Multicriteria analysis method of health, IEQ and energy use for sustainable buildings

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ABSTRACT

The stake of sustainable development is to ensure today's and future developments of a wealthy and healthy society in a high quality environment. This is also valid for sustainable buildings that should take account of environmental, economical and social stakes. This includes, among others, low energy use, good indoor environment quality (IEQ) and health. One of the aims of the European HOPE project is to evaluate buildings from these points of view. The multicriteria methodology developed in Europe during the last decades for decision-making can be used for deciding if a building is globally good or poor, or for giving a label. For this, stakes should be defined, criteria should be listed and an evaluation methodology should be built. This contribution outlines a methodology adapted to this type of decision and applies it to a first sample of buildings.

INDEX TERMS

Criteria; Health; Comfort; Energy index; Energy efficiency; Sustainability

INTRODUCTION

Sustainable Buildings

The building industry is one of the largest in terms of gross income, life-cycle energy use and mass of waste production. Buildings have a significant effect on human health since human beings spend most of their time in buildings. Therefore, sustainable development strategy is paramount for the development of the building industry and human health. This strategy addresses the three issues of sustainable development, i.e. environment, economy and society. These stakes can be translated into many criteria about building qualities and performance, these criteria often being contradictory. Multicriteria analysis is very useful to choose between various building design decisions, to sort buildings according to their quality or to give a 'sustainability' or IEQ label to a building (Flourentzou and Roulet, 2002).

The HOPE Project

Nine countries are participating in the EU HOPE R&D project (Bluyssen *et al.*, 2003). Its aims are to determine if there are differences—and if yes, which are the differences—between 'standard' and 'low energy' buildings with respect to IEQ and health, to provide advice on how to design, build and use buildings for enjoying a good IEQ together with using less non-renewable energy, and to allow any building owner or user to compare his building with an European building stock, from the point of view of energy and IEQ. The developments presented in this paper aim to reach this last objective. One of the research bases of this project is an audit of 180 buildings in nine countries, including questionnaires to occupants and inspection checklists.

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METHOD

The method aims to apply an appropriate multicriteria analysis complying with the stakes of the HOPE project, in order to sort buildings with respect to health and energy use. The main steps in this multicriteria process are: (a) identify the stakes of the decision; (b) build decision criteria; (c) evaluate the items according to each criterion; and (d) aggregate these evaluations (Roy, 1985). This paper presents the first attempts to apply this method to problems to be solved within the HOPE project. The project team is still discussing the details.

Definition of Stakes

The salient features of healthy buildings include indoor air quality (IAQ), thermal comfort, visual and acoustic characteristics. For the purpose of this work, based on available knowledge and HOPE research scope, the definition here adopted is as follows:

> A healthy and energy-efficient building does not cause or aggravate illnesses in the building occupants, assures a high level of comfort to the building's occupants in the performance of the designated activities for which the building has been intended and designed, and minimises the use of non-renewable energy, taking into account available technology including life cycle energy costs (Bluyssen *et al.*, 2003).

It is assumed in this paper that the three stakes (health, comfort and energy) have a similar importance: a building cannot be good if it fails in one of them.

Table 1 Stakes, criteria and factors for energy efficient, healthy and comfortable building

Stake	Criteria		Factors
Low energy use	Energy use per heated floor area		Heating and hot water energy index Electric energy index
Does not cause or aggravate illness	Health	Building related symptoms	Dry or irritated skin; blocked or stuffy nose; runny nose, dry throat; chest tightness; wheezing, dryness of the eyes; itchy or watery eyes, lethargy or tiredness; headaches
		Risks of illnesses	E. g. presence of radon, asbestos, heavy metals, microbes, allergens, etc.
High level of comfort for the building's occupants	Indoor environment quality	Indoor air quality	IAQ dissatisfaction Air stuffiness or dryness; odour
		Thermal comfort	Thermal discomfort in general Too cold or too hot; draughts
		Acoustical comfort	Noise dissatisfaction Noise from outdoors or building systems
		Visual comfort	Lighting dissatisfaction Glare and light flickering

Building Decision Criteria

The next important step in the decision process is building up a list of decision criteria. The criteria list should satisfy several conditions (Roy, 1985). It should be *exhaustive*: all stakes should be represented. It should be *non-redundant*: no stake should be represented by more than one criterion. The list should be *coherent*: the criteria should be expressed in such a way that the performance is improved if a criterion is improved or vice versa. Since human beings cannot give precise values or weights to qualitative data, but can easily judge equity, it is advisable to choose and organise the criteria in such a way that they have the *same qualitative importance* (Flourentzou, 2001). The number of criteria at each decision level should not be larger than 12, and preferably about 7 (Schärlig, 1990).

Table 1 outlines a possible development of the stakes of healthy and energy efficient buildings, as defined above, into criteria and factors. Note that every stake is represented by one criterion, itself evaluated by a family of factors, and that increasing the value of any one of the factors decreases the performance.

This proposal also takes account of the information available from the questionnaires developed for the HOPE project. However, only a first selection of factors is taken into account in the present, preliminary study; additional factors should be taken into account to interpret the complete HOPE database, which includes about 300 factors for each building.

Evaluation According to Each Criterion

Once the list of criteria is established, a building can be evaluated according each factor, sub-criterion and criterion. The evaluation may be fully *quantitative*, with figures in Euros, MJ, m^2, kg, etc. These figures can be represented on a ratio scale. The evaluation may also be *semi-quantitative* or *qualitative*, for example, using an interval or ordinal scale. Examples of such scales are: 'good to average to poor'; or 'acceptable to uncertain to unacceptable'.

Within the HOPE project, building performance is assessed using two types of criterion: directly measured quantities (e.g. prevalence of symptoms or energy use) and evaluated risks (e.g. presence of mould or of pollution sources). One of the aims of the project is to find relationships between these two types of criterion, between risks and measured performance. Therefore, the multicriteria analysis methodology should be able to handle both qualitative and quantitative criteria.

Aggregation

The synthesis of a multicriteria analysis is a global judgment: a choice, a ranking or a sorting of the assessed buildings. This operation is called aggregation. There are several ways to aggregate the evaluations for each criterion. The most well known multicriteria aggregation algorithms are described in detail elsewhere (e.g. Brans and Vincke, 1985; Schärlig, 1990, 1996; Maystre *et al.*, 1994; Roy, 1999). These methods, however, do not handle both quantitative and qualitative criteria in a way convenient for our purpose.

Table 2 Qualitative evaluation levels

G	Favourable, accepted	G^+	Exceptional
		G^o	Favourable
		G^-	Favourable with some minor reserve
Y	Uncertain	Y^+	Uncertain with positive elements
		Y^o	Uncertain
		Y^-	Uncertain with negative elements
R	Unfavourable, discarded	R^+	Unfavourable with positive elements
		R^o	Unfavourable
		R^-	Unfavourable with negative element
B	Veto	B	Downgrades the global judgement to red.

The rule-based aggregation method presented below is in the spirit of the Electre IV method (Roy, 1993), and this is why we call it Hermione, the sister-in-law of Electre. It holds the basic ideas of strong and weak preferences, indifference and veto. It also avoids compensation of a strong disadvantage by many minor advantages. It is based on thresholds and percentage of colours in each class. Three main classes are defined: favourable or clearly acceptable (green), uncertain (yellow) and unfavourable or rejected (red); plus a special class (black) considered as a veto. Subclasses are also defined for a more detailed evaluation (Table 2).

Each qualitative criterion is precisely defined with sentences describing each level. A fuzzy transformation is used to translate quantitative, continuous variables into the ten defined classes. A possible way to perform this transformation is described below.

Seven thresholds are first defined, as objectively as possible (Figure 1). The thresholds of clear acceptance (G) and clear rejection (R) are defined first. Values between these two thresholds lead to uncertain acceptance. G and R could be defined according to existing standards or commonly accepted values, or could be the boundaries of the first and last quartiles. The veto threshold B, if any, is fixed independently.

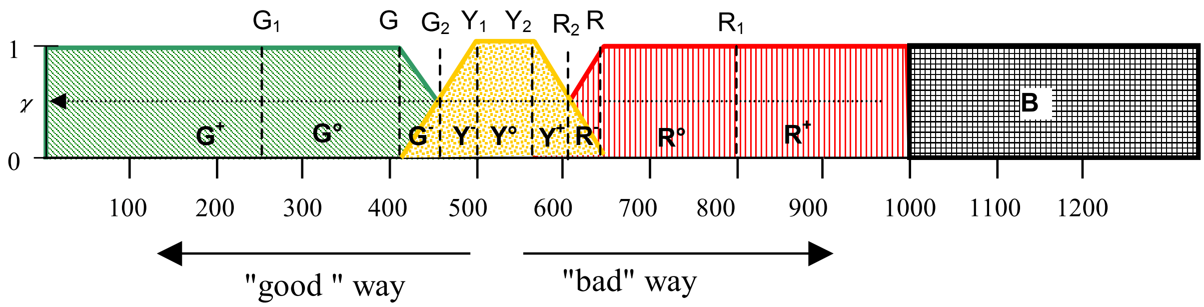

Figure 1 Application of fuzzy logic to define subclasses along a cardinal scale.

The thresholds of subclasses are then calculated as follows. Divide the $G-R$ interval into α parts ($\alpha > 2$). The first and last two parts are the fuzzy zones. The larger the α is the narrower are these zones. As an example, $\alpha = 5/2$ will give three equal yellow subclasses.

If the quality decreases with increasing value (Figure 1), the thresholds are calculated by:

$$G_1 = \frac{G}{2} \qquad Y_1 = \frac{(\alpha-1)G+R}{\alpha} \qquad R_1 = \frac{R+B}{2}$$

$$G_2 = \frac{(2\alpha-1)G+R}{2\alpha} \qquad Y_2 = \frac{(\alpha-1)R+G}{\alpha} \qquad R_2 = \frac{(2\alpha-1)R+G}{2\alpha}$$

If the quality increases with increasing value, exchange R and G in the above equations.

In the case of an optimum value in the centre of a scale (e.g. a thermal sensation scale from 'cold' to 'hot'), $G+$ is put at the optimal value, and two veto levels are defined if needed. The clear acceptance and rejection levels are also defined as above. Since the quality decreases when going away from the optimum, the thresholds can then be calculated using:

$$G_1^{\pm} = G_+ \pm \frac{G^{\pm}}{2} \qquad G_2 = G_+ \pm \frac{(2\alpha-1)G+R}{2\alpha}$$

$$Y_1 = G_+ \pm \frac{(\alpha-1)G+R}{\alpha} \qquad Y_2 = G_+ \pm \frac{(\alpha-1)R+G}{\alpha}$$

$$R_1 = G_+ \pm 2R \quad \text{or} \quad R_1 = G_+ \pm \frac{R+B}{2} \qquad R_2 = G_+ \pm \frac{(2\alpha-1)R+G}{2\alpha}$$

The aggregation is performed using the set of rules in Table 3. These rules are those commonly used in democracy: simple and qualified majority voting. The aggregation can be performed in two or more steps: from factors to sub-criteria to criteria. One advantage of this method is that the same rules can be used to aggregate the evaluations of jury members.

Table 3 Set of rules used for aggregation[a]

	Result	Rule valid as far as the result is not in an upper class
G	G^+	G = 100% and B = 0
	G°	$G \geq 80\%$ and R = 0 and B = 0
	G^-	$G < 80\%$ and $G \geq 60\%$ and R = 0 and B = 0
Y	Y^+	$G \geq 40\%$ and R = 0 and B = 0
	Y°	($G < 40\%$ and R = 0 and B = 0) or ($G \geq 60\%$ and $G \leq 20\%$ and B = 0)
	Y^-	$R \leq 20\%$ and $R \neq 0$ and B = 0 or $G \geq 60\%$ and $R \leq 40\%$ and B = 0
R	R^+	$R \leq 40\%$ and B = 0
	R°	$R > 40\%$ and B = 0
	R^-	$B \leq 20\%$ and $B > 0$
B	B	Else

[a]G = percentage of green judgment; Y = yellow, R = red, and B = vetoes.

EXAMPLE

The Hermione method was applied to residential buildings audited in Switzerland within the HOPE project, using the criteria listed in Table 1 and with thresholds defined as follows: The veto level (B) is arbitrarily defined at values generally accepted as too large. Threshold for energy indices are: G when fulfilling Swiss standards, R above Swiss average. For building-related symptoms, G is at the top of first quartile and R at the bottom of last quartile. Occupants evaluated most questions on comfort on a seven-point scale from 1 (satisfactory) to 7 (unsatisfactory). For these questions, G = 2, R = 4 and B = 6. Some comfort questions are evaluated on a bipolar scale: 4 is optimum, while 1 and 7 are too much. For example 1 is too cold, 4 is optimal comfort temperature and 7 is too hot. For these, $G^{\pm} = 4 \pm 1$; $R^{\pm} = 4 \pm 2$ and $B^{\pm} = 4 \pm 3$. The other thresholds were calculated using the method described above.

Table 4 Evaluation of criteria related to energy, health and indoor environment

Stakes		Criteria	Mean	Stdev	Building 09	08	07	05	06	04	03	02	01
		Heating and hot water	123	74	87	110	204	87	83	175	67	106	232
Energ		Electricity index	40.9	8.6	55.0	40	38.4	45.2	40	35.0	52.5	33.6	42.6
y		5 most prevalent symptoms	0.49	0.24	0.4	0.4	1.5	0.6	0.1	0.6	0.4	0.6	0.7
BRS		All 10 symptoms	0.90	0.45	0.7	0.4	2.4	0.8	0.2	1.2	0.7	1.2	1.1
Indoor environment quality	Thermal	Thermal discomfort inWinter	2.4	0.5	2.00	1.71	2.75	1.75	2.04	2.98	1.84	2.61	2.41
		Thermal discomfort in Summer	2.5	0.6	2.46	2.57	3.67	2.78	2.27	2.58	2.19	3.42	1.96
		Winter temp. is too hot/too cold	3.8	0.4	4.07	3.73	3.60	3.25	3.95	3.26	3.52	4.05	4.22
		Summer temp. too hot / too cold	3.1	0.3	2.80	2.43	2.18	2.56	3.26	3.24	2.91	2.75	3.37
		Air is too still/too draughty	3.5	0.2	3.00	3.60	3.73	4.22	3.41	3.54	3.25	3.48	3.89
	Noise	Noise from outside	2.8	0.4	2.80	2.64	3.42	2.50	2.97	2.83	2.68	3.42	2.22
		Noise from building system	2.0	0.4	2.00	2.86	1.67	1.88	1.93	2.33	2.03	2.21	1.28
		Noise from overall	2.4	0.4	2.73	2.33	2.91	2.13	2.48	2.54	2.39	2.67	1.70
	Light	Light overall in Winter	2.6	0.4	2.00	1.79	1.67	1.89	2.22	2.68	2.32	3.25	2.37
		Light overall in Summer	1.9	0.3	1.80	2.07	1.67	1.75	1.73	1.98	1.89	2.39	1.57
		Glare from sky in Winter	2.3	0.5	1.80	1.50	1.83	2.11	2.33	2.32	2.09	3.14	1.76
		Glare from sky in Summer	2.1	0.3	1.80	2.57	2.58	1.88	2.30	2.15	1.88	2.50	1.63
	IAQ	Air is stuffy in Winter	3.3	0.4	3.15	3.46	3.08	3.56	3.61	3.32	3.55	3.49	2.74
		Air is dry/humid in Winter	2.8	0.5	3.07	2.50	1.83	2.11	3.36	2.61	2.60	3.27	2.29
		Air smells in Winter	2.3	0.4	2.67	2.29	1.75	2.88	2.04	2.40	2.39	2.95	1.81
		Summer – Poor air quality	2.4	0.5	2.46	3.00	3.25	2.88	2.00	2.68	2.46	3.17	1.88
Aggregated evaluation			Energy		R	Y	B	G-	G-	R	R	G+	R
			Health		G	G	R-	Y	G+	R+	G-	R+	R
			IEQ		Y	Y	R+	G-	Y-	Y	Y	Y	G-

The result of the evaluation is shown in Table 4. These preliminary results from only nine buildings do not show any clear relationship or correlation between the evaluations of buildings according to the three criteria. One possible reason for this is that the statistical basis is much too small, but another possible reason is that there is no relationship.

CONCLUSIONS AND IMPLICATIONS

A methodology allowing the sorting of buildings into classes, according to qualitative and/or quantitative criteria assessed within the HOPE building audit is presented. The rules on which this method is based are easy to explain to decision-makers, because they are close to those used in democracy. It should be emphasised that one of the aims of HOPE is to find relations between the building fabric, indoor environment characteristics, health risks, health energy use and comfort. The application of the method presented here will then be extended to qualitative criteria assessed from building characteristics.

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