

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 would 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 Exergy 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 exergy 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.
- Abeyundara *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 pro-

ject 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:

- Coal based heating system;
- Gas based heating system;
- Biomass based heating system;
- 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;

A_4 - One flat dwelling house with combined biomass and gas based heating;

A_5 - Loft flat dwelling house with coal based heating;

A_6 - Loft flat dwelling house with gas based heating;

A_7 - Loft flat with biomass based heating;

A_8 - Loft flat dwelling house with combined biomass and gas based heating.

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

x_1 - Material, used for construction process (t/m^2);

x_2 - Energy, used for construction process (GJ/m^2);

x_3 - Water, used for construction process (m^3/m^2);

x_4 - Energy use for 50 year operation phase (kWh/m^2);

x_5 - Enclosures with heat losses (m^2);

x_6 - CO_2 use for 50 year operation phase (kg/m^2);

x_7 - Price of the apartment (EUR/m^2);

x_8 - Labor costs (human hour/ m^2);

x_9 - Fuel annual price ($EUR/100m^2$);

x_{10} - Price of energy use for 50 year operation phase (Lt/m^2).

Table 3 describes initial decision making matrix with 8 alternatives and 10 criteria.

Table 4 describes normalized decision making matrix, determined with formula (1) and with final results, which were determined with formula (2).

5. Methodology

Best alternative is calculated 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:

$$\bar{x}_{ij} = \frac{x_{ij}}{\sum_{i=1}^m x_{ij}} \quad (1)$$

\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 x_{ij} 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:

$$\sum_{i=1}^m q_i = 1 \quad (2)$$

q_i - 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 1. The Saaty's Judgment Scale

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

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

$$Q_i = S_{+i} + \frac{\min_i S_{-i} \cdot \sum_{i=1}^m S_{-i}}{S_{-i} \cdot \left(\sum_{i=1}^m (\min_i S_i / S_{-i}) \right)} =$$

$$= S_{+i} + \frac{\min_i S_{-i} \cdot \sum_{i=1}^m S_{-i}}{S_{-i} \cdot \min_i S_i \cdot \left(\sum_{i=1}^m (1/S_{-i}) \right)}$$

$$= S_{+i} + \frac{\sum_{i=1}^m S_{-i}}{S_{-i} \cdot \left(\sum_{i=1}^m (1/S_{-i}) \right)} \quad (3)$$

S_{+j} - maximizing criterion of j -th alternative;

$\min_i S_{-i}$ - Minimum value of the sum of the minimizing criteria of the j -th alternative;

S_{-i} - Sum of the minimizing criteria of the j -th alternative;

$\sum_{i=1}^m S_{-i}$ - Sum of the minimizing criteria of the j -th alternative, where i changes from 1 to m .

Table 2. Pair-wise comparison matrix

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	q
x_1	1.00	5.00	5.00	0.20	0.33	0.33	0.20	2.00	0.20	0.20	0.0552
x_2	0.20	1.00	1.00	0.20	0.33	0.20	0.20	3.00	0.20	0.20	0.0325
x_3	0.20	1.00	1.00	0.20	0.33	0.20	0.20	0.50	0.20	0.20	0.0248
x_4	5.00	5.00	5.00	1.00	5.00	1.00	1.00	5.00	0.50	1.00	0.1477
x_5	3.00	3.00	3.00	0.20	1.00	1.00	0.20	3.00	0.20	0.20	0.0611
x_6	3.00	5.00	5.00	1.00	1.00	1.00	0.33	3.00	0.20	0.20	0.0850
x_7	5.00	5.00	5.00	1.00	5.00	3.00	1.00	5.00	0.33	0.33	0.1406
x_8	0.50	0.33	2.00	0.20	0.33	0.33	0.20	1.00	0.20	0.20	0.0290
x_9	5.00	5.00	5.00	2.00	5.00	5.00	3.00	5.00	1.00	1.00	0.2193
x_{10}	5.00	5.00	5.00	1.00	5.00	5.00	3.00	5.00	1.00	1.00	0.2050
CR											0.18

Table 3. Initial decision making matrix

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}
	<i>min</i>	<i>min</i>	<i>min</i>	<i>min</i>	<i>min</i>	<i>min</i>	<i>min</i>	<i>min</i>	<i>min</i>	<i>min</i>
q	0.055	0.033	0.016	0.025	0.148	0.085	0.141	0.029	0.219	0.205
A_1	1.60	31.49	51.36	7969	308	2966	869.57	1005	800.58	3586.05
A_2	2.10	41.33	67.41	7054	308	1522	886.96	1012	317.06	3174.3
A_3	1.80	35.42	57.78	8843	308	314	897.39	1010	211.37	3979.35
A_4	2.30	45.26	73.83	7317	308	257	932.17	1004	268.22	3292.65
A_5	1.52	27.13	41.65	5903	362.5	2194	724.64	1220	800.58	2656.35
A_6	1.99	35.52	54.53	5149	362.5	1112	739.13	1229	317.06	2452.05
A_7	1.71	30.52	46.85	6408	362.5	228	747.83	1209	211.37	2883.6
A_8	2.19	39.09	60.01	5586	362.5	196	776.81	1202	268.22	2513.7

Table 4. Normalized decision making matrix with final results

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	Results
	<i>min</i>	<i>min</i>	<i>min</i>	<i>min</i>	<i>min</i>	<i>min</i>	<i>min</i>	<i>min</i>	<i>min</i>	<i>min</i>	Q_i
q	0.055	0.033	0.016	0.025	0.148	0.085	0.141	0.029	0.219	0.205	
A_1	0.0058	0.0036	0.0028	0.0217	0.0070	0.0287	0.0186	0.0033	0.0550	0.0300	0.0855
A_2	0.0076	0.0047	0.0037	0.0192	0.0070	0.0147	0.0190	0.0033	0.0218	0.0265	0.1183
A_3	0.0065	0.0040	0.0032	0.0241	0.0070	0.0030	0.0192	0.0033	0.0145	0.0332	0.1277
A_4	0.0083	0.0051	0.0040	0.0199	0.0070	0.0025	0.0199	0.0033	0.0184	0.0275	0.1299
A_5	0.0055	0.0031	0.0023	0.0161	0.0083	0.0212	0.0155	0.0040	0.0550	0.0222	0.0986
A_6	0.0072	0.0040	0.0030	0.0140	0.0083	0.0108	0.0158	0.0040	0.0218	0.0205	0.1380
A_7	0.0062	0.0035	0.0026	0.0175	0.0083	0.0022	0.0160	0.0039	0.0145	0.0241	0.1528
A_8	0.0079	0.0044	0.0033	0.0152	0.0083	0.0019	0.0166	0.0039	0.0184	0.0210	0.1494

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, big CO₂ 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

- Abeyesundara, U. G. Y.; Babel, S.; Gheewala, S. 2009. A matrix in life cycle perspective for selecting sustainable materials for buildings in Sri Lanka. *Building and Environment*. 44(5): 997-1004.
- Balaras, C. A.; Drousa, K.; Dascalaki, E.; Kontoyiannidis, S. 2005. Heating energy consumption and resulting environmental impact of European apartment buildings. *Energy and Buildings*. 37(5): 429-442.
- Daim, T. U. and Intarode, N. 2009. A framework for technology assessment: Case of a Thai building material manufacturer. *Energy for Sustainable Development*. 13(4): 280-286.
- Dawood, S.; Lord, R.; Dawood, N. 2009. Development of a visual whole life-cycle energy assessment framework for built environment, *Winter Simulation Conference (WSC), Proceedings of the 2009 December 13-16*. 2009: 2653-2663
- Gu, L.; Lin, B.; Zhu, Y.; Gu, D.; Huang, M.; Gai, J. 2008. Integrated Assessment Method for Building Life Cycle Environmental and Economic Performance. *Building Simulation*. 1(2): 169-177.
- Heiselberg, P.; Brohus, H.; Hesselholt, A.; Rasmussen, H.; Sejnre, E.; Thomas, S. 2009. Application of sensitivity analysis in design of sustainable buildings. Special Issue: Building and Urban Sustainability. *Renewable Energy*. 34(9): 2030-2036.
- Jarrar, O.M.. and Al - Zoabi, A.Y. 2008. The applicability of sustainable city paradigm to the city of Jerusalem: Criteria and indicators of efficiency. *Building and Environment*. 43(4): 550-557.
- Jovane, F.; Yoshikawa, H.; Alting, L.; Boër, C.R.; Westkamper, E.; Williams, D.; Tseng, M.; Seliger, G.; Paci, A.M. 2008. The incoming global technological and industrial revolution towards competitive sustainable manufacturing. *CIRP Annals - Manufacturing Technology*. 57(2): 641-659.
- Kofoworola, O. F.; and Gheewala, S. H. 2008. Environmental life cycle assessment of a commercial office building in Thailand. *The International Journal of Life Cycle Assessment*. 13:498-511.
- Liu, M.; Li, B.; Yao, R. 2010. A generic model of Exergy Assessment for the Environmental Impact of Building Life-cycle. *Energy and Buildings*. 42(9): 1482-1490.
- Lombera, J.-T. S.-J. and Rojo, J. C. 2010. Industrial building design stage based on a system approach to their environmental sustainability. *Construction and Building Materials*. 24(4): 438-447.
- Mora, E. P. 2007. Life cycle, sustainability and the transcendent quality of building materials. *Building and Environment*. 42(3): 1329-1334.
- Ortiz, O.; Castells, F.; Sonnemann, G. 2009. Sustainability in the construction industry: A review of recent developments based on LCA. *Construction and Building Materials*. 23(1): 28-39.
- Quaddus, M. A. and Siddique, M. A. B. 2001. Modelling sustainable development planning: A multicriteria decision conferencing approach. *Environment International*. 27(2-3): 89-95.
- Ruggieri, L.; Cadena, E.; Martinez-Blanco, J.; Gasol, C. M.; Rieradevall, J.; Gabarrell, X.; Gea, T.; Sort, X.; Sánchez, A. 2009. Recovery of organic wastes in the Spanish wine industry. Technical, economic and environmental analyses of the composting process. *Journal of Cleaner Production*. 17(9): 830-838.
- Saaty, T. L. and Erdener, E. 1979. A new approach to performance measurement the analytic hierarchy process. *Design Methods and Theories*. 13(2): 62-68.
- Shen, L.-Y.; Tam, V. W. Y.; Tam, L.; Ji, Y.-B. 2010. Project feasibility study: the key to successful implementation of sustainable and socially responsible construction management practice. *Journal of Cleaner Production*. 18(3): 254-259.
- Sobek, W.; Sedlbauer, K.; Schuster, H. 2009. *Sustainable Building*. In: Bullinger, Hans-Jörg (éd.): *Technology Guide. Principles – Applications – Trends*. Heidelberg: Springer, 2009. pp. 432-435.
- Ugwu, O.O. and Haupt, T.C. 2007. Key performance indicators and assessment methods for infrastructure sustainability—a South African construction industry perspective. *Building and Environment*. 42(2): 665-680.
- Wang, J.-J.; Jing, Y.-Y.; Zhang, C.-F.; Zhao, J.-H. 2009. Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renewable and Sustainable Energy Reviews*. 13(9): 2263-2278.
- Wang, N.; Chang, Y.-C.; Nunn, C. 2010. Lifecycle assessment for sustainable design options of a commercial building in Shanghai. *Building and Environment*. 45(6): 1415-1421
- Wong, J. M. W.; Ng, S. T.; Chan, A. P. C. 2010. Strategic planning for the sustainable development of the construction industry in Hong Kong. *Habitat International*. 34(2): 256-263.
- Xing, Y.; Malcolm, R.; Horner, W.; El-Haram, M. A.; Bebbington, J. 2009. A framework model for assessing sustainability impacts of urban development. *Accounting Forum*. 33(3): 209-224
- Zavadskas, E. K.; Kaklauskas, A.; Turskis, Z.; Tamošaitienė, J. 2008. Selection of the effective dwelling house walls by applying attributes values determined at intervals. *Journal of Civil Engineering and Management*. 14(2): 85-93. doi:10.3846/1392-3730.2008.14.3
- Zavadskas, E. K.; Kaklauskas, A.; Turskis, Z.; Tamosaitiene, J. 2009. Multi-attribute decision-making model by applying grey numbers. *Informatika*. 20(2): 305-320.
- Zhang, Z.; Wu, X.; Yang, X.; Zhu, Y. 2006. BEPAS—a life cycle building environmental performance assessment model. *Building and Environment*. 41(5): 669-675.