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Ecological properties of building materials

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1. INTRODUCTION

In his prospective article, Visvesvaraya [1] unfolded a strategy for the development of building materials, stressing their mass–energy balance with the consequences of using waste for manufacturing and minimizing energy consumption.

Although I heartily support such a strategy, it is my opinion that the issue is much wider in its scope, as I already indicated in 1973 [2]. Over the years, this approach has been further elaborated and can now be presented in what I think is its final form.

Material properties in relation to use can be classified into technical properties (related to bulk and skin), economic properties (cost per unit of property), properties influencing health (from liberated gases or fibres, radioactive radiation, washed out toxic compounds), psychological properties (effect of nature of material together with surface texture, colour, illumination and form) and ecological properties.

Ecological properties originate from the manufacturing of materials because this entails desoiling (for ore, natural stone, aggregates) or deforestation (for wood). Also to be accounted for are energy, water and labour – to manufacture and transport the materials from the mine to the final stage – and pollution and waste which arise during all these processes. Because all these activities interfere with the environment, they are called ecological properties and they can be expressed as energy, water, pollution, labour and waste as regards content and desoiling, and as deforestation as regards surface.

So the ecological properties are restricted to the final stage of materials to be used for the construction of buildings and structures. Of course, during the construction process, energy, water and labour are also used and pollution and waste occur but the construction procedures are so different that they have to be considered separately for each type of construction and therefore are not included in the ecological properties as previously defined. Again, during the lifetime of buildings, energy and water are used and pollution and waste are caused; this is also the case during most demolition processes. But here again the range is so wide that we can only consider specific categories of structures and buildings, so these processes are not included in the definition of ecological properties.

Nevertheless, the ecological properties as defined here are very important, as shown by some applications, though first reference must be made to the order of magnitude for the ecological properties of the several building materials. Naturally, the value of some of these properties also depends on the level of development of environmental laws and therefore may vary from country to country. The ecological properties given here are calculated in detail, mostly for the situation in the Netherlands, but give a reasonable order of magnitude for other countries. In the calculations only the direct factors of impact are measured and used for evaluation, the indirect factors of impact – ecological contents and surfaces necessary for the buildings and installations used for manufacturing or transport of the building materials – not being included in the calculations.

2. ECOLOGICAL PROPERTIES

The ecological properties of building materials can be derived from the flow diagram in Fig. 1 (which is an elaboration of Fig. 2 in [1]).

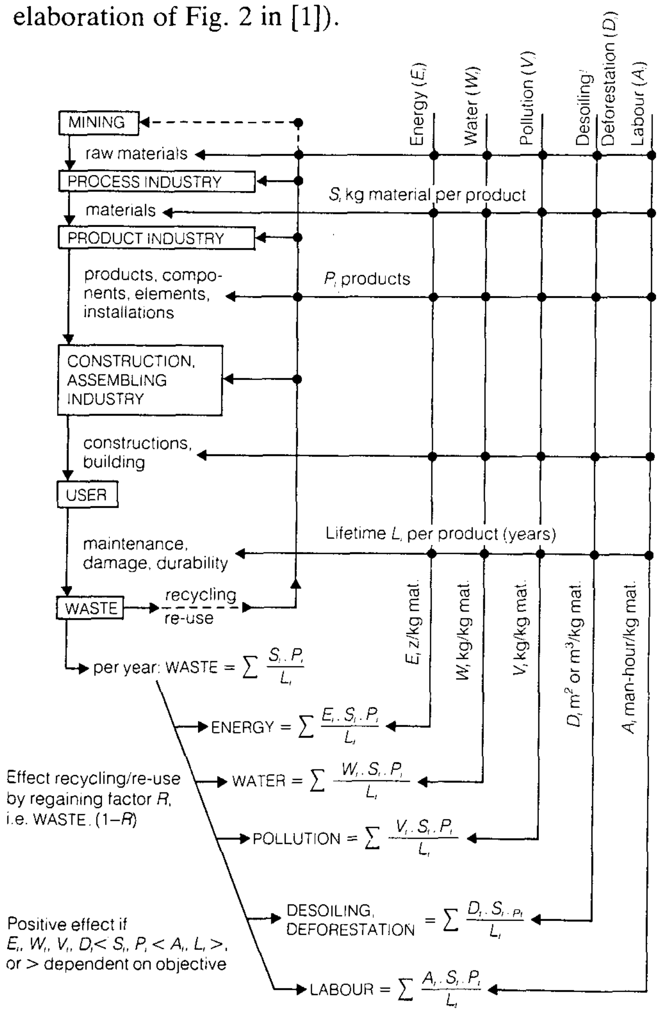

Fig. 1 Flow diagram for ecological parameters.

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Assuming that in the flow diagram there are manufactured P_i products which require S_i kg material per product and have a lifetime of L_i years, there will be $\Sigma S_i \times P_i/L_i$ kg waste per year. Assuming further that for each kilogramme of material, E_i joules energy, W_i kg water, D_i m^2 desoiling or deforestation, A_i man-hours (mh) labour are needed, causing V_i kg pollution, the ecological parameters in Fig. 1 are defined.

These parameters can now be calculated quantitatively. This has been done for several building materials (e.g. [3], [4]) until the stage when the building materials are ready to be used for further construction at the building site. A summary of some results is given in Table 1, together with costs (Dec. 1986: 1 US\$ = 2.1 DFl) and limiting values for strength and modulus of elasticity (see below). In Figs 2a and b (per unit of volume and mass, respectively) the ecological profile is traced.

This comparison, however, is not quite valid, since a design engineer is used to thinking in terms of strength, deformation, stability and these 'values for money', the costs per unit of volume, strength and modulus of elasticity. In a similar way, we can express the ecological properties per Nmm^{-2} strength and per Nmm^{-2} modulus of elasticity. For example, for the energy content this gives MJm^{-3} per Nmm^{-2} strength and per Nmm^{-2} modulus of elasticity; the same can be done with regard to water, pollution or labour for the bulk or content and to the desoiling/deforestation for surfaces. In this way, Table 2 was calculated for the same materials as given in Table 1. (For this reason the limiting values, as used in the Netherlands on average, are given for strength, σ, and modulus of elasticity, E.)

Table 2 also plots the outline of the ecological profiles which give the ecological comparison of the materials per Nmm^{-2} strength (Fig. 3) and per Nmm^{-2} modulus of elasticity (Fig. 4). Reinforced concrete seems relatively to be the most environment-friendly material for construction purposes.

It may be helpful to give some examples of application.

2.1 Example 1

A few years ago, a 685 m long prestressed concrete (PC) bridge was built in the Netherlands, which had also been designed in steel (S). The cost estimate of both designs was equal, the lowest sum contracted was that of the PC bridge and this bridge has recently been opened.

On the basis of the amount of materials, the ecological parameters were calculated to the stage when all materials were present on the building site. However, some aspects were not calculated: the construction of the bridges themselves, the maintenance and the future demolition. The design department, however, gave the

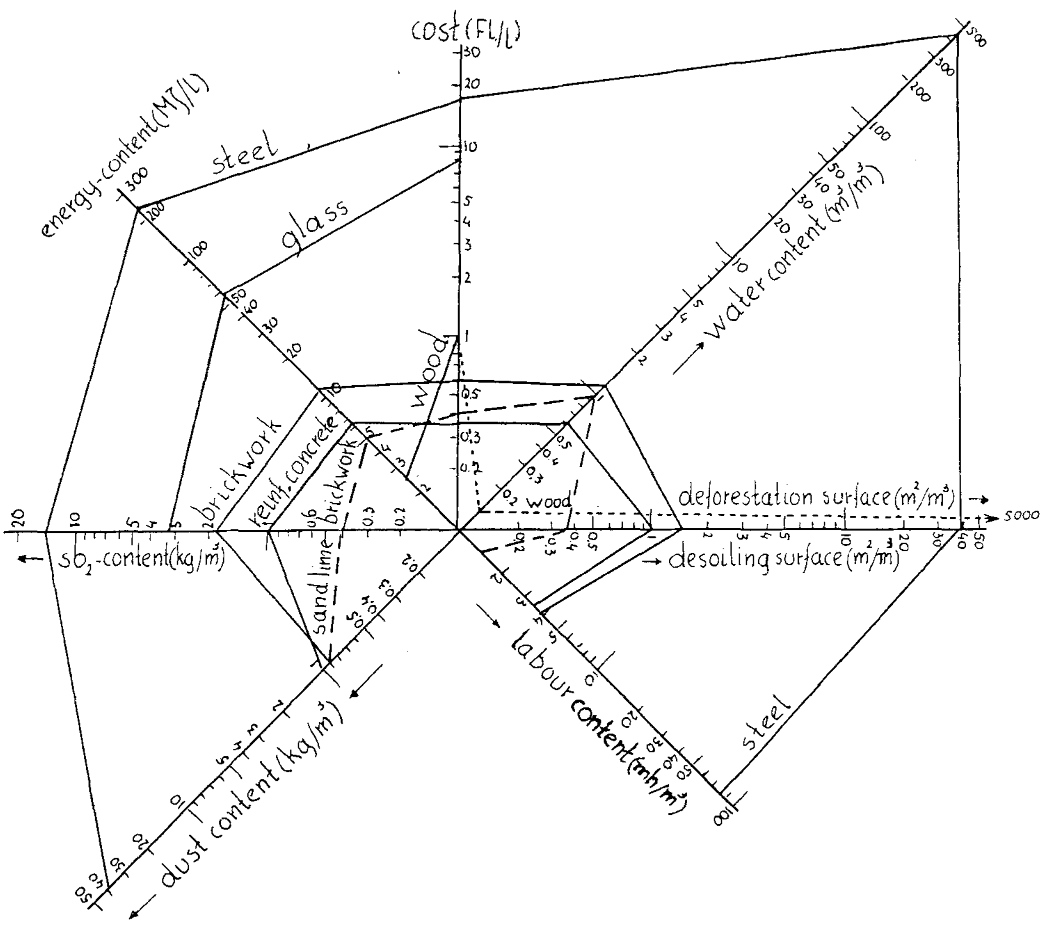

Fig. 2a Ecological profile for some materials, expressed per unit of volume.

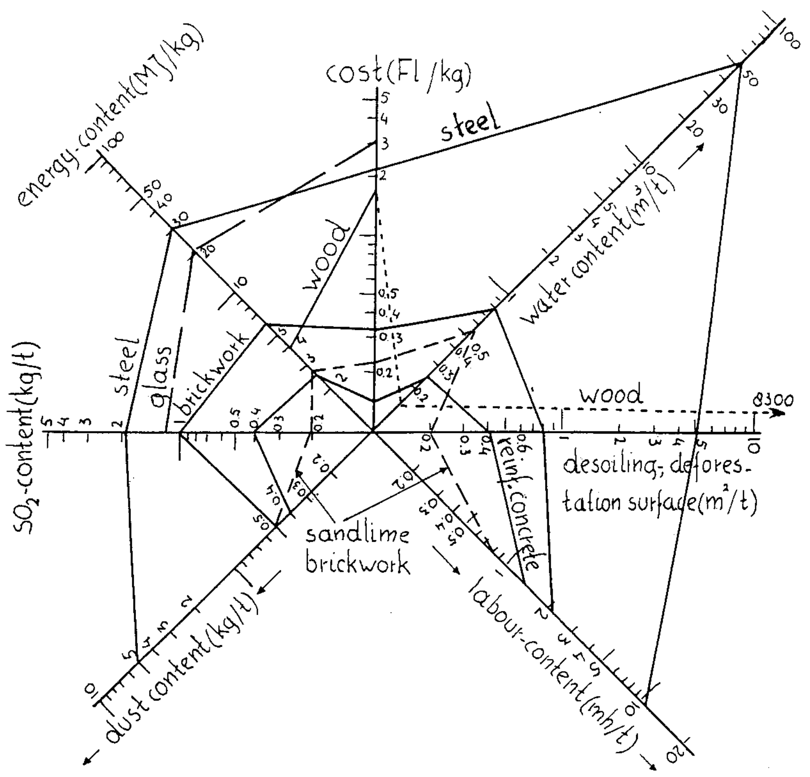

Fig. 2b Ecological profile for some materials, expressed per unit of mass.

Table 1 Ecological properties of some building materials

Properties	Steel* (Fe 360)	Glass	Brickwork	Sand lime brick work	Reinforced concrete†	Wood
Costs in Fl kg^{-1}	2.20	3.00	0.33	0.22	0.14	1.65
in Fl l^{-1}	17.20	8.10	0.59	0.40	0.35	1.00
Limiting calculation value strength in N mm^{-2}	240	30	7.5	7.5	13.5	14
Mod. of elasticity in 1000 N mm^{-2}	210	65	5.0	5.0	28	11
Energy content						
in MJ kg^{-1}	30	21	6.0	2.7	2.5	4
in MJ l^{-1}	236	56	11.1	4.9	6.3	2.4
Water content						
in m^3 t^{-1}	55	—	0.8	0.54	0.26	—
in m^3 m^{-3}	429	—	1.2	1.0	0.63	—
Pollution content						
SO_2 in kg t^{-1}	1.8	1.2	1.0	0.2	0.4	+
in kg m^{-3}	14	3.2	1.8	0.4	1.0	+
Dust/soot						
in kg t^{-1}	5	+	0.5	0.5	0.4	+
in kg m^{-3}	39	+	0.9	0.9	1.0	+
Desoiling deforestation						
in m^2 t^{-1}	5	—	0.8	0.2	0.4	8300‡
in m^2 m^{-3}	39	—	1.4	0.36	1.0	5000‡
Labour content						
in mh t^{-1}	10.6	—	2.1	0.75	1.37	—
in mh m^{-3}	81	—	3.8	1.35	3.43	—

† with 300 kg m^{-3} cement, 100 kg m^{-3} reinforcement, transport cement and aggregates over 100 km and fresh concrete from ready mix-plant over 12 km included.

* protection against corrosion (paint) included.

\+ at present, no reliable figures available.

– unknown by the author.

‡ based upon a yield of 1000 m^3 km^{-2} from which 20% rests for construction wood.

Table 2 Ecological properties per unit of volume material, given per N mm^{-2} strength and per N mm^{-2} modulus of elasticity.

Properties	Steel (Fe 360)	Glass	Brickwork	Sand lime brick work	Reinforced concrete	Wood
Costs in (Fl m^{-3})						
per σ	72	270	78.7	53.3	25.9	71.4
per E	0.082	0.12	0.12	0.08	0.013	0.091
Energy (MJ m^{-3})						
per σ	983	1867	1467	653	444	143
per E	1.12	0.86	2.2	0.98	0.21	0.18
Water (l m^{-3})						
per σ	1788	—	160	133	47	—
per E	2.04	—	0.24	0.20	0.023	—
Pollution SO_2 (kg m^{-3})						
per σ	0.058	0.107	0.24	0.053	0.074	+
per E (10^4)	0.67	0.49	3.6	0.80	0.36	+
Dust/soot (kg m^{-3})						
per σ	0.163	+	0.12	0.12	0.074	+
per E (10^4)	1.85	+	1.8	1.8	0.36	+
Desoiling/deforestation in m^2 m^{-3}						
per σ	0.16	—	0.19	0.027	0.074	357
per E (10^4)	1.9	—	2.8	0.40	0.36	0.455
Labour (mh m^{-3})						
per σ	0.34	—	0.50	0.18	0.26	—
per E (10^4)	3.9	—	7.6	2.7	1.23	—

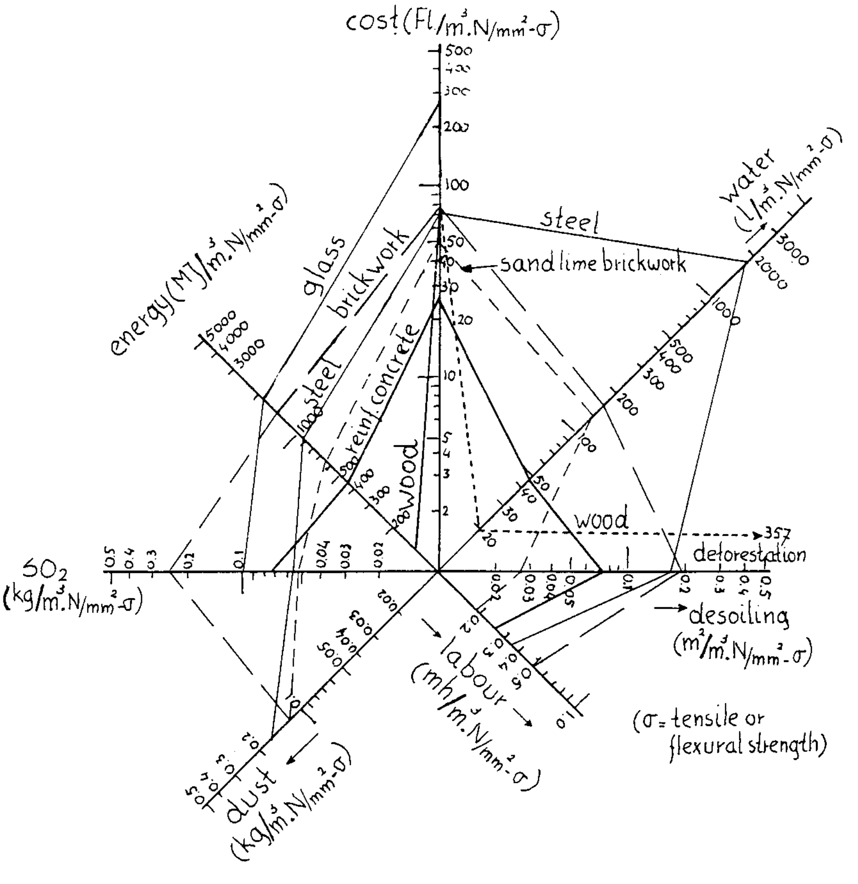

Fig. 3 Ecological profile for some materials, properties expressed in units per volume per Nmm^{-2} strength.

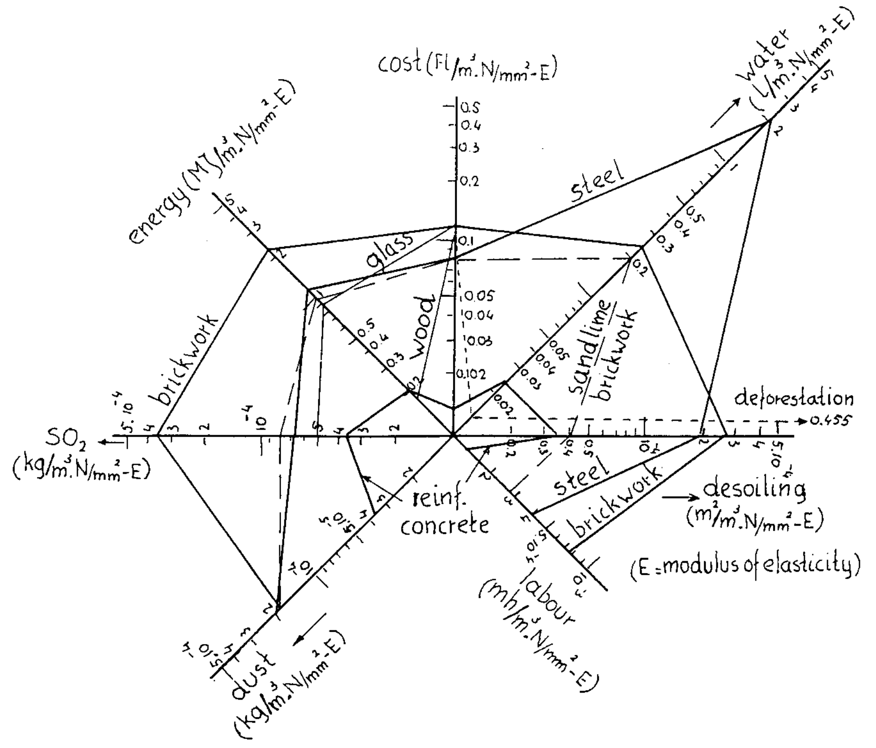

Fig. 4 Ecological profile for some materials, properties expressed in units per volume per Nmm^{-2} modulus of elasticity.

information that over a period of 100 years the sum of maintenance and demolition costs, including the updated value of the materials, was equal for both designs. Table 3 gives the overall view of the results [5].

Apart from the ratios, the other figures do not tell us much regarding energy and environment. Therefore they are translated as follows into practical consequences.

2.1.1 *Energy*

In the Netherlands, on average, central heating of a house needs 70 GJ energy per year. For the PC bridge materials, 3636 houses could be heated for 1 year; for the S bridge, 4222 houses.

2.1.2 *Water*

The average use of water per person in the Netherlands is $50 m^3$ per year. For the PC bridge materials, 4188 persons could use water during 1 year; for the S bridge, 7594 persons.

2.1.3 *Desoiling*

The PC bridge materials require desoiling equal to a canal of 20 m width and 1770 m long with a depth of 20 m; for the S bridge materials, this canal would have a length of 2000 m.

2.1.4 *SO_2 emission*

This emission causes acid rain. If we assume acid rain with $pH = 4$ (in the Netherlands 3.8–4.6) the PC bridge materials would give $6.46 \times 10^6 m^3$. Translated into acid rain per m^2, this means, for example, that for a city like Eindhoven ($78 km^2$), as a result of the PC bridge materials, there would be an acid rain fall of $83\ lm^{-2}$ and for the S bridge materials $74\ lm^{-2}$ (average rainfall in the Netherlands $760\ lm^{-2}$).

Table 3 Ecological comparison for bridge materials present on the building site

Ecological properties	PC-bridge	S-bridge	Ratio S/PC (%)
Energy content (GJ)	254521	295573	116.1
Water content (m^3)	209413	379691	181.3
Desoiling (m^2)	35342	40108	113.5
SO_2-emission (kg)	20661	18417	89.1
Dust/soot emission (kg)	43618	30100	69.0
Manufacturing labour (mb)	60860	76846	126.3
Transport labour (mh)	39584	16935	42.8
Total labour	100444	93781	93.4

2.1.5 *Dust/soot emission*

The average dust content over Eindhoven is $50\ \mu gm^{-3}$. Calculated to 1 km above Eindhoven this means that the PC bridge materials would give (at one moment) $641\ \mu gm^{-3}$ and the S bridge materials $443\ \mu gm^{-3}$.

2.1.6 *Labour*

If a man-year (my) consists of 1800 mh, the PC bridge materials would require 55.8 my labour (22.0 regarding transport and 33.8 regarding manufacturing) while the S bridge materials would require 52.1 my (9.4 for transport and 42.7 for manufacturing). So for the S bridge materials 58% less transport labour is necessary but 26% more manufacturing labour. In total, the S bridge materials need 6.6% less labour than the PC bridge materials.

The ecological conclusion regarding the two bridges may be that the PC bridge materials need less energy

(16%) and much less water (81%) but at the cost of increase of SO_2 emission (11%) and especially dust/soot emission (31%) whilst the labour involved was somewhat greater (7%).

So, for construction and building projects, apart from primary technical and economic criteria, it is possible to choose the energy, environmental or social aspects to which most attention is to be given. In the long run, however, this might change and possibly environmental criteria could be of paramount importance.

2.2 Example 2

As a further example, we have calculated the ecological consequences of the yearly consumption of building materials in the Netherlands (7.5×10^6t bricks, 36×10^6t concrete/mortar, 3.7×10^6t steel, together 90% of total use). Table 4 gives the results translated into a practical form, including the yearly waste from demolition (which will, however, grow as fewer new houses are built yearly). Renovation and rehabilitation are becoming more frequent and there is increasing demolition of the buildings of the boom directly after the second world war, there now being an exponential need to renew these buildings.

Table 4 Ecological consequences of (90% of) the yearly consumption of building materials in the Netherlands*

Ecological parameters	Ecological consequences
Energy	78% of all houses can be centrally heated for 1 year.
Water	307 800 inhabitants can be provided with water for 1 year.
SO_2-emission	Responsible for 8.9% of the yearly acid rain fall.
Dust/soot	Responsible for half of the average dust content yearly.
Desoiling	Provides a lake of 38.9 km^2, of depth 20 m yearly.
Waste (from demolition)	Necessitates yearly 1 km^2, height 5 m (from which ≈50% is reused).
Labour	Provides years 14439 my labour for production, 11983 my labour for transport; 56422 my in total

* Inhabitants 14.5×10^6, surface 41 200 km^2.

The table shows that important environmental consequences result from human activities.

3. CONCLUSION

Because it is people who determine how materials are used in society, each designer, in making his or her choice of building materials, is also responsible for the ecological and social consequences of that choice. He or she must therefore be aware of the ecological properties as given in this article, although the values may vary somewhat from country to country, depending on the level of development of environmental laws. In other words, for construction and building projects, the designer could choose not only from technical and economical criteria, but also from among the energy, environmental or social aspects which he or she feels merit consideration.

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