LIFE-CYCLE ANALYSIS OF A SUSTAINABLE BUILDING, APPLYING MULTI-CRITERIA DECISION MAKING METHOD

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Abstract. Sustainability in construction industry became a concurrent part of contemporary building development. The reason is not only increased account of building maintenance, but there is another part of this problem – it is an impact of building’s life cycle on the environment. Part of this article is intended to a building life-cycle assessment (LCA) in sustainability and the conception of sustainability. Authors proposed the review of the LCA and sustainability in construction industry. The main purpose of sustainable building is to reduce the building impact on environment, during all buildings’ life, using environmental friendly technologies. The paper deals with a few building alternatives, which describes two types of living apartments with few different types of heating system. All the alternatives are defined with several criteria. Those criteria are not only an emission of construction process, but the construction price, work input, fuel annual price, water, energy and material, used for construction process and etc. By using Complex Proportion Assessment (COPRAS) multi-criteria method, the best alternative of viewed buildings is developed.

Keywords: LCA, sustainability, building, MCDA, COPRAS, AHP, environment, criteria.

1. Introduction

The major global challenges we are facing today need to be addressed in the multifaceted context of economy, society, environment and technology (ESET) (Jovane et al. 2008). Making the world’s villages, towns and cities environmentally, economically and socially sustainable is humanity’s most urgent challenge for the 21st century (Jarrar and Al-Zoabi 2008).

Buildings have direct environmental impacts, ranging from the use of raw materials for their construction and renovation to the consumption of natural resources, like water and fossil fuels, and the emission of harmful substances (Balaras et al. 2005). The design of buildings should take into consideration long-term environmental and economic benefits (Wang et al. 2010). Technology assessment is a critical process in managing technology. It is critical to select the right technologies that will meet the needs of the organization acquiring the technology. This becomes even more challenging in an era of globalization and exponentially increasing emerging technologies (Daim and Intarode 2009). It is well known how the construction sector wields an enormous influence over economic activity, employment and growth rates. Further consideration still needs to be given to sustainability (Lombera and Rojo 2010).

Efficiency is one of the main key issues closely related to the sustainable city agenda (Jarrar and Al-Zoabi 2008). The study of Shen et al. (2010) demonstrated that there is a need for shifting the traditional approach of project feasibility study to a new approach for embracing the principles of sustainable development. More than ever, the construction industry is concerned with improving the social, economic and environmental indicators of sustainability (Ortiz et al. 2009). The promotion of sustainable construction practice is to pursue a balance among economical, social, and environmental performance in implementing construction projects. Sustainable construction practice refers to various methods in the process of implementing construction projects that involve less harm to the environment (Ruggieri et al. 2009).

Excessive fluctuations in construction volume are undesirable and a comprehensive strategic planning is needed to sustain the development of the construction industry (Wong et al. 2010). The expression “sustainable construction” is being used more and more, it is necessary to distinguish between the sustainability of the construction activity and the sustainability of works constructed (Mora 2007).

Sustainable building has an effect on ecology and the economy, as well as socio-cultural factors such as the health and comfort of users. Sustainable building takes a holistic approach, looking at the ecological, economical
and social effects of the built environment on human beings as well as on the natural environment (Sobek et al. 2009).

In the next parts of this article are presented the review of a Life cycle assessment in sustainability, a review of multi-criteria, used in sustainability and the proposition of the COPRAS method, used in case study, which deals with sustainability.

2. Life cycle assessment (LCA) in sustainability

Life cycle assessment (LCA) is a powerful tool to identify a building’s environmental impact throughout its life cycle (Gu et al. 2008). The life cycle environmental impacts of commercial buildings are dominated by the operation stage, especially electricity consumption. Significant reductions in the environmental impacts of buildings at this stage can be achieved through reducing their operating energy (Kofoworola and Gheewala 2008). Here are some authors, which presented their works of LCA in sustainability:

- Liu et al. (2010) proposed a generic model of Energy Assessment for the Environmental Impact of the Building Lifecycle, with a special focus on the natural environment. The paper evaluates a building’s environmental sustainability through its energy footprint and environmental impacts.
- Mora (2007) explores the relationship between the life cycle of engineering works and their sustainable and transcendent qualities, and considers the possibility of creating durable works with ephemeral materials.
- Abeyesundara et al. (2009) presents a matrix to select sustainable materials for buildings in Sri Lanka, taking into consideration environmental, economic and social assessments of materials in a life cycle perspective.
- Zhang et al. (2006) presented a building environmental performance analysis system—BEPAS, which was developed based on the life cycle assessment (LCA) framework. In BEPAS, environmental impacts were investigated in three main aspects of a building that were closely related to environmental performance—building facilities, building materials and location.
- Dawood et al. (2009) presented a framework, methodologies and technologies that facilitate the integration of Environmental Impact Assessment (EIA), Whole Life Cycle Cost Assessment (WLCCA) and Life Cycle Assessment (LCA) using 3D and Building Information Model (BIM) technologies. The results showed, that building could be designed with full knowledge of the environmental impact of the building over its life cycle by the use of VR (Virtual Reality)/3D images in the whole life cycle analysis.

The life cycle assessment tool combined feasibility study, life cycle costing, environmental evaluation, and risk analysis in the design decision making of a real project for the first time (Wang et al. 2010). Multi-criteria decision making methods will propose the owner responsibility to make the decision from his point of view, considering his conditions of the financial abilities and his wishes.

3. Sustainability and multi-criteria decision making methods

Multi-criteria decision analysis (MCDA) methods have become increasingly popular in decision-making for sustainable energy because of the multi-dimensionality of the sustainability goal and the complexity of socio-economic and biophysical systems (Wang et al. 2009). In the design of sustainable buildings, it is beneficial to identify the most important design parameters in order to more efficiently develop alternative design solutions or reach optimized design solutions (Heiselberg et al. 2009).

Quaddus and Siddique (2001) offered a decision conferencing approach to sustainable development planning based on a multi-criteria model. The integrated model is presented and applied to a sustainable development planning exercise in a third world country. The results show that there are a number of environmental variables that are sensitive to the final outcome. The planners must identify these and pay special attention for feasible and sustainable planning.

Ugwu and Haupt (2007) used the ‘weighted sum model’ (simply additive weight (SAW)) technique in multi-criteria decision analysis (MCDA) and the ‘additive utility model’ in analytical hierarchical process (AHP) for multi-criteria decision-making, to develop the model for computing the sustainability index—a crisp value for evaluating infrastructure design proposals.

Xing et al. (2009) reports on the development of an Urban Development Sustainability Assessment Model (UD-SAM) which allows decision makers to identify sustainability indicators (economic, environmental and social) and which may lead to more holistic evaluation of the sustainability impact of elements of the urban environment.

4. Case study

One flat dwelling house and loft type apartment were selected for investigation. All the values are determined by simulation, according to the prices of the market. There are two alternatives with four types of heating system:

- One flat dwelling house with coal based heating;
- One flat dwelling house with gas based heating;
- One flat dwelling house with biomass based heating;
- One flat dwelling house with combined biomass and gas based heating system.

Alternatives describes as follows:

$A_1$ - One flat dwelling house with coal based heating;
$A_2$ - One flat dwelling house with gas based heating;
$A_3$ - One flat dwelling house with biomass based heating;
A₁ - One flat dwelling house with combined biomass and gas based heating;
A₂ - Loft flat dwelling house with combined biomass and gas based heating;
A₃ - Loft flat dwelling house with coal based heating;
A₄ - Loft flat dwelling house with biomass based heating.

Ten criteria, of each alternative, which describes apartment’s life cycle, were selected for decision making. They are:

- Material, used for construction process (t/m²);
- Energy, used for construction process (GJ/m²);
- Water, used for construction process (m³);
- Labor costs (human hour/m²);
- Price of the apartment (EUR/m²);
- Price of energy use for 50 year operation phase (kg/m²);
- Fuel annual price (EUR/100m³);
- Enclosures with heat losses (m²);
- Plane flat dwelling house with coal based heating;
- Plane flat dwelling house with biomass based heating;
- Plane flat dwelling house with gas based heating;
- Plane flat dwelling house with combined biomass and gas based heating.

Hierarchy Process (AHP) method (Saaty and Erdener 1979), using pair-wise questioners. Sum of weights of each criterion equals to one:

\[
\Sigma_{i=1}^{n} q_{i} = 1
\]  

(2)

- Sum of weights of i-th criterion of j-th alternative;
- Weight of i-th criterion of j-th alternative;

Pair-wise comparison matrix is presented in Table 2. Pair-wise comparisons on the decision elements are performed using a weighting scale, to generate the input data. All values are determined using Saaty scale, which is presented in Table 1.

<table>
<thead>
<tr>
<th>Intensity of importance</th>
<th>Definition</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equal importance</td>
<td>Two factors contribute equally to the objective</td>
</tr>
<tr>
<td>3</td>
<td>Somewhat more important</td>
<td>Experience and judgement slightly favour one over the other</td>
</tr>
<tr>
<td>5</td>
<td>Much more important</td>
<td>Experience and judgement strongly favour one over the other</td>
</tr>
<tr>
<td>7</td>
<td>Very much more important</td>
<td>Experience and judgement very strongly favour one over the other. Its importance is demonstrated in practice</td>
</tr>
<tr>
<td>9</td>
<td>Absolutely more important</td>
<td>The evidence favouring one over the other is of the highest possible validity</td>
</tr>
<tr>
<td>2, 4, 6, 8</td>
<td>Intermediate values</td>
<td>When compromise is needed</td>
</tr>
</tbody>
</table>

Optimum values Q by COPRAS method are calculated by formula (3):

\[
Q_{j} = S_{m} + \min_{i} \left( \frac{\sum_{i=1}^{n} S_{ij} \cdot \sum_{i=1}^{n} S_{i} \cdot \sum_{i=1}^{n} (1/S_{ij})}{S_{m} \cdot \sum_{i=1}^{n} (1/S_{ij})} \right) \]

(3)

- Sum of the minimizing criteria of the j-th alternative;
- Sum of the minimizing criteria of the j-th alternative;
- Sum of weights of each criterion equals to one;
- Minimizing criteria of the j-th alternative;
- Maximizing criterion of the j-th alternative;
- Sum of the minimizing criteria of the j-th alternative.

5. Methodology

Best alternative is calculates by Complex PRoportion ASsessment (COPRAS) multi-criteria decision making method (Zavadskas et al. 2008, 2009).

The normalized \( \bar{x}_{ij} \) values of the j criterion for i alternative by COPRAS methods are calculated as follows:

\[
\bar{x}_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}
\]  

(1)

\( \bar{x}_{ij} \) - normalized i-th criterion value for j-th alternative;
\( x_{ij} \) - i-th criterion value for j-th alternative;
\( \sum_{i=1}^{m} x_{ij} \) - Sum of xij criteria, where i changes from 1 to m;

This formula for normalized values \( \bar{x}_{ij} \) is preferable for minimizing and maximizing criteria. All criteria of these alternatives are minimizing.

Weights of each criteria are calculated by Analytical Hierarchy Process (AHP) method (Saaty and Erdener 1979), using pair-wise questioners. Sum of weights of each criterion equals to one:
### Table 2. Pair-wise comparison matrix

<table>
<thead>
<tr>
<th></th>
<th>$x_1$</th>
<th>$x_2$</th>
<th>$x_3$</th>
<th>$x_4$</th>
<th>$x_5$</th>
<th>$x_6$</th>
<th>$x_7$</th>
<th>$x_8$</th>
<th>$x_9$</th>
<th>$x_{10}$</th>
<th>$q$</th>
</tr>
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<td>0.33</td>
<td>0.33</td>
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<td>1.00</td>
<td>0.20</td>
<td>0.33</td>
<td>0.20</td>
<td>0.20</td>
<td>3.00</td>
<td>0.20</td>
<td>0.20</td>
<td>0.0325</td>
</tr>
<tr>
<td>$x_3$</td>
<td>0.20</td>
<td>1.00</td>
<td>1.00</td>
<td>0.20</td>
<td>0.33</td>
<td>0.20</td>
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<td>5.00</td>
<td>1.00</td>
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<td>5.00</td>
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<td>1.00</td>
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<td>5.00</td>
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<td>5.00</td>
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<td>0.33</td>
<td>0.33</td>
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<td>5.00</td>
<td>5.00</td>
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<td>5.00</td>
<td>3.00</td>
<td>5.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.2050</td>
</tr>
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</table>

**CR** 0.18

### Table 3. Initial decision making matrix

<table>
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<th>$x_1$</th>
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<th>$x_3$</th>
<th>$x_4$</th>
<th>$x_5$</th>
<th>$x_6$</th>
<th>$x_7$</th>
<th>$x_8$</th>
<th>$x_9$</th>
<th>$x_{10}$</th>
</tr>
</thead>
<tbody>
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<td>$q$</td>
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<td>0.033</td>
<td>0.016</td>
<td>0.025</td>
<td>0.148</td>
<td>0.085</td>
<td>0.141</td>
<td>0.029</td>
<td>0.219</td>
<td>0.205</td>
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<td>7969</td>
<td>308</td>
<td>2966</td>
<td>869.57</td>
<td>1005</td>
<td>800.58</td>
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<td>308</td>
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<td>27.13</td>
<td>41.65</td>
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<td>362.5</td>
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<td>724.64</td>
<td>1220</td>
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<td>1.99</td>
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<td>60.01</td>
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<td>776.81</td>
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</table>

### Table 4. Normalized decision making matrix with final results

<table>
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<tr>
<th></th>
<th>$x_1$</th>
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<th>$x_3$</th>
<th>$x_4$</th>
<th>$x_5$</th>
<th>$x_6$</th>
<th>$x_7$</th>
<th>$x_8$</th>
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<th>$x_{10}$</th>
<th>$Q_i$</th>
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<td>0.025</td>
<td>0.148</td>
<td>0.085</td>
<td>0.141</td>
<td>0.029</td>
<td>0.219</td>
<td>0.205</td>
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<td>0.0265</td>
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<td>0.0030</td>
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<td>0.1277</td>
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<td>0.0040</td>
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</tbody>
</table>

### 6. Conclusion

This investigation was made with a purpose to show the possibility to use multi-criteria decision making method in building alternatives, which can be described with sustainable criteria. And show the impact of the life cycle on these criteria.

For investigation were selected one flat dwelling house and loft-type apartment with different heating systems.

The results show that the best alternative is solution number $A_7$ - Loft flat dwelling house with biomass based heating system.

According to the calculations it should be noted, that the best results showed the loft-type apartment with gas based, biomass based and house with combined biomass and gas based heating system. But loft-type apartment with coal based heating system showed low results. These results depend on a big energy use for 50 year operation phase, high CO$_2$ use for 50 year operation phase and high fuel annual price.

Best alternatives within a one flat dwelling house are $A_3$ and $A_4$ alternatives - one flat dwelling house with biomass based heating and one flat dwelling house with combined biomass and gas based heating. But in comparison with the loft house, results of one flat dwelling house are very low. This depends on high energy use for 50 year operation phase, high price of the apartment and high fuel annual price.
References


