization Project, owned by the Municipality of Piraeus and a consortium of companies.

The benchmarking refers to the hypothetical scenario of demolishing the existing building (before the works start) and re-erecting it or renovating the building, a solution which has finally been chosen and implemented. The figures that were considered as a basis for the comparative evaluation are the Embedded Energy and the Carbon Footprint.

Based on the analysis and calculations, the renovation solution appears to be much more preferable and environmentally compatible in both of these dimensions, compared to the rebuild scenario. Precisely because of its innovation, this project is proposed to be continued in the next phase as follows:

1. A detailed energy study is needed that also considers the energy during the use of the building.

2. Accordingly, a detailed environmental study will highlight all the environmental indicators of this complex construction project and will comprehensively propose ways to reduce them.

3. Every technical decision is governed and influenced by economic choices as well. Therefore, a detailed technical / economic analysis will be required.

Recapitulating, the main advantage and the added value of this work lies primarily in the fact that it can be used as a methodological tool. This method can be used in future corresponding projects as a decision-making tool regarding preferred materials and construction methods based on its overall energy and environmental analysis. Finally, in the next stage the entire methodology can be extended to overall technical and economic optimization.

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