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Energy use during the Life Cycle of Buildings: a Method

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*So far, research has mainly been concentrated on the energy use for buildings during their period of use, that is to say, the energy needed for space heating, hot water and electricity. But what about the energy use for a building during its life cycle? This paper presents a method on how to calculate the energy use during the life cycle of a building. In the companion paper "Energy use during the life cycle of single-unit dwellings: examples" [Building and Environment, 1997, **32**, 321–329] the method is applied on three single-unit dwellings built in Sweden in 1991 and 1992. © 1997 Elsevier Science Ltd.*

BACKGROUND

Studies on the total energy use during the life cycle of a building are desirable, considering the urgent necessity to save energy. To date, research has mainly focused on the energy use for buildings during their period of use: space heating, hot water and the need for electricity. The purpose of this study is to present a developed methodology on how to estimate the energy use during the life cycle of a building.

In the present context, the expression "the life cycle of a building" refers to all temporal phases or stages, from the point where the construction materials are produced until the building is to be demolished. Energy is required during every one of these stages. The temporal phases involved are presented in Fig. 1.

Pertinent conditions, definitions and restrictions

In order to be able to calculate the energy use during the life cycle of a building, some definitions and restrictions have to be made. When calculating the amounts of construction materials, all the quantities have to be included: from the excavation for the foundation (including the drainage and capillary-severing layer) up to the chimney on the roof.

The period of use for buildings, the so-called "management" phase, has to be assumed. In this study the management phase is assumed to be 50 years, as the economic life-span of a building in Sweden is about 40–50 years. The energy use during the management period is based on the assumption that no extensions or considerable changes are made during the relevant 50-year period. Only "normal" maintenance has been taken into account.

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METHOD

Manufacturing energy use during production and renovation

Energy is required whenever construction materials are going to be manufactured. Table 1 presents a compilation of the manufacturing energy requirements (primary energy) regarding construction materials [1]. The energy uses stated are general in character. It would be desirable for the manufacturers of these materials to be able to supply information regarding the energy use associated with their particular product. Such a statement would ensure that more specific energy requirement data for each type of construction material would become available. At the same time, this energy use would be monitored and adjusted as product development continued.

In Table 1, the waste of each material produced during the erection of the building is also presented. The waste is expressed as a waste factor w_i (%).

The energy requirement for producing all the building materials, Q_{manuf} (kWh), is estimated as follows:

$$Q_{\text{manuf}} = \sum_{i=1}^{n} m_i \cdot (1 + w_i/100) \cdot M_i$$

where n = number of materials, i = the material of concern, m_i = amount of the building material i (ton), w_i = the factor for waste of the material i produced during erection of the building (%), and M_i = energy required for manufacturing the building material i (kWh/ton).

In order to be able to calculate the energy use during the renovation phase, some assumptions regarding the life-span of the various construction materials have to be made (see Table 2). These life-spans are collected from the maintenance norm of the Organisation for Municipal Housing Companies [3]. The assumed life-spans contained in the maintenance norm are based on experience. The relevant materials are exchanged (number of times)

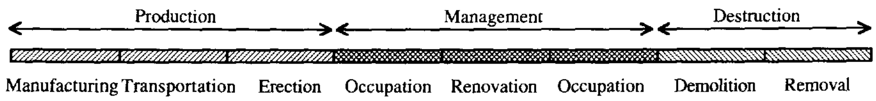

Fig. 1. The shifting temporal phases of a building during its life cycle.

Table 1. Energy use for manufacturing construction materials. M_i (kWh), collected from Andersen *et al.* [1]. Manufacturing energy (primary energy) comprises energy required for the extraction of the raw material and the production and transport of semi-manufactures; the heating of manufacturing and administration premises; and the production of the final construction material. The combustion value of the construction materials is also included in the manufacturing energy, i.e. no deduction for such a value has been made. The factor for waste w_i (%) produced during erection or renovation of the building is based upon a study by Larsson [2]

Materials	M_i (kWh/ton)	w_i (%)
Concrete, reinforced	560	20
Concrete, plain	210	10
Gypsum wallboard	2400	10
Tiles and clinkers	2000	10
Timber: rough saw (0.5 ton/m^3)	1440	10
Timber: planed (0.5 ton/m^3)	2240	10
Timber: shingles and shavings (0.6 ton/m^3)	3150	7
Glass	7230	0
Mineral wool	5330	10
Polyvinyl chloride (PVC)	24 650	5
Polythene	16 400	5
Polystyrene	29 650	10
Coatings: paints and lacquers	7000	5
Steel	8890	5
Copper	19 500	5
Ventilating channels, sheet metal	9000	10
Electric wires, copper	19 780	5
White goods, 1110 kWh/item	—	0

according to the following formula:

$$\frac{\text{life-span of a building}}{\text{life-span of material}} - 1$$

An example of this is as follows. A plastic carpet is assumed to have a life-span of 17 years, according to Table 2. Our calculations thus inform us that it will be exchanged $(50/17) - 1 = 1.9$ times.

The exact meaning of the concept "life-span" in relation to a product varies. Sometimes a product will be exchanged because it has expired or has become worn out. In such a case, the life-span may be the "technical life-span", for instance the life-span of white goods. In another case, a product might be replaced due to altered fashions, or because the user has become tired of the appearance of a certain product. In such a context, the life-span may be considered as the "aesthetic life-span", e.g. wallpaper or indoor paint.

Table 2. The life-spans of some construction materials

Life-span of building	Life-span (years)
Life-span of building	50
Frame (external walls, interior walls, joists, fundament, insulation)	50
Parquet flooring	50
Water pipes and electric wires	50
Ventilating channels	50
Facing: wooden panelling	30
Windows and doors	30
Wardrobes and cupboards	30
Roofing tiles and drainpipes	30
Plastic carpeting	17
Water heater	16
White goods	12
Painting and wallpapering	10

The energy use for producing the building materials during the renovation, $Q_{\text{manuf,renov}}$ (kWh), is estimated as follows:

$$Q_{\text{manuf,renov}} = \sum_{i=1}^{n} m_i \cdot (1 + w_i/100) \cdot M_i \cdot \left(\frac{\text{life-span of a building}}{\text{life-span of material } i} - 1\right),$$

where n = number of materials; i = the material concerned; m_i = amount of the building material i (ton); w_i = factor for waste of the material i produced during erection of the building (%); and M_i = energy required for manufacturing the building material i (kWh/ton).

Energy use for transportation during the production, renovation and destruction

Energy is required whenever construction materials are to be moved from one place to another. Transport takes place from the manufacturer to the building site, both while the building is being erected and when it is renovated. It should be pointed out that the transportation of raw and semi-manufactured materials is included in the manufacturing energy category. This transport energy accounts for approximately 5–10% of the manufacturing energy for each construction material.

There will also be transportation from the building to waste disposal sites in connection with renovation and demolition. This study assumes that there is a waste disposal plant in the municipality where the building is located. The relevant transportation distance is assumed to be 20 km.

Table 3 presents various energy uses associated with different kinds of transportation. In the context of transportation, the relevant source of energy is made up of fossil fuels.

One reason for the difference in energy use between lorries for long-distance and short-distance transportation is that lorries which have long distances to go

Table 3. Energy use (primary energy) for various types of transportation according to Tillman *et al.* [4]

Means of conveyance	Transport energy, T_c (kWh/ton km)
Road, long-distance (distances > 50 km)	0.28
Road, short-distance (distances ≤ 50 km)	0.75
Coastal vessel	0.13
Deep-sea transport	0.06

Table 4. Energy use (primary energy) for various processes during the erection and demolition of buildings [1]

Types of processes	P_j
Drying of standard concrete on building site	44 kWh/ton
Drying of concrete element	25 kWh/ton
Excavation and removal of soil	32 kWh/m^3
Smoothing of soil	3 kWh/ton
Crane lifting	2 kWh/m^2
Lighting of construction object	26 kWh/m^2 usable floor area
Heating of construction object	26 k/Whm^2 usable floor area
Heating of sheds	14 kWh/m^2 usable floor area

will carry larger loads (see Table 3). Another relevant factor is that short-distance transportation tends to take place on streets and roads in cities, whereas long-distance transport primarily occurs on country roads and hence requires less fuel.

The energy use, Q_{transp} (kWh), for transporting the building materials to and from the building site when erecting, renovating and demolishing the building is estimated as follows:

$$Q_{transp.erect} = \sum_{i=1}^{n} m_i \cdot (1 + w_i/100) \cdot d_i \cdot T_c$$

$$Q_{transp.renov} = \sum_{i=1}^{n} m_i \cdot (1 + w_i/100) \cdot \left(\frac{\text{life-span of building}}{\text{life-span of material}} - 1\right) \cdot (d_i + 20) \cdot T_c$$

$$Q_{transp.renov} = \sum_{i=1}^{n} m_i \cdot (1 + w_i/100) \cdot 20 \cdot T_c$$

where n = number of materials; i = the material concerned; m_i = amount of the building material i (ton); w_i = factor for waste of the material i produced during erection of the building (%); d_i = distance from the manufacturer of material i to the building site (km); 20 = the assumed distance from the building site to the waste disposal site (km); and T_c = energy required for the conveyance concerned (kWh/ton km).

Energy use during the erection and demolition

When erecting a building, energy will be needed for a variety of processes, for instance drying and drainage, the heating of sheds and of the building itself, electricity for lighting purposes and for machinery, and so on. Conversely, processes associated with the demolition phase involve similar requirements. The energy data pertaining to the various processes, P_j, were collected from Andersen *et al.* [1] (see Table 4).

During the renovation, some energy will also be needed for different processes in order to exchange the renovation materials. However, most of this energy is made up of manual work and therefore this energy demand is not considered in this study.

The energy use for different processes when erecting and demolishing the building, Q_{erect} and Q_{demol} (kWh), is estimated as follows:

$$Q_{erect} = \sum_{j=1}^{m} p_j \cdot P_j$$

$$Q_{demol} = \sum_{j=1}^{m} p_j \cdot P_j$$

where m = number of processes; j = the type of process; p_j = the amount of the process j (ton, m^3 or m^2 usable floor area); and P_j = energy required for the process j (kWh/ton, kWh/m^3 or kWh/m^2 usable floor area).

Energy use during the occupation

Finally, the energy use during occupation (space heating, hot water and electricity) was calculated with the aid of the Swedish computer program Enorm [5]. This program computes the energy and average power requirement during a period of 12 months, based on average outdoor temperatures on a 24-hour basis and average solar radiation. Factors taken into account by the program include: the U values of the building concerned; air leakage; thermal bridges; window orientation in different directions; heating system; and ventilation including the heat exchanger (heat from the exhaust air being transferred to the supply air). Computations do not include the accumulation of heat in the frame and furnishings of the building, as this would call for climate data for every hour at least.

The energy needed during the occupation phase, Q_{occup} (kWh), is obtained by multiplying the energy use per year, Q_{occup} (kWh/year), by the life-span of the building concerned, in this case 50 years:

$$Q_{occup} = Q_{occup.year} \cdot 50$$

Energy use during the life cycle

The different energy demands during the whole life cycle are now presented. In order to obtain the total energy demand during the life cycle, $Q_{life\ cycle}$ (kWh), the different energy demands during the different phases have to be summarised:

$$Q_{lifecycle} = Q_{manuf} + Q_{transp.prod} + Q_{erect} + Q_{occup} + (Q_{manuf.renov} + Q_{transp.renov}) + Q_{demol} + Q_{transp.remov}$$

It should be pointed out that the energy requirement, or energy gain, that arises in the context of reuse, recycling or combustion (energy extraction) is not taken into consideration here. The reason for this is that the energy use or gain engendered during the handling of "leftover products" depends on the quality of the worn-out material and on the extent to which it is processed. The data available at the present time are still incomplete and too vague to be included.

CLOSING REMARKS

In this paper a method to calculate the total energy use during the life cycle is presented. In the companion paper "Energy use during the life cycle of single-unit dwellings: examples" [7] the method is applied. The paper gives examples of the total energy use for three single-unit dwellings built in Sweden in 1991 and 1992. The purpose is to gain an insight into the total energy use for a dwelling during its life cycle. This and the companion paper are also presented in [6].

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