PERGAMON

Building and Environment 34 (1999) 751–758

BUILDING AND ENVIRONMENT

A quantitative approach to the assessment of the environmental impact of building materials

D.J. Harris

Department of Building Engineering and Surveying, Heriot-Watt University, Riccarton, Edinburgh, U.K.

Received 7 July 1998; accepted 14 September 1998

Abstract

The materials from which a building is constructed make a significant contribution to its overall impact on the environment. This impact is felt in a number of ways; locally, through the effects of activities such as quarrying; globally, as a result of carbon dioxide released by using energy used to manufacture the materials; and internally, in the effects on the health of the occupants of the building.

Some of these effects are easier to measure than others, and comparisons between the seriousness of the different effects are difficult to make. It therefore seems unreasonable to attempt to devise a single figure of merit for the overall environmental impact of a building; what is needed is a profile which gathers together a range of indicators, but allows them to remain separate. This article describes the development of such an environmental profile which can be used as a design aid, and illustrates its use with a case study of a typical British house. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Public awareness of environmental issues such as global warming and ozone depletion has increased substantially over the last few years, and the implications for energy conservation in buildings are widely appreciated. The energy used to service buildings constitutes approximately 50% of all primary energy used in the U.K. [1], while it has been estimated that the energy to manufacture and transport building materials accounts for an additional 8% (350 PJ per year) [1], representing about 6 tonnes of building material per capita [2]. Apart from the energy consumed, the construction (and ultimate demolition) of buildings has other significant environmental consequences associated with the extraction of raw materials, disposal of wastes, and the effects of building materials on the health of building workers and occupants. In the pursuit of a sustainable society, therefore, improvements in the performance of the built environment have a considerable effect, and it is essential to have tools available to allow the relative performance of building designs to be assessed.

The impact of buildings on the environment can take many forms, as illustrated broadly in Fig. 1. While some of these effects, such as noise and dust created during the construction process, are transitory, others are more permanent, such as atmospheric carbon dioxide from combustion.

The wide range of natural and man-made materials now used in building work has a significant environmental impact, and in this article an environmental profiling tool for building materials is described. The effects of changes to the construction of the building and the materials used can be quickly assessed, and it can therefore be used as a design tool in the pursuit of more environmentally-friendly alternatives.

2. Assessing the environmental impact of buildings

A building environmental assessment system requires;

- Knowledge of the different modes by which a process affects the environment.
- A measure of the scale of each of the effects caused by the process.
- A yardstick against which to measure the damage caused to the environment.

The most widely used assessment method in Britain is the Building Research Establishment Environmental Assessment Method (BREEAM) [3] which analyses a building's impact in a number of key areas—local, global, and internal. Points are awarded in various categories (low carbon dioxide emissions, use of recycled materials, avoidance of air conditioning, etc.), and the points totalled, a higher score indicating a less environmentally-

PII: S0360-1323(98)00058-4

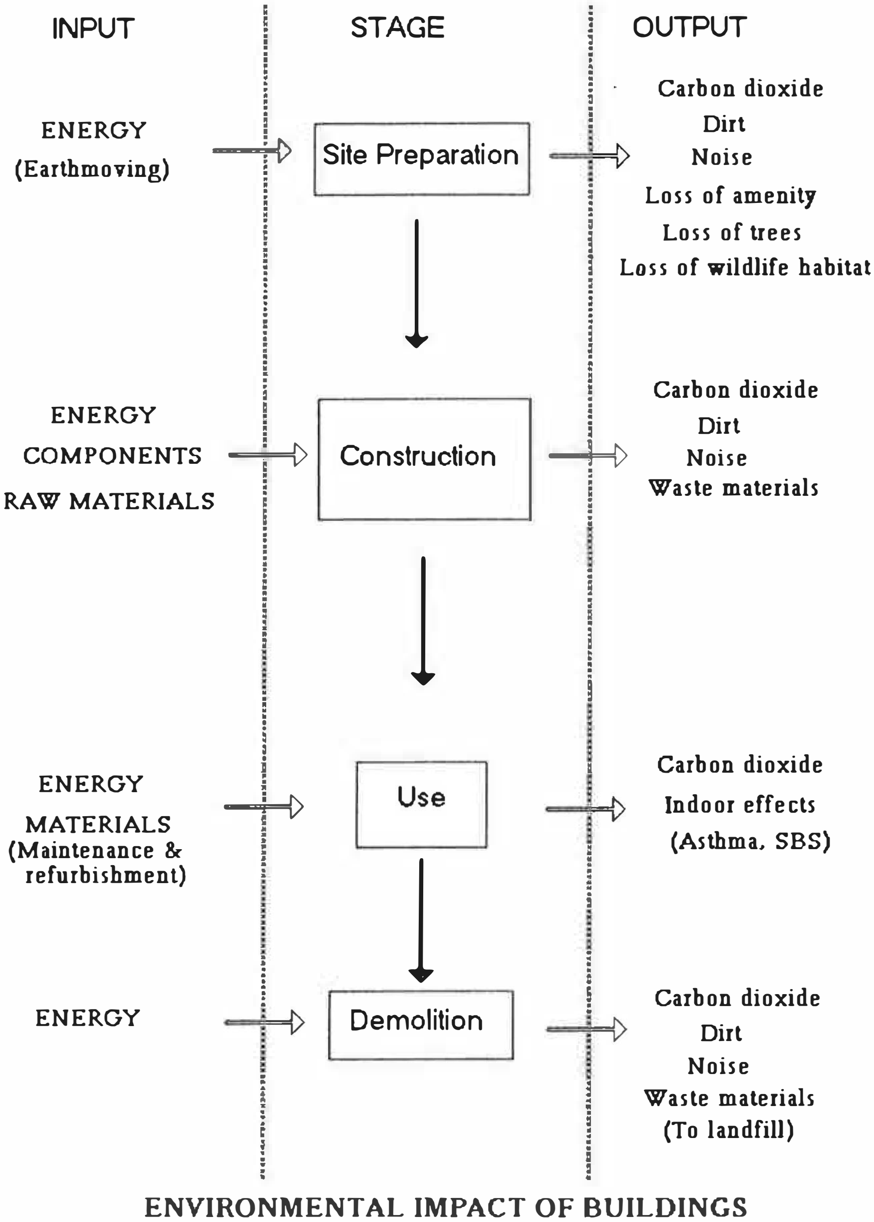

Fig. 1. Impact of a building through its lifetime.

damaging building. A range of BREEAM schemes are available to take into account the varied requirements of different building types, such as housing [4], new offices [3], and superstores [5]. A number of other countries have developed similar systems [6].

These methods sum the points scored in different areas of impact, such as the use of recycled materials, low CO_2 emissions, etc., to give a single figure which may be described on a scale ranging from 'poor' to 'excellent'. Useful though this is, the performance in specific areas of impact remains hidden. For use as a design aid, and also as an educational tool, it is more useful if, instead of a single figure-of-merit covering all aspects of the building, a profile is produced in which the individual effects remain separate.

One reason for keeping the individual indicators separate is that it sometimes happens that an improvement in one aspect of performance may sometimes be accompanied by a deterioration in another. An example of this is the relationship between the thickness of thermal insulation used in an outer wall (embodied energy, CO_2 emissions, etc.) and its effects in lowering the heating energy requirement of a building. If a substantial thickness of insulation is built into a wall, the carbon dioxide emissions incurred in the production of the insulation (i.e., through its *embodied energy*) may exceed the lifetime energy savings resulting from its use (Fig. 2). There is an inverse non-linear relationship between insulation thickness and total energy use, and a direct linear relationship between thickness and embodied energy. The figure

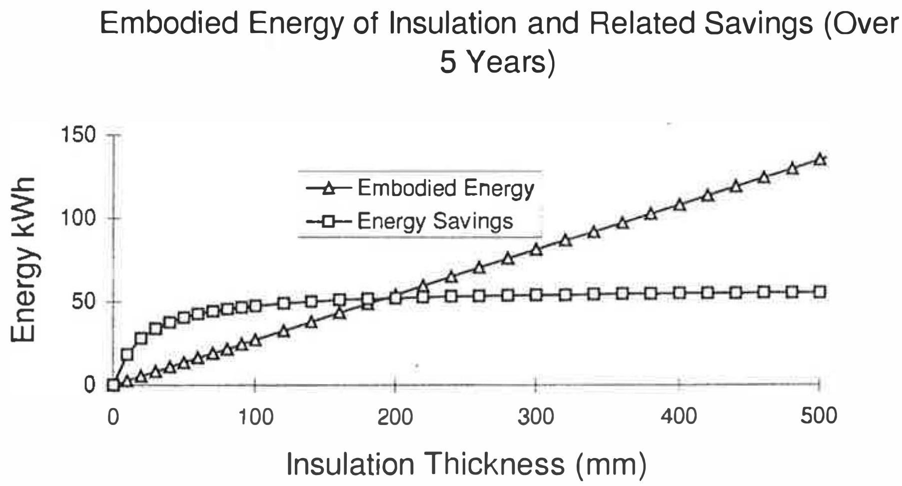

Fig. 2. Effect of embodied energy in limiting useful insulation thickness.

shown here represents only a first approximation; since insulation is not generally available in infinitely variable thicknesses, the continuous line is in reality a series of discrete points, and, if the whole building is being considered, there could also be a reduction in embodied energy, as the heating load would be lower and smaller pipes, radiators, etc., could be used.

3. Difficulties in environmental assessment

A number of difficulties arise in environmental assessment;

- There is no established set of indicators.
- There is no agreed system for weighting one indicator against another.
- There are few existing criteria for individual indicators.
- There are few targets for individual indicators.

3.1. Indicators

An environmental assessment method must take into account a number of factors, such as those listed in Table 1, and include a number of measures of suitability, i.e., a number of environmental indicators. There is no general agreement as yet on an appropriate range of indicators, nor are there any specific benchmarks or agreed standards; these subjects are currently being researched by BRE, CIRIA and others [6].

A number of environmental considerations such as global warming, Ozone layer depletion, acid rain, depletion of hardwood forests, etc., are considered to be of major importance and would therefore merit inclusion in most environmental assessment methods. Other effects are considered insignificant and are ignored by some commentators [7], e.g., toxic substances which are only a problem in the workplace but scarcely occur in the outside environment because they decompose rapidly. Others, such as raw material depletion and water economy, may be serious or not, depending on the location. The list of indicators used in the example is shown in Table 2.

3.2. Weighting

Because of the points system used in methods such as BREEAM, some form of weighting is implicit, but the

Table 1
Some indicators of the environmental impact of building materials

Indicator	Form of environmental impact
1. Embodied energy	CO_2 emission, other gaseous pollutants, NO_x, SO_x. Quantifiable
2. Raw materials consumption (Resource conservation)	Quarrying local nuisance, noise, dust. Partially Quantifiable
3. Scarcity factor	Raw material consumption. Are there better alternative uses for the material? Partially Quantifiable
4. Recycling potential	Difficult to quantify. Affects indicators 1–3 above
5. Effects on occupants of building or handlers (Toxic hazard)	Asthma, etc. Difficult to quantify (reactions vary between individuals)
6. Potential for using recycled materials	Difficult to quantify
7. Influence on energy consumption	CO_2 emission, other gaseous pollutants, NO_x, SO_x. Possible to quantify, but depends on location (i.e. climate)

Table 2
List of indicators used

• Carbon dioxide emissions (Energy-in-use) (global warming)
• Effect on the health of occupants of a building. (e.g.. Asbestos)
• Indoor air quality. (e.g.. VOCs)
• Carbon dioxide (Embodied energy)
• Depletion of non-renewable resources
• Use of recycled materials
• Landfill

criteria used are not made clear. Weighting of the various indicators against each other is not possible in an objective way; there are a number of reasons for this:

- Difficulties in agreeing on the relative importance of different effects, e.g., how does a reduction in energy consumption of a building compare with consumption of raw materials in environmental terms?
- A particular effect may be not only material-dependent but also use-dependent (see example above).
- The importance may vary geographically (e.g., water conservation, thermal insulation).
- Geographical variations in embodied energy arising from different transport requirements and variations in energy efficiency in manufacturing.

Weighting is the most complex area of environmental impact, and there is no agreed method for determining the appropriate weighting factors [7]. The reasons for these difficulties are easy to see. For example, does 1 tonne of material put into landfill have an impact on the environment equivalent to the emission of 1 tonne of carbon dioxide? In the method presented here, the question of weighting does not arise directly, but the user will implicitly apply their own weighting criteria in order to analyse the results.

3.3. *Criteria and targets*

Because this is a relatively new field, there are few existing criteria. In the field of global warming, simulations may be used to estimate the scale of a reduction in carbon dioxide emissions necessary to stabilise global temperatures, and we can set up targets for CO_2 emissions, but in other areas there is much more doubt. In general too, we have little information on the performance of existing buildings with respect to many indicators. Energy consumption and related CO_2 benchmarks for a range of building types are now widely available [8].

While energy consumption and embodied energy can be measured, other aspects of environmental performance, such as the effect of indoor air quality on the occupants' health, are substantially more difficult to assess quantitatively, in either an absolute or a comparative way.

4. Embodied energy of building materials

In recent years the focus of concern has widened to include all energy and material flows in the construction process, from extraction of raw materials through to demolition. The question of embodied energy—the energy required to produce the materials from which a building is constructed—is being addressed with increasing precision, and the embodied energy of a building may constitute 15% of its lifetime energy consumption. The emphasis on energy stems partly from its significance (carbon dioxide, global warming) and also reflects the ease with which energy use can be assessed. Energy modelling software enables accurate predictions of energy consumption to be made, although the accuracy of the embodied energy figures available is substantially lower than that of energy-in-use [9].

Embodied energy analysis may be carried out at a number of levels. At a primary level of analysis, the embodied energy in a brick, for example, can be estimated by calculating the total energy used by the brick industry, and dividing by the number of bricks produced. More sophisticated methods of analysis have improved the reliability of the figures substantially, but wide variations remain in the published figures, partly due to local differences in energy efficiency and transport requirements.

The use of recycled material enables reductions in the embodied energy to be made. The scale of the reduction available depends on the energy requirements of the material and the quantity used in the building. The issue of material quantity is not addressed directly in methods such as BREEAM, but is essential in evaluating the viability of using recycled materials; earlier work by Elliot and Palmer [10] showed that the specific embodied energy and material quantity strongly affect the feasibility of recycling. An example of the effect of recycling on different constructions is shown by Harris and Elliot [11] for a simple building having either a steel or concrete frame. While recycling the concrete had little effect on the total embodied energy (even for the concrete-framed building), recycling the steel had a critical influence in both cases. Without this information on material quantities, a correct assessment of the feasibility of recycling materials cannot be made.

Building materials such as concrete are of high density and low value, and transport energy forms a high proportion of the total embodied energy [9]. For such materials the location of the recycling plant in relation to the buildings is crucial in determining the viability of recycling; where considerable distances are involved, then the use of new materials may in fact consume less energy than recycling. In contrast, recycling a high-value, low density material such as aluminium is almost always viable, because the embodied energy of recycled product is less than one-tenth of that of virgin material, and transportation energy is considerably lower.

4.1. Difficulties in recycling

Recycling may seem to be an ideal solution to many problems, but there are a number of barriers to its implementation; sorting and cleaning add to the financial and energy burdens incurred, and require the disposal of waste water. In addition, substantial practical difficulties add to the cost; separation of bricks and mortar without damage, or problems in excluding foreign material which may impair the performance. Furthermore, designers' and contractors' doubts concerning the specifications and performance standards of recycled materials often act as a deterrent to their use, forcing down the price of recycled materials or suppressing the market.

Re-use of materials and components is another option to be considered. This implies a substantially lower amount of reprocessing, or may involve merely cleaning (Fig. 3). However, re-use is substantially more difficult than recycling, since it is difficult to remove components such as window frames without damage.

5. Environmental assessment of building materials

The environmental effects of building materials are shown in a general way in Fig. 1, and in Tables 1 and 3 for a selection of materials [12]. A number of assessment methods for building products have been devised. These include Environmental Preference [13] and the BBA Environmental Profile [14], among others. Aspects of environmental performance covered by these schemes include raw material usage, embodied energy, thermal properties, installation, maintenance requirements, design life, toxicity, disposal, and recycling.

The effect of certain indicators (CO_2 emissions, use of raw material, production of waste material) is directly proportional to the quantity of that material in the building, which is taken into account in this profiling method by using the Bill of Quantities. Other effects, such as asthma attacks caused by outgassing of solvents, etc., may be related to quantity in a less specific way. The presence of a threshold quantity of material may be

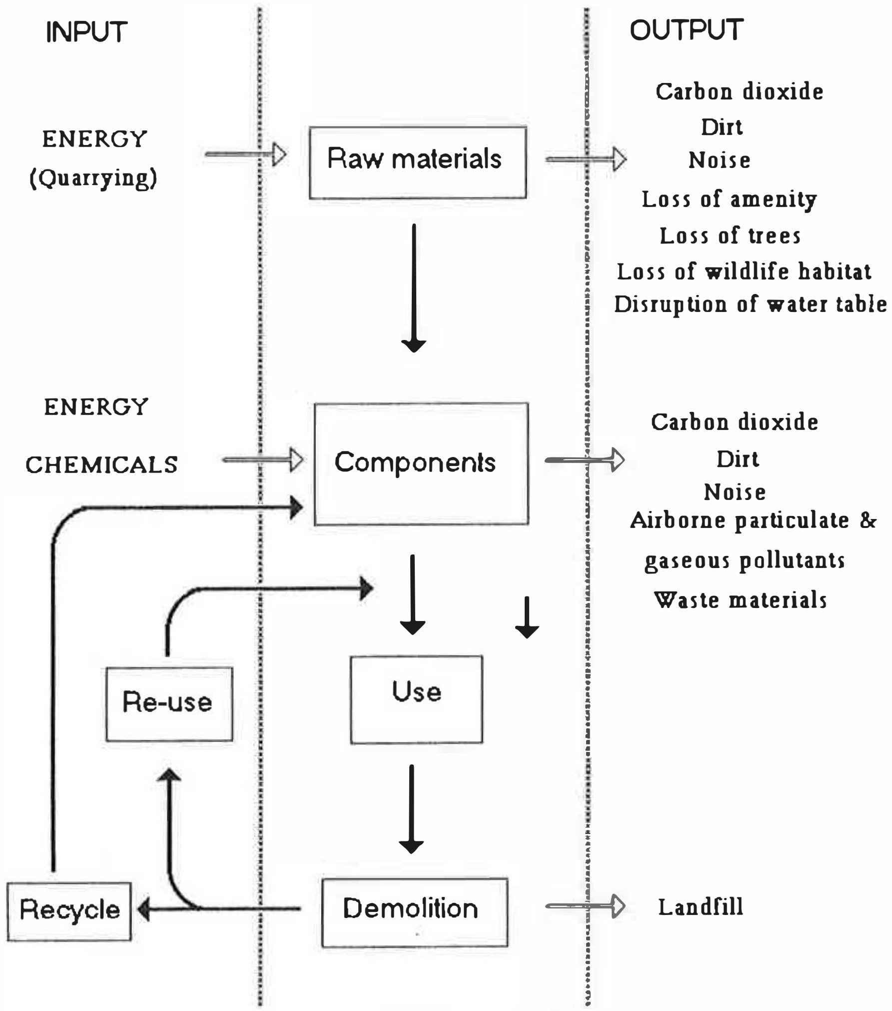

Fig. 3. The environmental effects of building materials—impact of recycling or reuse.

Table 3
Environmental impact of specific materials. Adapted from [13]

Material	Impact
Brick	Made of burnt or fired clay or calcium silicate—high energy use. Requires extraction of clay and the hazards associated with quarrying—loss of habitat, dust, noise, destruction of water table. Old brick quarries used as landfill sites. Essentially a non-renewable source. Firing leads to undesirable material in flue gases—corrosive substance which make heat recovery through heat exchangers difficult. Can be recycled if treated with care and lime mortars used (cement-based mortar more difficult to separate).
Cement and concrete	Cement extracted by quarrying with the usual hazards. Up to 5% in form of silicon dioxide which when breathed in can cause silicosis. Calcium oxide (quicklime) cause burns to skin and permanent damage to eyes. Other skin problems may arise from additives such as calcium chloride and plasticisers to aid workability.
Clay products	All clay quarrying destroys habitats and water-tables, although many useful building products can be made. Much energy is required for firing to harden the material. Capacity for recycling depends on the product made. Can be recycled as hardcore.

sufficient to have an effect, while increasing the quantity above this level may not lead to any observable change. However, much remains unknown in this area.

Apart from the qualities of the material itself, much depends on the use to which it is put. Material used in the outer envelope of a building will have an effect on the energy consumption, which is also dependent on its location.

6. Use of the bill of quantities

The information given by the above methods is useful to the designer, but gives information only about the material itself, not the application. To obtain a picture of the environmental impact of the material in use, additional information is required. Firstly, those effects dependent on the quantity of material used in the building can be evaluated from the Bill of Quantities [10].

Secondly, if the material forms part of the building's outer envelope, the choice of material construction will affect the energy consumption. For this the thermal properties and the geographical location of the building need to be known.

7. The building environmental profile

Profiles for the environmental impact of a number of materials were devised. The choice of indicators was made, drawing information from a number of sources [12, 15]. Where indicators are difficult to quantify, they have been put on scale of 0–3, 0 indicating that the impact is low or negligible, 3 indicating serious environmental damage. The thermal properties have also been included so that the effect of outer-envelope materials on energy consumption can be estimated. For comparison, the thermal resistance of a 1 m^2 section of a 100 mm thick layer is shown. An environmental profile Table for a range of materials has been devised (Table 4). To convert the material profile to a whole building profile, we multiply the profile 'score' in Table 4 by the quantity used, obtained from the Bill of Quantities. At the same time, an estimate of the heating energy consumption of the building is made, in this case using a degree-day method.

8. Case study

A case study was carried out to illustrate the use of the profile, using a typical British house design of the type produced by a large builder. The basic construction is a double brick cavity wall with mineral wool insulation and aluminium window frames. This base case was compared with the same building, but with timber-framed construction, recycled cellulose insulation, and timber window frames. The resulting profiles are shown in Tables 5–6. The alternative greener house shows a reduction in environmental impact in most of the indicators.

9. Other issues not included

A number of other issues remain to be addressed and are currently under development. For the full environmental impact to be evaluated, life-cycle issues, such as maintenance and refurbishment requirements (i.e., inputs of energy and materials) should be addressed, and different parts of a building may last for different lengths of time.

While an assessment may give a profile or a total, this does not give any measure of how effectively the building uses the space. A block of flats is a very efficient way of building, as it uses the minimum of materials per dweller, and energy consumption is lower than a detached house, because the outer envelope is smaller in relation to floor area. A block of flats will overall have a greater impact than a single house, but since it houses many more people, the impact per householder or tenant is likely to be substantially lower. An appropriate basis for such comparisons has yet to be devised.

10. Conclusions

The impact of buildings on the environment depends on their design, construction, use and location. This arti-

Table 4
Environmental profiles for a range of building materials

Material	Embodied energy kWh/m³	Renewable resource?	Scarcity of raw materials	Local extraction disruption	Indoor effects (Toxicity)	Recycling potential	Energy (Resistance per 100 mm)
Brick (Fletton)	300	Non-renewable	Common	High	Dust if exposed	Low-med	0.125
Timber (imported softwood)	7540	Renewable	Common	Low	None	Med	0.714
Timber (local oak)	110	Renewable	Common	Low	None	Med	0.588
Clay tiles	1520	Non-renewable	Common	High	n/a	Low	0.175
Concrete	800	Non-renewable	Common	High	Dust if exposed	Med	0.078
Lightweight blocks	600	Non-renewable	Common	High	Dust if exposed	Low-med	0.077
Crushed granite aggregate	150	Non-renewable	Common	High	n/a	High	0.04
Cement	2860	Non-renewable	Common	High	Dust if exposed	Med	0.139
Steel	103,000	Non-renewable	Common	High	None	High	0.002
Copper	133,000	Non-renewable	Scarce	High	None	High	0.00027
Aluminium	75,600	Non-renewable	Scarce	High	None	High	0.0005
Glass	23,000	Non-renewable	Common	High	None	High	0.095
Cellulose insulation	133	Made from recycled material	Common	Low	n/a	It is recycled material	2.5
Mineral wool	230	Non-renewable	Common	High	Dust if exposed	Low	2.22
Synthetic finishes	High	Non-renewable	Common	High	Asthma etc.	Low	n/a
Plastics	47,000	Non-renewable	Common	High	None	Low-med	0.625

Table 5
Environmental profile for a typical house

	Totals (= factor × quantity of material in building)							
Material	Quantity m³	Embodied energy kWh	Renewable resource?	Scarcity of raw materials	Local extraction disruption	Indoor effects (Toxicity)	Recycling potential	Energy transmittance per 100 mm, 0 if not external wall
Brick (Fletton)	21.16	6348	63.48	0	42.32	21.16	42.32	169.28
Timber imported s	3.3	24882	0	0	3.3	0	6.6	0
Clay tiles (roof)	1.35	2052	4.05	0	2.7	0	4.05	7.71
Concrete external wks	1	800	3	0	3	1	2	0
Crushed granite external wks	1	150	3	0	3	0	1	0
Cement	3	8580	9	0	9	3	6	21.6
Steel	0.1	10300	0.3	0	0.3	0	0	0
Copper	0.002	266	0.006	0.004	0.006	0	0	0
Aluminium (window frames)	0.0144	1088	0.0432	10.0288	0.0432	0	0	28.8
Glass	0.036	828	0.108	0	0.072	0	0.036	0.379
Mineral wool	10.58	2433	31.74	10.58	31.74	10.58	31.74	4.76
Plastics	1	47000	3	0	3	0	2	0
		EE kWh	Renewable resource?	Scarcity	Local disruption	Indoor effects	Recycling potential	Energy
Totals		104727	117.7272	10.6128	98.48	31.74	95.74	232.529

Table 6
Environmental profiles for the two building designs

	Embodied energy kWh	Renewable resource?	Scarcity	Local disruption	Recycling potential	Energy GJ
Standard	106898	117.7	10.6	98.4	95.7	22.6
Timber-framed	91519	65.6	0.004	53.9	64.4	19.1

cle considers the effect of the construction materials on the environment, and shows how it can be assessed in a quantitative way, by combining information on the material properties with the building quantities.

The environmental profiling tool developed enables the impact of building designs to be compared, taking into account the significant indicators. The indicators remain separate, enabling the user to weight the factors as appropriate. By allowing changes to be made to the design, priority areas for improvement can be identified.

The overall impact of the material on the environment may depend on:

- The material properties only.
- The application in the building.
- The location of the building.

The use of such profiles will enable fuller information to be obtained concerning the environmental impact of a building and will assist architects and other building professionals in both design and procurement processes.

References

[1] Adalberth K. Energy Demand During the Life Cycle of a Building. CIB Symposium Energy and Mass Flow in the Life Cycle of Building. Vienna, 1996.

[2] Curwell S, Cooper I. The Implications of Urban Sustainability. BRIA Vol 26 no. 1. Jan/Feb 1998.

[3] BREEAM Building Research Establishment Environmental Assessment Method for New Office Buildings 1/93. BRE 1993.

[4] BREEAM Building Research Establishment Environmental Assessment Method for New Homes 3/91. BRE 1991.

[5] BREEAM Building Research Establishment Environmental Assessment Method for Superstores and Supermarkets 2/91. BRE 1991.

[6] Cole R. Emerging Trends in Building Environmental Assessment Methods. BRIA Jan/Feb 1998.

[7] The Eco-Indicator 95. NOH Report 9523. PRe consultants/DUIJF Consultancy BV. 1996.

[8] Energy efficiency Office Best Practice Case Studies (various). HMSO.

[9] Howard NP. CIB Symposium Energy and Mass Flow in the Life Cycle of Building. Vienna. 1996.

[10] Elliot CJ, Palmer A. Total Resource Assessment Based on Extension of Traditional Procurement Systems. 1995. CIB W65 Conference, Glasgow, 1996.

[11] Harris DJ, Elliot CJ. Energy Accounting for Recycled Building Components. 2nd CIB Conference on Buildings and the Environment. Paris, June 1997.

[12] Fox A., Murrell R.Green Design. Architecture Design and Technology Press. London. 1989.

[13] Boonstra C. Method of Environmental Preference for Building Materials. CIB First International Conference: Buildings and the Environment. BRE 16–20 May 1994.

[14] Hewlett PC, Oliver MS. Assessing Innovative Products and Compiling an Environmental Report. CIB First International Conference: Buildings and the Environment. BRE 16–20 May 1994.

[15] West J, Atkinson C, Howard NP. Embodied Energy and Carbon Dioxide Emissions from Building Materials. CIB First International Conference: Buildings and the Environment. BRE 16–20 May 1994.