ENERGY CONTENT AND CARBON EMISSION AUDIT OF BUILDING MATERIALS

by

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SUMMARY

The main thesis examined in this research is that "the embedded energy of construction is much more significant than the operational energy for buildings in a tropical country such as Sri Lanka".

All building elements (e.g. brickwall), materials (e.g. bricks) and "primitive" raw materials (e.g. clay) are placed in an aggregation-decomposition hierarchy. The process analysis carried out here basically captures most of the energy inputs associated with levels 1 and 2 in the IFIAS (1974) scheme, and accounts for around 90% of the embedded energy in a product. These calculations are based on Tonnes of Oil Equivalent (TOE). The data required to estimate these embedded energies were collected from building materials manufacturers.

A computerised database was implemented using a relational database management system. This can be used to represent and calculate the embedded energies and carbon coefficients of building materials and elements that are hierarchically arranged. It can also handle multiple sources of data and perform calculations to give the average, maximum and minimum embedded energies, which are also classified according to fuel type and process stage. Though the analysis was done assuming that the final building is located in the City of Colombo, these database values can be used, with some caution, for buildings even outside the Colombo City or District.

The embedded energy requirements were also calculated on the basis of the lowest quality energy (bio-equivalent energy), in addition to the more conventional basis of TOE. According to energy quality calculations carried out (based on efficiency considerations), 1 GJ of energy from electricity is equivalent to 5 GJ of biomass energy, 1 GJ of fossil fuel energy is equivalent to 1.8 GJ of biomass energy and 1 GJ of electrical energy is equivalent to 2.78 GJ of fossil fuel energy.

It is seen that the price per unit of biomass energy based on the actual prices of products is around one third of the actual price per unit of biomass energy. For fossil fuel and electricity on the other hand, the actual prices of products are much higher than the actual prices of the energy sources used for their production.

In order to minimise adverse energy effects and to give a beneficial effect to halting global warming, policy measures to promote timber products are desirable. It is also seen that though materials which use timber fuels (e.g. bricks and tiles) consume more energy, the use of timber fuels is more competitive when compared on a bio-equivalent unit basis. Furthermore, with respect to carbon emissions, wood fuels are considered to be self-sustaining. The use of timber, whether as a construction material or a fuel, will require properly planned re-forestation strategies.

The energy contribution from walls for a typical two storey house is from 10 - 44%; for a single storey house it is from 29 - 49%. The contribution from roofs for the two storey house is from 4 - 7%, whereas it is 8 - 16% for the single storey house. The contribution from windows is 0.6 - 3% for the single storey house and 0.2 - 4.5% for the two storey house. The contribution from the floor slab for the two storey house is 6 - 7%. The above ranges are a result of the difference of the between the use of low and high energy materials.

The ratio between total embedded energy and annual operational energy for the buildings selected lies between 14 to 35 for the houses while for an office building with air-conditioning loading it is 5. Though air conditioning has a large contribution towards the annual operational energy of a building, the total number of air conditioned buildings are small for a developing country such as Sri Lanka. Nevertheless, the results of the analysis show that the focus of energy efficient designs for buildings with air conditioning has to be on the operational energy. On the other hand, for houses, which are largely not air conditioned, the way to promote efficiency is by reducing the embedded energy through the appropriate choice of building materials. This is borne out not only by the high ratio of construction to operational energy ratio obtained, but also by the fact that the ratios for

houses with low energy materials is almost half those for the houses with high energy materials.

Key Words : Embedded Energy, Process Analysis, Building Materials, Carbon Emissions, Energy Database

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DECLARATION

This thesis is a report of research carried out in the Department of Civil Engineering, University of Moratuwa, between July 1998 and March 2000. Except where references are made to other work, the contents of this thesis are original and have been carried out by the undersigned. The work has not been submitted in part or whole to any other university. This thesis contains 199 pages.

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CONTENTS

1. INTRODUCTION

1.1. Background

Energy and environmental considerations are becoming increasingly important today. This is primarily because there is an appreciation of the non-renewable and limited nature of many of our energy resources and environmental assets. However, any sort of development inevitably consumes energy resources and depletes environmental assets. This is particularly true of industrial development. The construction industry is one of the largest contributors to Gross Domestic Capital Formation in Sri Lanka (and in many other countries). Building construction consists of approximately 69% of the total activities carried out in construction work (Statistical 1995). Out of the total building construction carried out approximately 64% is residential buildings. As such, the above concerns regarding energy and environmental issues should particularly be applied to this industry as well. Also, we may not be able to place too much reliance on studies performed elsewhere as our building material manufacturing processes could be very different.

Most of the energy and environmental considerations that have been made with respect to the Construction Industry have been with respect to the construction phase - e.g. environmental impact assessment (Biswas and Geping 1987) - and the operational phase- e.g. energy saving buildings (Energy 1988).

In cold countries such as U.K. and U.S.A. the ratio between construction and annual operational energy is around 3 to 6; in a temperate country that is a little warmer (such as New Zealand), this ratio goes up to around 9 (Baird and Chan 1983). However in a tropical country such as Sri Lanka, the operational energy is likely to be very small as very little heating is required. Such energy, even over a nominal service life of around 40 years may be lower than the energy embedded in the building, except in the case of air conditioned buildings. Therefore there is a clear need for research to be carried out into energy inputs and environmental costs of building materials, in order for building construction industry professionals and policy makers to make choices regarding the type of building materials that should be used if adverse energy and environmental effects are to be minimised.

As mentioned above, in order that building construction industry professionals become aware of the energy related consequences of their designs, an accurate database has to be developed to store all the energy related data of building materials and elements to retrieve data when needed. Baird and Chan (1983) recommended the setting up of such a database in a readily accessible form as an extension of their own study of building materials in New Zealand.

The embedded energy of building materials will vary from one country to another, depending on the sources of energy used for manufacturing (Energy 1978). In Sri Lanka, for example, there is a wide range of energy sources used for building materials manufacture, from firewood for brick production to fossil fuel and electricity for cement production. An energy policy would clearly need to take into account such differences in quality of the energy sources (Perera 1992) that are used for manufacture, and not merely the quantity.

There is also the issue of the energy of imported building materials or raw materials. The question arises as to how concerned we should be about energy contents in such materials, as the actual energy expenditure is not incurred within the country.

Most authors (Munasingha and Schramm 1983) agree that the energy supply has often not been accurately reflected in the market prices of energy products due to monopoly practices, external economies and diseconomies, and interferences in the market process through taxes, import duties, subsidies etc. Though the market price does not represent the actual energy usage of a product, a relationship can be found between the price per unit energy source based on actual market prices of products and compared with the actual price per unit of different energy sources.

1.2. Objectives

The main thesis examined in this research is that "the embedded energy of construction is much more significant than the operational energy for buildings in a tropical country such as Sri Lanka ".

The objectives can be defined as follows :

1. To arrive at basic data regarding the energies embedded and carbon emissions of building materials and elements.

2. To structure the above data in a way that reflects the hierarchical arrangement of building elements and their sub components.

3. To store information regarding embedded energies and carbon coefficients in building materials using a computerised database.

4. To compare the embedded energy requirements on the basis of the total equivalent amount of lowest quality energy, in addition to the more conventional basis of tonnes of oil equivalent (TOE).

5. To investigate a relationship between prices of building materials and fuel types.

6. To compare alternative forms of construction materials for energy and carbon saving.

7. To find the gross embedded energy input to various types of buildings, both residential and office buildings.

8. To find the influence of the various building components on the embedded energies of residential buildings.

9. To compare the significance of construction energy with that of operational energy in Sri Lanka.

1.3. Guide to Thesis

The thesis comprises of 9 chapters, followed by references.

In this first chapter the background for this research is presented, followed by the objectives and a brief guide to the thesis.

The second chapter gives a detailed literature review on all aspects covered in this research.

Chapter 3 describes the basic approach used in this thesis for calculating energy contents and carbon coefficients of building materials, including the hierarchical structuring of building materials in an aggregation - decomposition hierarchy.

Chapter 4 describes the manufacturing process and hence energy contents and carbon coefficients of primitives (i.e. materials that have no raw materials), materials and elements that contribute to make a building.

Chapter 5 describes the database that was designed to store the energy contents and carbon coefficients obtained for building materials.

Chapter 6 contains the energy quality analysis carried out in this study for finding the energy requirements on the basis of the total equivalent amount of lowest quality energy (called “bio-equivalent units“); and also the analyses carried out to find the relationship between the price per unit energy source based on actual prices of products and the actual price per unit of different energy sources.

Chapter 7 contains the analyses carried out for comparing alternative forms of construction to identify materials with low energy inputs and carbon emissions.

Chapter 8 contains the embedded and operational energy calculations for buildings together with analyses carried out to find the influence of various building components and materials on the embedded energy.

Conclusions and Recommendations are given in Chapter 9.

2. LITERATURE REVIEW

2.1. Methods of Energy Analysis

Energy analysis is a formalised method for calculating the energy required to produce goods and services. These requirements include not only the fuel and electricity consumed directly by the particular process in question, but also the fuel and power used indirectly to produce the goods and services associated with the process. Thus the energy required to build a house includes the fuel and power used at the building site and in transporting the materials to the site together with that used to manufacture the materials, the tools and machinery plus the energy required to extract the raw materials, and so on.

There are many methods and conventions for evaluating the energy requirements of a product or service. Calculations of energy requirements carried out using different conventions and methods will often give very different results. There are, however some widely accepted terminologies, procedures and conventions. The methodologies and conventions established at the 1974 IFIAS workshop (IFIAS 1974) are the most frequently used and will be adopted, to some extent, in this research. They provide a coherent framework for carrying out energy analysis and for comparing the results of different researchers.

There are four commonly accepted methods of energy analysis (Baird and Chan 1983), namely

1. Statistical analysis
2. Input-output analysis
3. Process analysis
4. Eco-energetics

The method used will depend mainly on the overall objectives of the analysis and the availability of data. Statistical, input-output, and process analysis appear to be the more widely used methods for calculating the energy requirements of building materials.

Energy analyses are seldom better than 10 percent accurate (Honey and Buchanan 1992). The total energy requirement of a process or industry can vary widely between manufacturers because of (i) The efficiency of energy, material and labour use; (ii) Technology used for the process; (iii) Difference in handling of wastes; and (iv) Differences in raw materials input.

2.1.1. Statistical Analysis

The supply of energy to an industry, along with data on its output, can usually be obtained from published national statistics. This data allows the estimation of the energy requirements per unit of output. However, for a number of reasons, the results obtained can be misleading. For example, (i) There is aggregation of diverse industries into a group; (ii) Sometimes only the costs of fuels are published and different fuels are sometimes aggregated; (iii) The amount of material used and product sold are not completely listed, with only money values given in some cases; (iv) The energy requirements associated with the consumption of raw materials, plant description and delivery of materials and products, can be difficult to estimate from the published information; and (v) Data is not published to avoid disclosure of confidential information. In general this method can provide an order of magnitude estimate of the energy requirements of products classified by industry.

2.1.2. Input-Output Analysis

Input-Output (I-O) Tables present an overview of the inter relationship between different sectors of the economy by showing the money value transactions between sectors of the economy. If the energy cost (MJ/Rs) to each industry were known, then it would be possible to calculate the direct energy requirements of the industrial sector from their purchases. From the energy supply sectors, all the indirect energy, the energy requirements for administration, transport and capital, could then be calculated from the table. The possibility for capturing most indirect energy requirements is one of the major advantages of the I-O technique of analysis.

There are however three major disadvantages in using I-O analysis, i.e. (i) The data is often outdated by about five years; (ii) There is often insufficient breakdown of information, and two products for which coefficients are required may be combined into the same industrial group; and (iii) Where companies produce varied products, they are classified according to their principal product and the energy intensity (MJ/Rs) for the principal and secondary product may be different causing considerable inaccuracies in a diverse industry group.

2.1.3. Process Analysis

Process analysis is the most frequently used method. It involves the study of the inputs and outputs in a process. The energy requirements of a process or product are determined from all the material, equipment and energy inputs into the process.

Unfortunately, many problems can arise at the detailed level for this apparently simple method, i.e. (i) In many cases, data on the energy and material inputs to a production process are confidential or difficult to separate from aggregated company records; (ii) The direct energy inputs to any production process can vary considerably among producers and also from one year to the next for the same producer; variations can occur because of the differences in locality, processing techniques, age and type of processing plant, and efficiency with which energy and materials are used; (iii) In any production process, a base-load exists, where a certain level of energy is expended regardless of the production level; this marginal energy requirement can be a problem in industries where the operating capacity fluctuates much below the 100 percent mark; and (iv) There is the problem of partitioning: when a factory produces a multitude of products, it becomes difficult to apportion the energy use. The IFIAS workshop in 1974 (IFIAS 1975) suggested assignments in proportion to some physical parameter such as weight or volume. Regression techniques could also be used (Baird and Chan 1983).

In this study, following Honey and Buchanan (1992), process analysis is used because it involves the study of the inputs and outputs in a process and the energy requirements of a process or product can be determined by field visits to identify all the material and energy inputs into the process. This is further described in Chapter 3 of this thesis.

2.1.4. Eco-Energetics

Eco-Energetics is the term used to describe the techniques used by Howard Odum and the Florida school of analysts. Odum's methods are described in his book "Environment, Power and Society" (Odum 1971). His methods cover a far broader range of factors and have a much wider boundary than those defined at the 1974 IFIAS workshop (IFIAS 1974). There are several basic differences between Odum's methods and those of other analysts. First, he places a weighting value on all forms of energy; a unit of electricity is valued as four units of fossil fuel, for example. Second, the energy requirements of labour and of environmental damage are included.

2.1.4.1. Human Energy

Considerable controversy exists as to what part of the energy support of humans as consumers should be included in the calculation of energy requirements. Odum suggests that "because of its high quality and thus high energy cost, human service is the major part of any energy analysis and cannot be omitted" (Odum 1978). The 1974 IFIAS workshop however, recommended that "where the analysis refers to developed or industrialized economies it is not necessary to consider the energy for life-support or man-power as they do not play an important role in the calculations" (IFIAS 1974). Most researchers involved with the calculations of energy requirements for building materials have not included the human energy factor. Hill (1978) took a compromise approach and included direct energy requirements but not the indirect ones. Thus the energy needed for a workman to drive a typical distance to and from work, about 48 GJ/Yr, was included.

Bearing in mind the labour intensiveness of the building process and that in some instances an energy intensive process can in part be replaced by human labour, the importance of considering it in any analysis of the energy requirements for construction is clear. However, the methods for assessing the contribution of human labour and deciding what to include are not yet satisfactorily resolved. It is mainly for this reason, following Baird and Chan (1983), that the contribution of human labour has not been included in the analysis carried out in this research

2.1.4.2. Environmental Effects

Mining and quarrying operations result in disrupted underground water circulation, damaged landscapes, and soil run-off due to stripped vegetation, that reduce the productive land area. Hydro-electric power projects can result in lower quantities of water being supplied to farm areas, flooding of valuable agricultural land and sometimes damage to the fishing industry. Disposed industrial wastes in rivers and lakes result in poorer water quality both for farming and recreation. These indirect costs and "hidden subsidies" due to "loss of ecological capital" are included in the analyses carried out by Odum (1971,1978). The 1974 IFIAS workshop (IFIAS 1974) however, made no specific recommendations on a method or convention for analysis of these environmental costs. There is also no wide agreement among researchers on conventions. Most energy analysts have ignored them.

Lacking Sri Lankan data and a proper frame work to compare with results from other sources this research, following Baird and Chan (1983) has not included these environmental costs in the ensuing energy analysis. However, following Honey and Buchanan (1992), this report makes an independent assessment of environmental costs, in terms of Carbon dioxide emissions. This is discussed further in Chapter 4.

2.2. System Boundaries

In energy analysis it is often only possible or necessary to calculate the process energy requirements of a product. In such cases, it is necessary to draw the boundary between energy supply and demand. The boundary adopted depends in part on the availability of data but mainly on the overall aims and thus the assumptions that are made. The IFIAS workshop (IFIAS 1974) suggested that for most materials four boundary levels can be drawn as illustrated in Figure 2.1.

In general a process will require decreasing amounts of energy with an increase in the boundary level. While Process analyses are commonly used to calculate energy requirements at Level 1 and 2, Input-Output tables at industry and national levels are required to extend the calculations to Level 3 and 4 respectively (Baird and Chan 1983).

Level 1	The direct and transport energy inputs to the process are analyzed, Depending on the process involved, Peet and Baines (1986) estimate that Level 1 energy can vary from as much as 70 percent of the total energy requirement to below 10 percent, the balance being transport energy.
Level 2	The energy required to make the material inputs to the process is included. As much as 90 percent of the total energy sequestered in the process should have been included in the first two levels (IFIAS 1974).
Level 3	The energy required to make the capital equipment for the process is included. This extra energy is rarely greater than 10 percent of the total energy requirement. The energy input upto Level 3 is commonly around 98 or 99 percent (IFIAS 1974).
Level 4	This takes into account the energy to make the machines that make the capital equipment. Level 4 requirements commonly account for only 1 or 2 percent and is almost certainly within the range of uncertainty of the final energy sequestered (IFIAS 1974).

In this research energy requirements at Level 2 are used, and this is discussed further in Chapter 3.

2.3. TOE Values and Carbon Coefficients

2.3.1. TOE Values

In order to compare energy values from different sources, a common unit, i.e. Tonnes of Oil Equivalent (TOE) is used. This is a hypothetical oil chosen as a base for presentation of all energy forms in a common unit. This is a thermal unit equivalent to 41.84 GJ.

Table 2.1 gives the conversion factors to convert different energy forms to TOE values. TOE values for fuels relevant to Sri Lanka are discussed in Chapter 3 of this thesis.

2.3.2. Carbon Coefficients

The gross quantity of carbon (dioxide) emitted in the manufacture of each material per unit of weight or volume has been named the "carbon coefficient".

Table 2.2 shows carbon dioxide emission rates for consumer energy in New Zealand (Collins 1990).

To obtain carbon coefficients from energy intensities, fossil fuel energy components (that is energy from gas, oil, coal and the proportion of electricity generated from fossil fuel) are each multiplied by a factor of 0.02 kg carbon per MJ of energy. This figure was derived by Buchanan (1991) from reported world consumption of 260,000 PJ of fossil fuel releasing 5.2 billion tonnes of carbon in 1984 (World Resource Institute, 1987). This is the value used in this report for energy in imported raw materials. These calculated values are further discussed in Chapter 3 and

4 of this thesis. A more recent report (Hollinger and Hunt 1990) gives a value of 0.013 kgC/MJ.

2.3.2.1. Additional Releases of Carbon

Carbon dioxide is released to the atmosphere via chemical reactions in the aluminium and cement industry.

(i) Aluminium

Carbon is released in the smelting of bauxite when producing aluminium. A figure of 130 kg of carbon per tonne of aluminium (Buchanan 1991) has been added to the carbon coefficient for aluminium.

(ii) Cement

The chemical carbon dioxide released in the calcination of limestone in the production of cement has been estimated as 136 kg of carbon per tonne of cement (Hollinger and Hunt 1990); this figure has been added to the carbon coefficient for cement. A more recent paper (Hennessy et al. 1991) uses a figure of 142 kg of carbon per tonne of cement.

2.3.2.2. Carbon Storage

As well as the emission of carbon to the atmosphere during the production stage of the material, carbon can be contained or stored by certain materials.

(i) Carbon Storage of Wood

Plants take in carbon dioxide and release oxygen during the process of photosynthesis in which chlorophyll uses the sun's energy to produce food. Plants respire during the night when the energy from the sun is not available for photosynthesis to occur. This report uses a figure obtained by Buchanan (1991) of 250 kg of carbon stored per cubic metre of wood. This assumes wood has an oven dry density of 450 kg/m^3, of which 57 percent is carbon.

(ii) Carbon in Steel

Erasmus and Smail (1989) determined the mean carbon content of BHP structural steel sections as 0.20 percent. Considering that 1.07 kilograms of carbon is released in the manufacture of one kilogram of steel section, this amount is neglected in the energy analysis in this study.

2.4. Energy Sources in Sri Lanka

The main types of energy used in Sri Lanka are from biomass (inclusive of fuelwood and agro-waste), oil (petroleum crude based) and electricity (hydro and thermal based). Of these, oil and electricity are normally classified as "commercial" energies and biomass as "non commercial". Further, commercial energy is considered as "fossil fuel energy" and "electrical energy" in two parts. This standard classification (Perera 1992) will be used here, though this classification is not strictly correct in the context of Sri Lanka, because a considerable quantity of fuelwood is now traded and utilised for domestic and industrial applications.

Biomass accounts for nearly 71% of the primary energy consumed in Sri

Lanka, when commercial as well as non-commercial forms of energy are taken into account (Perera 1992). This is due to the low cost of these fuels. Biomass and fuelwood are widely used in building materials manufacturing, for example in brick, tile, lime manufacturing etc. Biomass like coconut husk and paddy husk is also used in brick manufacturing due to the ready availability of these raw materials and their low cost.

To the user, irrespective of whether electricity is produced through thermal or hydro resources, the product is the same. Thus the demand is for electricity; not specifically for hydro or thermal electricity. The operating policy is therefore to supply as much electricity as possible using hydro resources, depending on water availability, and to meet the balance through thermal plants which burn oil and are operationally expensive. Thus, the proportion of hydro to thermal generation in any particular year depends to a large extent on the rainfall and hydro plant availability. However a 66% hydro and 34% thermal electricity production is used in the energy analysis of this research (Siyambalapitiya 1997). Electricity is used in factory based building materials manufacture, for example in cement, steel, cement blocks and asbestos production.

Sri Lanka has a single oil refinery, owned by the Ceylon Petroleum Corporation and situated at Sapugaskanda. Crude oil is imported and processed (refined) at this refinery. Most of the product demands of the country are met through processing at the refinery. When certain product quantities fall short of the demand due to output ratios of different refined products (e.g. as in the case of Kerosene and L.P. Gas), such balance requirements are imported in the refined form itself. Certain products which emerge from the production process and are in excess of the requirements of the country (e.g. naptha and fuel oil) are exported. The total demand for oil products pertaining to the past has normally been derived by considering the imported quantity of crude oil and refined products, exported refined products and process as well as other losses. Fossil fuels are consumed in the building materials manufacturing process in production processes involving high temperatures, for example in cement and steel manufacture, and also in the transportation of materials.

2.5. Energy Costs of Building Materials and Construction

Most authors (Gartner and Smith 1976, Baird and Chan 1983, Honey and Buchanan 1992) agree that the energy consumption during construction and transport energy of raw materials is small compared to the material energy, especially where building construction is concerned. In other words, the Level 1 process energy is small for building construction and has been ignored by many researchers. Baird and Chan (1983) quote a figure of 4 % of total energy for direct process energy during building construction. Higher figures have been obtained by Stein et al. (1977), quoted by Baird and Chan (1983) as being between 10% and 20%. These figures appear to include labour as well as materials transport to site, and a study by Keegel (1975), also quoted by Baird and Chan (1983), indicates that around half the direct energy is made up of labour travel to job site and temporary heating.

Various researchers have produced a number of tables giving energy costs of building materials. Table 2.3 shows the range of energies embedded in building materials for a number of common building materials in New Zealand (Honey and Buchanan 1992). This table gives the various sources of energy, and also indicates energy components for capital and imports. The energy analysis carried out in the present study is further discussed in Chapter 4 of this thesis.

Baird and Chan (1983) give a comparison of Gross Energy Requirements (GER) in GJ/m^2 obtained by various researchers from different countries for house construction (see Table 2.4).

In order for designers and those involved in building construction to become aware of the energy related consequences of their decisions, however, an accurate data base has to be developed for them to draw on. Baird and Chan (1983) recommend the setting up of such a database in a readily accessible form as an extension of their study. The database design carried out in this project is described in Chapter 5.

2.5.1. Energy for Alternative Forms of Construction

Based on their materials energy coefficients, Honey and Buchanan (1992) have made comparisons of energy required for different structural elements (e.g. Table 2.5) and framing systems (Table 2.6). This shows that timber products use much less energy than steel ones. In addition, they carried out case studies of different forms of construction used for domestic, hostel, industrial and medium rise office buildings, calculating the total energy inputs into such buildings. Their results are summarised in Figure 2.2. Once again timber performs better than concrete, which in turn is better than steel.

Haseltine (1975) tabulated the energy required to make, transport and erect the most common structural materials, together with the energy to make unit areas of several building elements. In his review an energy audit is carried out for 12 different layouts of basic structures including reinforced concrete, structural steel and load bearing brickwork. Similar calculations for 11 elevations of cladding suitable for use with the selected structures are also given. Where appropriate, the results for different elevations and structures are combined to give figures for total structures.

Where structural layouts are concerned, he concluded, inter alia, that (i) medium span structures use less energy than long span ones; (ii) a loadbearing brick "frame" (i.e. with load bearing piers) uses less energy than crosswall construction, which in turn is less energy consuming than a reinforced concrete frame; and (iii) a steel frame uses considerably more energy than an equivalent concrete frame. Where elevations are concerned, some of his conclusions are that (i) precast concrete backed with concrete blockwork uses the most energy, while curtain walling made of glass and aluminium is almost as high; (ii) brick cavity walls use the lowest amounts of energy; and (iii) elevations containing aluminium windows are more energy intensive than those containing timber ones.

Gartner and Smith (1976) attempted to evaluate the total primary energy inputs to major building materials. These are then followed through to their usage in various types of housing construction to obtain an estimate of the total energy requirements for housebuilding. Typical two storey houses (80 m^2) with loadbearing walls were found to require between 95 and 180 GJ of primary energy input (for major building components only). For 4 storey blocks of flats with loadbearing walls the energy requirement per 55 m^2 flat was 95-145 GJ; while for large blocks of flats (9 storeys) constructed in load bearing reinforced concrete, the energy requirement was about 230-265 GJ per (55 m^2) flat.

Baird and Chan (1983) produced a comprehensive report on the energy coefficients of building materials used in New Zealand. The energy embodied in the building materials of a standard house was determined. The energy used in variations to this standard house with regard to the type of building materials used was also determined. It was found that brick veneer wall construction, concrete floors and galvanised iron roofing were relatively high energy building materials; timber wall cladding, timber floors and concrete roof tiles were the lower energy options (see Table 2.7)

Finally, Figure 2.2 from Honey and Buchanan (1992) and Table 2.8 from Stein et al. (1976), quoted by Baired and Chan (1983), indicate variations in GER values for functionally different types of buildings. Office buildings and hospitals tend to require high energy inputs, while industrial buildings are at the low energy end. Residential buildings can have varying inputs, but on balance may not be too energy intensive.

Alternative forms of construction relevant to Sri Lanka are discussed in Chapter 7 of this thesis.

2.6. Comparison of Construction and Operational Energy

The ratios of construction (i.e. GER) to annual operational energies obtained by various researchers are presented by Baird and Chan (1983) (see Table 2.9) - they caution against the figure obtained by Gartner and Smith (1976) since only major building materials have been used in their construction energy calculations. The lower figures obtained for U.K. and U.S.A houses would be as a result of their high space and water heating requirements. Although New Zealand is also a temperate country, their heating requirements are probably not that great, and hence there is an increase in the ratio.

Table 2.10 shows some figures quoted by Honey and Buchanan (1992). The space heating requirement should be seen in the light of Figure 2.3, also from Honey and Buchanan (1992), where heating (both space and water) accounts for around 2/3 rds of the operational energy and space heating alone around 30%. The non-heating requirements would therefore be approximately equal to the space heating requirements shown in Table 2.10.

In a tropical country such as Sri Lanka, the operational energy is likely to consist only of the non-heating requirements described above. These requirements (approximately equal to space heating requirements in New Zealand), even after 50 years, will be lower than the materials energy requirements, except in the case of a house with the "greatest energy requirement" (see Table 2.10). Therefore, although initiatives in energy efficiency should probably focus on operational energy in cold countries, such initiatives are probably better directed at construction energy in warm, tropical countries. This is one of the most compelling reasons for carrying out this research. Comparison of construction energy and operational energy for typical houses constructed in the city of Colombo in Sri Lanka are presented in Chapter 8 of this thesis.

2.7. Energy Quality Analysis

Though it appears that the least energy intensive material is the preferred option, there are however other issues that have to be considered. One of the main issues is regarding the differences in energy quality.

For simple heating needs such as in cooking, it is possible to obtain the required heat energy by burning kerosene oil, firewood, paddy husk, saw-dust, agro-waste, peat, coal, L.P. Gas, electricity, etc. using simple appliances. But for turning a grinding machine the choices available are much less; usually an electric motor or an oil driven engine has to be used. To work a radio, operate an amplifier or a telephone exchange, there is no choice; electricity is essential. Thus it is seen that certain types of energy are more versatile than others from the point of view of the user. It is therefore possible to think of the more versatile types (or sources) of energy as being of a higher "quality" because they lend themselves to a multiplicity of end-uses relatively easily (Perera 1992).

In another attempt to define the quality of energy, it is possible to examine the intensity or concentration of extractable energy in the energy source material. For example, peat contains lesser calories per kilogram than coal; coal contains lesser calories per kilogram than diesel or furnace oils. Hence peat, coal and oil can be viewed as sources of energy categorized in an ascending order of "quality". In a similar way, wind energy and wave energy are "dilute forms" of energy or of "low quality" in comparison to oil, coal or peat. To some degree this notion of quality is consistent with that brought out in the earlier definition (Perera 1992).

A third way of looking at the "quality" of a type of energy is through an examination of the sophistication required to produce it. Wood, peat and coal are obtained in relatively raw form. Extraction of mineral oils generally involve heavy initial investments and need refining to various degrees. To produce electricity, sophisticated and high capital cost equipment is often required, and oil may in fact be the "raw material" (Perera 1992).

It is possible for a variety of other interpretations (some of which are scientifically better definitions) to be given to the term "quality of energy". For the purpose of this study the concept that "a high-quality energy or energy source can be used for a variety of end-uses with relative ease" will be generally accepted (Perera 1992).

We can attempt to classify different types of energy according to their quality class. The classification shown in Table 2.11 is such an attempt; it is not a complete classification but is only an approximate guide (Perera 1981).

The next step should be to find a methodology for comparing different energy qualities. One approach to this could be to assess the amount of the lower quality energy that is required to obtain a given quantity of the higher quality energy via established processes (e.g. obtaining electricity by burning firewood - dendro electricity). All the energy requirements can then be compared on the basis of the total equivalent amount of lowest quality energy.

Consider electricity versus kerosene oil (fossil fuel) for cooking. A kerosene burner is a fairly simple and inexpensive device; it could easily be used to convert the chemical energy in kerosene to heat energy required for cooking. If electricity is to be used for cooking, the generation of electricity itself may be by oil (diesel or furnace) or coal which may be very slightly cheaper than kerosene. In the process of generating electricity by oil or coal, it is first converted to heat and then to mechanical energy and thereafter to electricity with conversion efficiencies of the order of 36%. The electricity has usually to be transmitted, distributed and reconverted to heat for cooking. All these are associated with further losses. Thus it requires nearly three times the quantity of oil for cooking through electricity compared with directly using oil in the kitchen itself. In other words, use of oil directly should cost only about a third of using electricity generated through oil (Perera 1992).

In Odum's method of energy analysis he placed a weighting value on all forms of energy. A unit of electricity is valued as four units of fossil fuel, for example (Odum 1971).

These energy comparisons (energy quality analysis) together with the embedded energy calculations based on the lowest quality energy are discussed in Chapter 6 of this thesis.

In addition to the traditional energy analysis above using the first law of thermodynamics, the concept of exergy provides a method of quantifying the thermodynamic potential and subsequent degradation of this potential during a process due to its irreversibilities. The method is currently receiving much attention as a supplementary feature in the design of thermal systems in addition to traditional first law analysis (Attalage 1997).

Properties measured on a laboratory steam condenser showed that around 71% of the energy of the hot steam is transferred to the coolant while the balance is lost to the surroundings. If one was able to eliminate this loss the efficiency would reach 100%. However, the exergy analysis provides a more realistic picture. It shows that only 22% of the available thermodynamic potential has been transferred to the coolant. In addition to the losses to the surroundings it also presents an unavoidable loss in the thermodynamic potential as a result of irreversibilities due to heat transfer across the walls separating hot and cold fluids (Attalage 1997).

2.8. Relationship Between Energy and Prices of Building Materials

Most authors (Munasingha and Schramm 1983) agree that the energy supply has often not been accurately reflected in the market prices of energy products due to monopoly practices, external economies and diseconomies, and interferences in the market process through taxes, import duties, subsidies etc.

The border price of an energy good is defined as its international price plus costs of transportation, insurance, and freight. Energy analysis should begin with an examination of energy use by end-use sector and fuel type. To understand the effects of pricing policies on energy use and sectoral output, the relationship among these factors must be characterized. Analytic tools that can quantify these relationships include economic models (to relate energy demand to prices and output), input-output (IO) models (to capture intersectoral effects and direct and indirect energy use), and engineering process analysis (based on such factors as generic process analysis and plant visits with energy audits) (Russell et al. 1994).

Costs appeared to depend as much on material abundance and scarcity as they did on the availability and the efficiency of conversion of energy. Max Weber (1864-1920) pointed to the low energy cost in hand weaving compared with machine weaving, but machine weaving was less costly in money terms (Juan and Klaus 1994).

Though the market price does not represent the actual energy usage of a product, a relationship can be found between price per unit energy source based on actual market prices of products and actual price per unit of different energy sources. These issues are further discussed in Chapter 6 of this thesis.

Table 2.1 - Conversion Factors for TOE Values

TYPE OF ENERGY SOURCE	QTY	TOE
Crude Oil	1MT	1.03
L.P. Gas	1MT	1.06
Petrol/Naphtha	1MT	1.09
Kerosene/AVTUR	1MT	1.05
Diesel	1MT	1.05
Fuel Oil	1MT	0.98
Residual Oil	1MT	0.98
Coal	1MT	0.70
Firewood	1MT	0.38
Charcoal	1MT	0.65
Bagasse	1MT	0.40
Electricity (100% efficiency)	1MWh	0.086
Electricity (Thermal)	1MWh	0.24

Table 2.2 - Carbon dioxide emission rates for consumer energy in New Zealand (Turbott et al. 1991)

Energy Source	**CO_2 Emission rate (kgC/ GJ)**
Thermal electricity	54
Coal	25.4
Oil products average	20.3
Natural gas	15.0
Geothermal	1.2

Table 2.3 - New Zealand Energy Coefficients of Building Materials (Honey and Buchanan 1992)

No	MATERIAL/WORK	Unit	Elect	Gas	Oil	Coal	Capital	Imports	Energy Coeff. MJ/Unit	Level
1	Profits	no	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
2	Preliminaries	$	5.20	0.90	11.20	4.50	0.30	17.40	-39.50	4
3	Administration	$	2.20	1.00	8.50	3.90	0.00	6.90	22.50	4
4	Earthwork	m^3	0.00	0.00	100.00	0.00	0.00	0.00	100.00	1
5	Labour	no	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
6	Site.Work(Oil)	MJ	0.00	0.00	1.00	0.00	0.00	0.00	1.00	1
7	Timber.Rough	m^3	232.40	16.80	378.00	86.80	14.00	120.40	848.40	4
7b	Timber.air-dry, treated	m^3	328.71	23.76	534.65	122.77	19.80	170.30	1200.00	4
7c	Timber.Glulam	m^3	1223.79	81.52	1807.86	448.85	54.67	883.31	4500.00	4
8	Timber.kiln-dry, treated	m^3	1276.00	85.00	1885.00	468.00	57.00	921.00	4692.00	4
9	Timber.Formwork	m^3	77.00	6.00	126.00	29.00	5.00	40.00	233.00	4
10	Hardboard	m^3	5915.00	379.00	7052.00	2654.00	531.00	4095.00	20626.00	4
11	Softwood	m^3	4436.00	284.00	5289.00	1991.00	398.00	3071.00	15469.00	4
12	Particleboard	m^3	3697.00	237.00	4408.00	1659.00	332.00	2559.00	12892.00	4
13	Plywood	m^3	1941.00	603.00	2359.00	3096.00	84.00	1356.00	9439.00	4
14	Veneer	m^3	2305.00	715.00	2802.00	3677.00	99.00	1610.00	11208.00	4
15	Wall.Paper	m^2	4.25	0.73	3.80	4.02	0.06	2.06	14.92	4
16	Building.Paper	m^2	2.13	0.36	1.90	2.01	0.03	1.03	7.46	4
17	Cement	t	880.00	10.00	430.00	7340.00	60.00	260.00	8980.00	4
18	Concrete.Precast	m^3	575.00	69.00	1379.00	1726.00	89.00	942.00	4780.00	4
19	Concrete.Insitu	m^3	403.00	10.00	906.00	2182.00	19.00	321.00	3841.00	4
20	Lime.Mortar.1:2	m^3	345.00	7.00	748.00	1023.00	30.00	348.00	2501.00	4
21	Cement.Mortar.1:2	m^3	589.00	7.00	313.00	4844.00	40.00	187.00	5980.00	4
22	Structural.Clay	kg	0.53	0.01	3.30	2.23	0.38	0.44	6.90	4
23	Other.Clay	kg	25.00	24.00	41.00	75.00	2.00	32.00	199.00	2
24	Plaster.Solid	kg	0.81	0.33	2.61	0.33	0.00	2.60	6.68	2
25	Plaster.Fibrous	kg	0.81	0.33	2.61	0.33	0.00	2.60	6.68	2
26	Gib.board	m^3	590.00	170.00	1530.00	1080.00	0.00	1630.00	5000.00	2
27	Asbestos.Cement	kg	0.96	0.27	2.49	1.76	0.08	2.65	8.21	4
28	Asbestos.Others	kg	0.96	0.27	2.47	1.76	0.08	2.65	8.19	4
29	Asphalt.Felts	kg	1.10	0.70	24.70	1.90	0.10	2.60	31.10	4
30	Bitumen.Felt	kg	1.30	0.80	30.30	2.30	0.10	3.20	38.00	4
31	Glass	kg	3.51	3.56	10.70	5.04	0.32	8.37	31.50	4
32	Steel.General	kg	10.70	1.80	2.20	7.10	0.20	12.90	34.90	4

Table 2.3 (cont.) - New Zealand Energy Coefficients of Building Materials

No	MATERIAL/WORK	Unit	Elect	Gas	Oil	Coal	Capital	Imports	Energy Coeff. MJ/Unit	Level
33	Steel.Rods	kg	4.74	1.19	3.56	3.56	0.21	21.68	34.94	4
34	Steel.Sections	kg	8.00	2.00	6.00	6.00	0.40	36.60	59.00	4
35	Galvanised.Iron	kg	3.40	1.30	3.40	3.00	0.20	25.60	36.90	4
36	Steel.Pipes	kg	7.70	1.90	5.80	5.80	0.40	35.30	56.90	4
37	Metals.Non-ferrous	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
38	Aluminium.General	kg	65.50	0.00	17.50	7.50	0.00	39.00	129.50	2
39	Aluminium.Sheets	kg	72.50	0.00	26.00	7.50	0.00	39.00	145.00	2
40	Aluminium.Extrusion	kg	72.50	0.00	26.00	7.50	0.00	39.00	145.00	2
41	Aluminium.Foil	kg	81.50	0.00	26.00	7.50	0.00	39.00	154.00	2
42	Copper	kg	6.20	1.60	4.70	4.70	0.30	28.40	45.90	4
43	Zinc	kg	9.30	2.30	7.00	7.00	0.40	42.40	68.40	4
44	Lead	kg	3.40	0.90	2.60	2.60	0.10	15.60	25.20	4
45	Plastics.General	kg	18.00	7.00	16.00	14.00	1.00	104.00	160.00	4
46	Polyethylene	kg	2.00	0.00	2.00	0.00	0.00	108.00	112.00	2
47	Polystyrene	kg	2.00	0.00	2.00	0.00	0.00	96.00	100.00	2
48	PVC	kg	2.00	0.00	2.00	0.00	0.00	92.00	96.00	2
49	Polypropylene	kg	2.00	0.00	2.00	0.00	0.00	171.00	175.00	2
50	Paints.General	m²	0.52	0.20	1.51	0.51	0.09	12.07	15.00	4
51	Paints.Water-soluble	kg	0.31	0.10	0.75	0.26	0.04	6.04	7.50	4
52	Paints.Emulsion	m²	0.41	0.13	1.01	0.34	0.06	8.05	10.00	4
53	Paints.Oil-based	m²	0.50	0.16	1.21	0.41	0.07	9.65	12.00	4
54	Electrical.Work	$	5.20	0.90	11.20	4.50	0.30	17.24	39.34	4
55	Wiring	m	0.59	0.15	0.45	0.45	0.03	2.70	4.37	4
56	Electric.Equipment	$	5.00	1.80	5.00	4.10	0.40	30.50	46.80	4
57	Electric.Range	no	816.00	552.00	816.00	912.00	48.00	3324.00	6468.00	4
58	Aggregate	t	50.00	0.00	140.00	20.00	10.00	70.00	290.00	4
59	Masonry.Stone	t	50.00	0.00	140.00	20.00	10.00	70.00	290.00	4
60	Sand	t	10.00	0.00	20.00	0.00	0.00	10.00	40.00	4
61	Rubber.Synthetic	kg	13.00	1.00	18.00	14.00	2.00	100.00	148.00	4
62	Insulation.Fibre	kg	2.70	0.80	7.00	4.90	0.20	7.40	23.00	4
63	Fibreglass.Batts	kg	17.60	5.00	45.50	32.00	1.50	48.50	150.10	4
64	Brass	kg	6.70	1.70	5.00	5.00	0.30	30.50	49.20	4
65	Asphalt.Strip.Shingle	m²	9.70	6.00	223.00	17.00	0.70	23.70	280.10	4

Table 2.3 (cont.) - New Zealand Energy Coefficients of Building Materials

No	MATERIAL/WORK	Unit	Elect	Gas	Oil	Coal	Capital	Imports	Energy Coeff. MJ/Unit	Level
66	Asphalt.Surface.Rolled	m^2	2.90	1.80	67.70	5.20	0.20	7.20	85.00	4
67	Chip-seal.Pavement	m^2	0.20	0.22	7.98	0.02	0.00	0.00	8.42	1
68	Lime.Hydrated	kg	1.40	0.03	3.06	4.35	0.13	1.42	10.39	4
69	Quicklime	kg	1.00	0.02	2.18	3.10	0.09	1.01	7.40	4
70	Site.Power	MJ	1.00	0.00	0.00	0.00	0.00	0.00	1.00	1
71	Site.Power	$	300.00	0.00	0.00	0.00	0.00	0.00	300.00	1
72	Transport.Road.30km	tonne	0.00	0.00	114.00	0.00	0.00	0.00	114.00	1
73	Transport.Road.50km	tonne	0.00	0.00	190.00	0.00	0.00	0.00	190.00	1
74	Transport.Road.100km	tonne	0.00	0.00	230.00	0.00	0.00	0.00	230.00	1
75	Transport.Rail.200km	tonne	0.00	0.00	146.00	0.00	0.00	0.00	146.00	1
76	Transport.Rail.500km	tonne	0.00	0.00	365.00	0.00	0.00	0.00	365.00	1
77	Transport.General	$	0.00	0.00	35.00	0.00	0.00	0.00	35.00	1

Table 2.4 - Comparison of GER for House Construction (Baird and Chan 1983)

HOUSE	AUTHOR	FLOOR AREA m^2	GER GJ/m^2
UK 2 storey brick/block load bearing outer wall	Gartner & Smith (29)	80	1.2-2.3
UK 3 bedroom semi-detached	Brown & Stellon (43)	100	4.0
UK Parker-Morris Std 3 bedroom semi-detached	MacKillop (46)	100	1.9
UK Std mid-terrace house	Markus & Slesser (40)	96	7
AUST 1 storey brick veneer slab on ground	Hill, R.K. (30)	144	3.6
USA 1 family (from I-O data)	Stein et.al. (24)	-	8
NZ timber frame house. BIAC (Materials only)	Baird & Chan (Table 4.1)	94	3.2
NZ timber frame house. BIAC (using I-O data)	Baird & Chan (Table 4.3)	94	3.3
NZIV Modal house timber frame (process analysis)	Baird & Chan (Appendix A5)	93	3.56
NZIV Modal house (using I-O data)	Baird & Chan (Appendix A5)	93	3.64

Table 2.5 - Energy Burned and Carbon Released for Beams and Cladding (Honey and Buchanan 1992)

	Light beam (1 metre)		Heavy beam (1 metre)		Cladding (1 sq. metre)	
	Steel BP 200/19	Timber 300x50	Steel 310UB40	Glulam 550x135	Steel 0.5 mm	Plywood 12 mm
Mass (kg)	5.6	7.5	40.0	37.0	4.7	6.0
Specific Energy (MJ/kg)	59	2.4	50	9	36.9	18.9
Energy (MJ)	330	18	2360	333	173	113
Carbon coefficient (kg C/kg)	1.07	0.04	1.07	0.16	0.68	0.35
Carbon released (kg)	6.0	0.3	42.8	5.9	3.2	2.1
Carbon stored (kg)	0	3.8	0	18.5	0	3.0
Nett carbon emitted (kg)	6.0	-3.4	42.8	-12.6	3.2	-0.9
Carbon difference (kg)	9.4		55.4		4.1	
kg C per kg steel	1.7		1.4		0.9	

Table 2.6 - Energy Burned and Carbon Released for House Framing (Honey and Buchanan 1992)

Average 180 m² house		Steel frame	Timber frame
Mass	(t)	5.0	6.6
Specific energy	(MJ/kg)	59.0	2.4
Energy	(GJ)	295.0	15.8
Carbon coefficient	(kg C/kg)	1.07	0.04
Carbon released	(t)	5.4	0.3
Carbon stored	(t)	0	3.3
Nett carbon emitted	(t)	5.4	-3.0
Carbon difference	(t)	8.3	
kg C per kg steel		1.7	

Table 2.7 - Comparison of GER Values - BIAC Standard House (Baird and Chan 1983)

	GJ/m²	
	ROOFING MATERIAL	
	GALVANISED IRON	CONCRETE TILE
CONCRETE FLOOR		
Weatherboard	3.5	3.1
Conc. Block	4.0	3.6
Brick Veneer	4.4	4.0
TIMBER FLOOR		
Weatherboard	3.2	2.7
Conc. Block	3.7	3.2
Brick Veneer	4.1	3.7

Table 2.8 - Energy Requirement of Construction in U.S.A. (Baird and Chan 1983)

CONSTRUCTION	ENERGY REQUIREMENTS GJ/m² FLOOR		
	TOTAL	DIRECT	PERCENT DIRECT
Residential Family	8.0	1.0	13
Educational Building	15.7	3.0	19
Office Building	18.6	4.0	22
Industrial Buildings	11.0	1.1	10
Stores/Restaurants	10.7	2.5	23
Hospitals	19.6	4.0	20
Hotels/Motels	12.8	2.9	23
Religious Buildings	14.3	2.9	20
Warehouses	6.3	0.9	14

SOURCE : Stein et.al. (24)

Table 2.9 - Construction to Operation Energy Requirements (Baird and Chan 1983)

BUILDING	AUTHORS	CONSTRUCTION/OPERATION (YEARS)
UK House	Gartner & Smith (29)	1-2
UK House	Brown & Stellon (43)	4.8
-	Stein, R.G. (34)	6
USA College	Kegel, R.A. (26)	6
Australian House	Hill, R.K. (30)	6
UK House	MacKillop (46)	4.5
UK House (MK1)	Markus & Slesser (40)	3.1
BIAC Std House*	Baird & Chan	8
MZIV Model House*	Baird & Chan	9

NOTE : *The GER calculated by process analysis have been used in both cases.

Table 2.10 - Extreme Energy Requirements of House Construction and Space Heating for 94 m^2 house (Honey and Buchanan 1992)

House construction type	Materials (GJ)	Space Heating requirements		25 yr total Materials and heating (GJ)
		Annual (GJ/yr)	25 yrs (GJ)	
Greatest energy requirement	540	32.5	812	1316
Most common	372	5.4	135	507
Smallest energy requirement	250	1.9	47	297

Table 2.11 - A Classification according to Quality of Energy (Perera 1981)

Energy Quality (Class)	Type or Source of carrier
Very high (VH)	Electricity
High (H)	Diesel, Furnace oil, Bunker oil, Coal
Medium & (M)	Peat, Firewood, Wood-waste
Low (L)	Paddy husk, Saw dust, Agro-wasts
Very Low (VL)	Wind, Tidal, OTEC, Wave

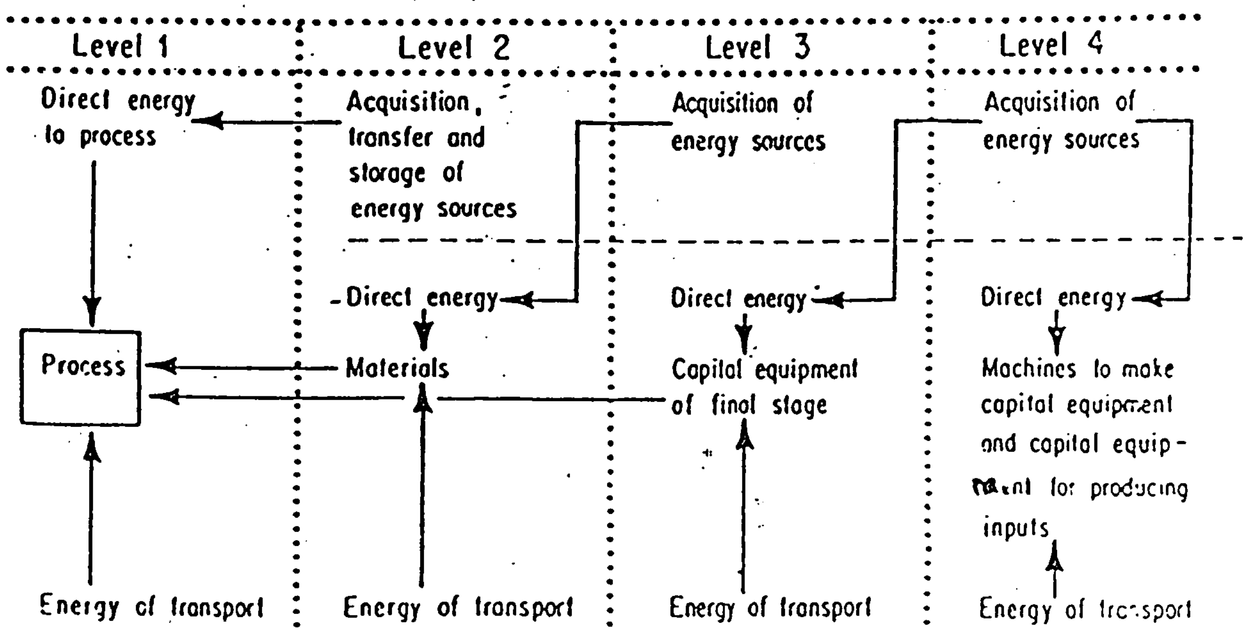


Figure 2.1 - Levels in the definition of System boundaries (IFIAS 1975)

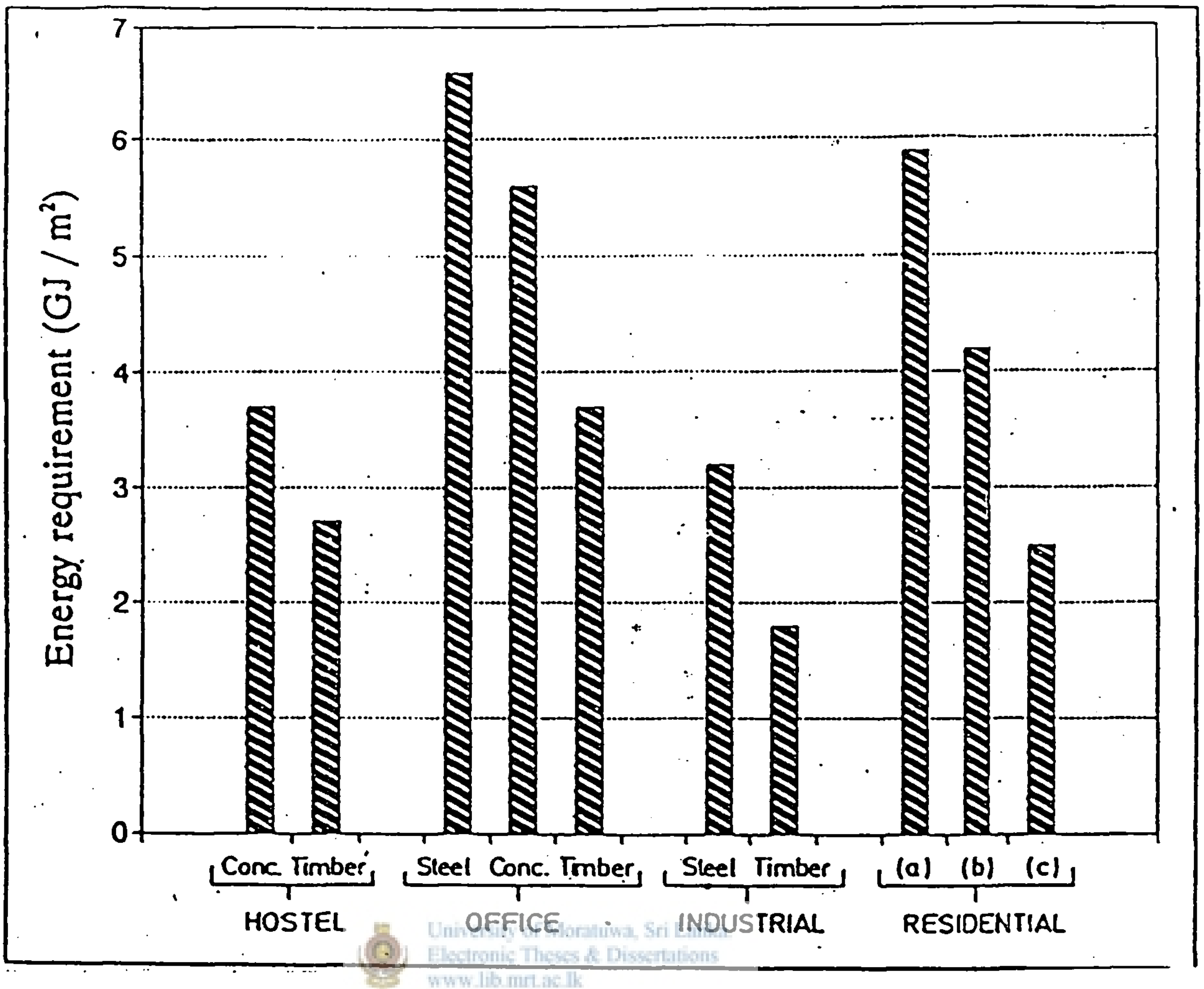


Figure 2.2 - Energy Required to Manufacture Building Materials and Construct Buildings (GJ/m^2) (Honey and Buchanan 1992)

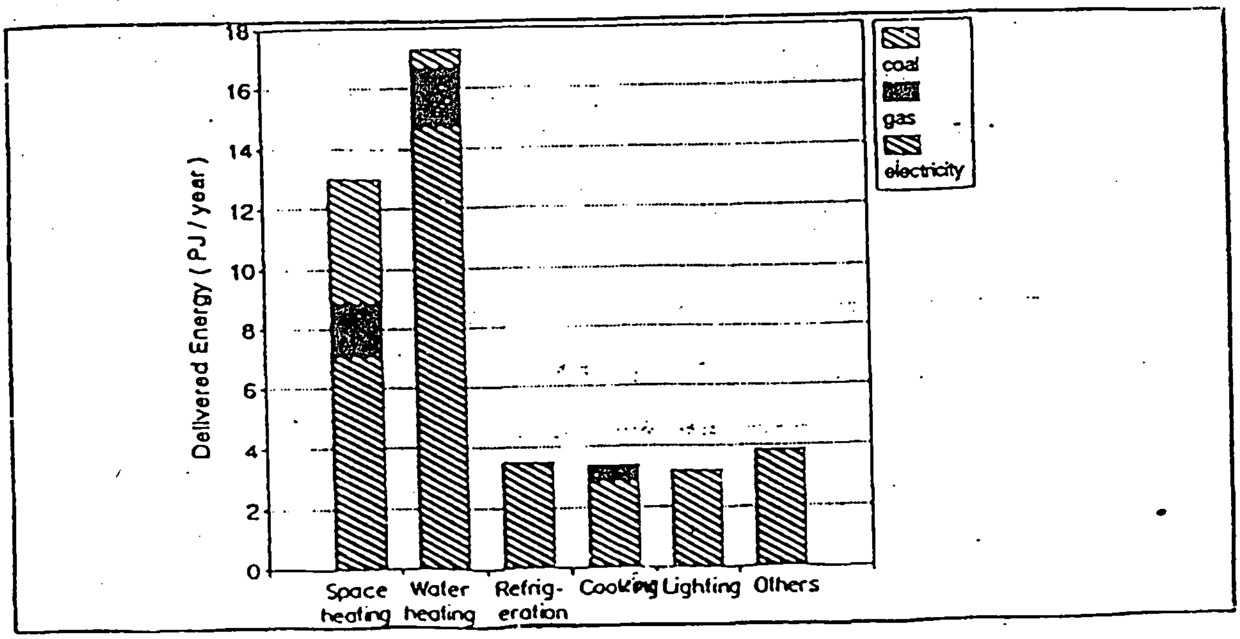


Figure 2.3 - End uses of energy by delivered fuel type in New Zealand dwellings (Turbott et al. 1991)

3. METHODS & LIMITS

3.1. Introduction

This chapter describes the basic approaches used in this thesis for calculating energy contents and carbon coefficients of building materials.

The method of analysis used is Process Analysis (see Section 2.1.3.), since it was the easiest way to get fairly upto date information, and because it lent itself to support the hierarchical structuring of building materials adopted here, and described later in Section 3.3.

3.2. TOE Values and Carbon Coefficients Relevant to Sri Lanka

TOE values were used as a common base for energy calculations (see Section 3.2.1 below); a departure from this (incorporating a notion of energy quality) is described later in Chapter 6.

3.2.1. TOE Values

As outlined in section 2.3, in order to compare energy values from different sources, a common unit, i.e., Tonnes of Oil Equivalent (TOE) is used. Table 2.1 gives the conversion factors that have been used in this research.

In addition to those values, for the conversion of electricity consumption into TOE values, it is taken that 66% is hydro electricity and 34% is thermal (Siyambalapitiya 1997).

A TOE value for hydro electricity (based on 100% efficiency) is commonly used, although it lacks theoretical vigour. It is arrived at by a comparison with oil based electricity which has a 36% efficiency. Losses of energy in the production and transmission of hydro electricity are also not accounted for, as for the energy for extraction and transporting all other energy sources (see Section 3.3).

For hydro electricity (assuming 100% efficiency),

$$\begin{aligned} 1 \text{ MWh} &= 0.086 \text{ TOE} \\ &= 41.84 \times 0.086 \text{ GJ} \\ &= 3.60 \text{ GJ} \end{aligned}$$

For (oil based) thermal electricity which is generally understood to have a conversion efficiency of 36 % (Perera 1992),

$$\begin{aligned} 1 \text{ MWh} &= 0.24 \text{ TOE} \\ &= 41.84 \times 0.24 \text{ GJ} \\ &= 10.0 \text{ GJ} \end{aligned}$$

Thus for electricity in general

$$\begin{aligned} 1 \text{ MWh} &= (0.66)(3.6) + (0.34)(10.0) \text{ GJ} \\ &= 5.78 \text{ GJ} \end{aligned}$$

3.2.2. Carbon Coefficients

As outlined in Section 2.3, the gross quantity of Carbon (mostly in the form of Carbon dioxide) emitted in the manufacture of each material per unit of weight or volume has been named the " Carbon Coefficient". Table 2.2 shows the Carbon Coefficients that have been used in this research.

Most of the carbon emissions arise as a result of the burning of fossil fuels. In addition to that, assuming that 34% of electricity is thermal, a value of 18.36 kg of carbon per GJ of electricity has been used.

Burning of wood emits carbon dioxide too, but no more than was absorbed when the tree was growing (250 kg of carbon is stored per cubic metre of wood as described in Section 2.3.2.2), so wood fuels are sustainable, giving a net value of zero kg of carbon per MJ of energy.

Apart from this any timber used in construction is considered to "lock up" carbon and contributes a negative carbon coefficient equal to the value above. Such locking up is not ascribed to formwork, which has a very short life span and will hence release carbon to the atmosphere fairly soon by decay or other means. Carbon is locked up in steel too, but the amount is negligible and hence ignored.

As described in Section 2.3.2.1 Carbon dioxide is released to the atmosphere via chemical reactions in the Aluminium and Cement industries. Therefore a figure of 130 kg of carbon per tonne of aluminium has been added to the carbon coefficient for aluminium and a figure of 142 kg of carbon per tonne of cement has been added to the carbon coefficient for cement.

3.2.3. Energy and Carbon Coefficients of Imports

Fossil fuel power stations are the main source of the world's electricity producing 66 percent of the world total (World Resource Institute 1987). and rest of the industrial fuel for energy use is derived mainly from fossil fuel alone. Therefore it can be assumed that imported raw materials are made out of fossil fuel neglecting nuclear power, hydro power etc. Therefore in this research, in order to obtain carbon coefficients from energy intensities, the embedded energy in imported items is multiplied by a factor of 0.02 kgC per MJ based on a report by Honey and Buchanan (1992). This value accounts for energy from gas, oil, coal and the proportion of electricity generated from fossil fuel.

3.3. Hierarchical Structure of Building Materials

All building elements (e.g. brick wall) and materials (e.g. bricks, clay etc.) can be placed in an aggregation-decomposition hierarchy. Each stage of a building material (e.g., brick wall, bricks, clay etc.) can be considered to have both proximate and remote energy inputs. Hence we can say that the distinction between elements, materials and raw materials is blurred. The proximate energy comprises (i) the energy for the actual production process, (ii) the transport of raw materials and (iii) the transport of the energy sources. The remote energy comprises (i) the energy embedded in raw materials and (ii) the energy for extracting the energy sources used as direct energy. Figures for the extraction and transport of energy sources are neglected; as they are not expected to contribute very much (see also discussion on electricity in Section 3.2.1).

The above analysis basically captures most of the energy inputs associated with levels 1 and 2 in the IFIAS scheme (1974). These two levels account for around 90% of the embedded energy in a product. Energy required to make the capital equipment for the process (level 3 in the IFIAS scheme) and the energy to make the machines to make the capital equipment (level 4 in the IFIAS scheme) are ignored. The indirect energy of production (i.e., energy for lighting etc.) has been omitted in most cases other than where production energy has been computed via electricity meter readings. Also production processes in the informal sector (e.g. brick making, roof carpentry etc.) consume little if any indirect energy. Such energy can be neglected in Sri Lanka because energy for heating (which is the greatest contribution to indirect energy of production) is not required. The different types of process energies are depicted in Table 3.1.

The energy inputs into materials are summed incrementally, resulting in a hierarchical scheme. Thus, bricks are raw materials for the brickwall and clay is a raw material for the bricks. The analysis can be represented by a table for each material, the total energy for a material at a given level becoming the embedded energy of raw material at the next higher level. Therefore these tables are termed "hierarchical tables". In this hierarchical structure the lowest level any building material can reach is a raw material stage which cannot be divided further. These are called "primitives". The highest level is the finished building. So before reaching the final stage every building material will undergo intermediate levels i.e. building material stage (e.g., cement) and element stage (e.g. brickwall), although the distinction between materials and elements is blurred, as explained before. The hierarchy of materials for a brickwall is shown in Figure 3.1. Examples of such hierarchical arrangements for major building elements are shown in Figure 3.2. Examples of hierarchical tables for a brick wall are given in Tables 3.2 to 3.4. Although the final level considered in this research is the finished building, the hierarchy is open-ended (at least at the upper end) as it can be expanded to find the embedded energy of a city or even a country.

It must be emphasised that the hierarchy proposed here is one of materials or products, whereas the IFIAS hierarchy is one of processes. They can be considered mutually "orthogonal" to each other. At every level of these materials hierarchies, it is sought to incorporate the IFIAS hierarchy upto level 2.

3.4. Energy Breakdown by Process & Fuel Type

As discussed in Section 3.3, the energy embedded in a building material at intermediate levels in the hierarchy will in general comprise (i) production energy, (ii) energy to transport its component materials and (iii) the energy embedded in its component raw materials (since the energy to extract and transport energy sources is ignored). All these energies can also be classified according to input energy type as biomass, fossil fuel and electrical energy. Figure 3.1 shows this schematically for the brick wall element, while the 2 dimensional matrix type arrangement in the hierarchical tables (Tables 3.2 to 3.4) enable energy contents and carbon coefficients of materials to be classified both according to process and fuel type. In addition to biomass, fossil fuel and electricity, the database (see Chapter 5) has a field for "imports", i.e. raw materials imported to the country and another one to account for carbon emissions (or storage) not related to the fuel type (see section 3.2.2). These fields are not represented in Figure 3.1. or Tables 3.1 to 3.4 (where the net value is shown for carbon emission calculations) for the sake of simplicity. Each energy component (whether classified by process or fuel type) also has a minimum, average and a maximum value since a number of samples were used to arrive at the energy contents. This is further described in Chapters 4 and 5.

3.5. Embedded Energy Calculations

The embedded energies of materials are found for a convenient unit (e.g. 1000 nos. for bricks - see Table 3.2). However, the fraction of this energy to be carried forward as embedded energy in a brick wall will depend on the unit chosen for brick wall. These units are based on SMM7 (Standard 1988) standards, in this case 10 m^2, and the number of bricks required for it (in this case equal to 1173). Hence, the embedded energy of 1000 bricks has to be factored by 1173/1000 (see Table 3.1). Such calculations are performed via an "amount" column in the tables. The tables also differentiate the energy input by energy type, whether biomass, fossil fuel or electricity. Similar hierarchical tables can be constructed for carbon emissions as well (see Table 3.3).

The data required to do the above embedded energy calculations were collected from different building material manufacturers, since process analysis has been used for estimating energy inputs. The process details are discussed further in Chapter 4.

3.6. The Use of Calculated Values

Apart from documenting the values of energy contents and carbon coefficients in a database (see Chapter 5), this study also utilises these values in various ways. For example the energy contents and carbon coefficients for building element alternatives are compared in Chapter 7, and the embedded energy content of various buildings are compared with their operational energy expenditure in Chapter 8. The approach taken in these chapters is to use spreadsheets to aggregate the energy contents and carbon coefficients based on prepared Bills of Quantities and guidelines in the Building Schedule of Rates (1988). All assumptions used and limits imposed are described fully in Chapters 7 and 8.

Table 3.1 - Different Types of Process Energies

Energy input at each stage	Process		IFIAS level	accounted/ neglected
Proximate	Production	indirect	1	neglected
		direct	1	accounted
	Transport of Raw Materials		1	accounted
	Transport of Energy Sources		1	neglected
Remote	Embedded energy of Raw Materials		2	accounted
	Extraction of Energy Sources		2	neglected

Table 3.2 - Energy Analysis for Brickwork(MJ)

Amount	Brickwork(9"): 10 m^2	Biomass	Fossil fuel	Electricity	
	Production Energy				
	Transport of Raw material				
1173	(1) Bricks		48		**148**
0.16	(2) Cement		11		
0.59	(3) Sand		89		
	Embedded energy in Raw material				
1173/1000	(1) Bricks	10,004	99		**10,767**
0.16	(2) Cement		589	76	
0.59	(3) Sand				
		10,004	**836**	**76**	**10,915**

Table 3.3 Energy Analysis for Bricks (MJ)

mount	Bricks:1000 Nos	Biomass	Fossil fuel	Electricity	
	Production Energy	8,528			**8,528**
	Transport of Raw material				
1.87	(1) Clay		39.84		**39.84**
	Embedded energy in Raw material				
1.87	(1) Clay		8.13		**8.13**
		8,528	**47.97**		**8,576**

Table 3.4 - Carbon Emission Analysis for Brickwork (KgC)

Amount	Brickwork(9"):10m^2	Biomass	Fossil Fuel	Electricity	
	Production Energy				
  1173 0.16 0.59	Transport of Raw material (1) Bricks (2) Cement (3) Sand		 0.97 0.23 1.81		 **3.01**
  1173/1000 0.16 0.59	Embedded energy in Raw material (1) Bricks (2) Cement (3) Sand		 2.01 11.95	 1.39	 **38.07**
			16.98	**1.39**	**40.31**

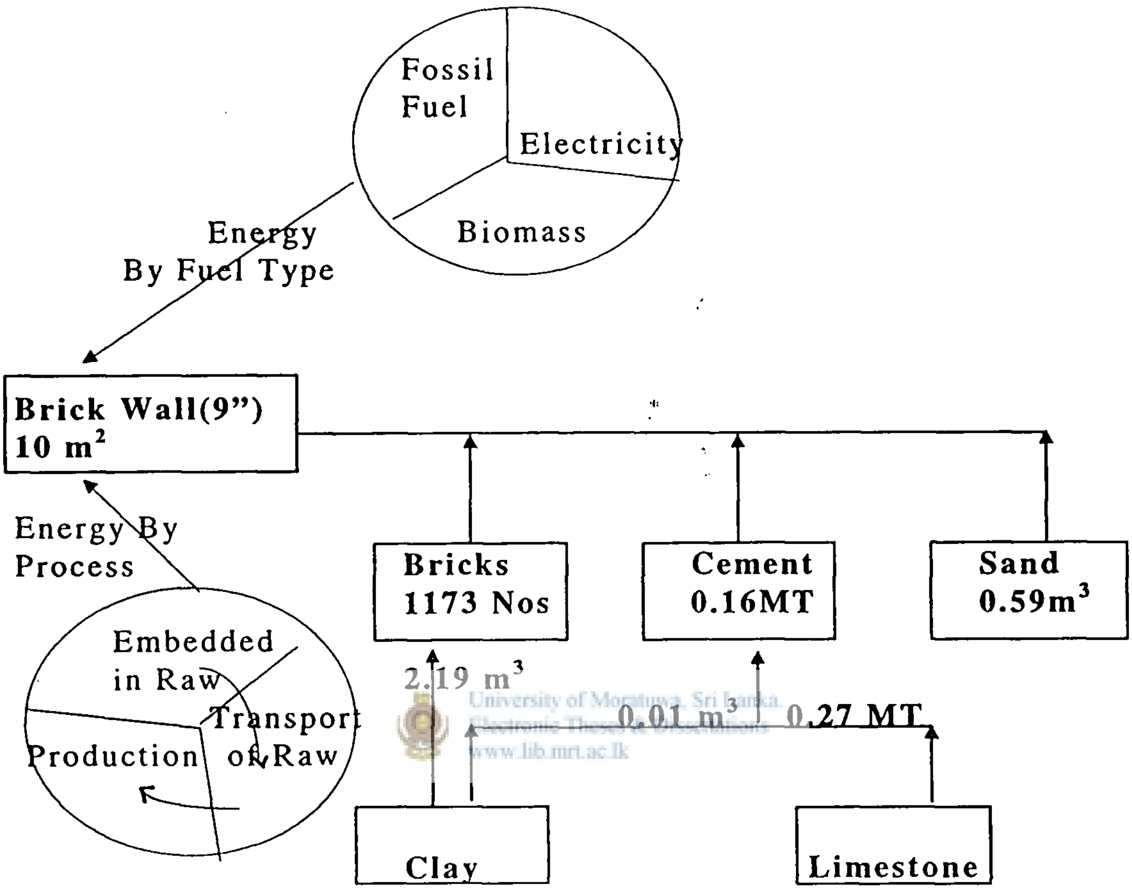


Figure 3.1 - Hierarchical arrangement of Materials for Brickwork

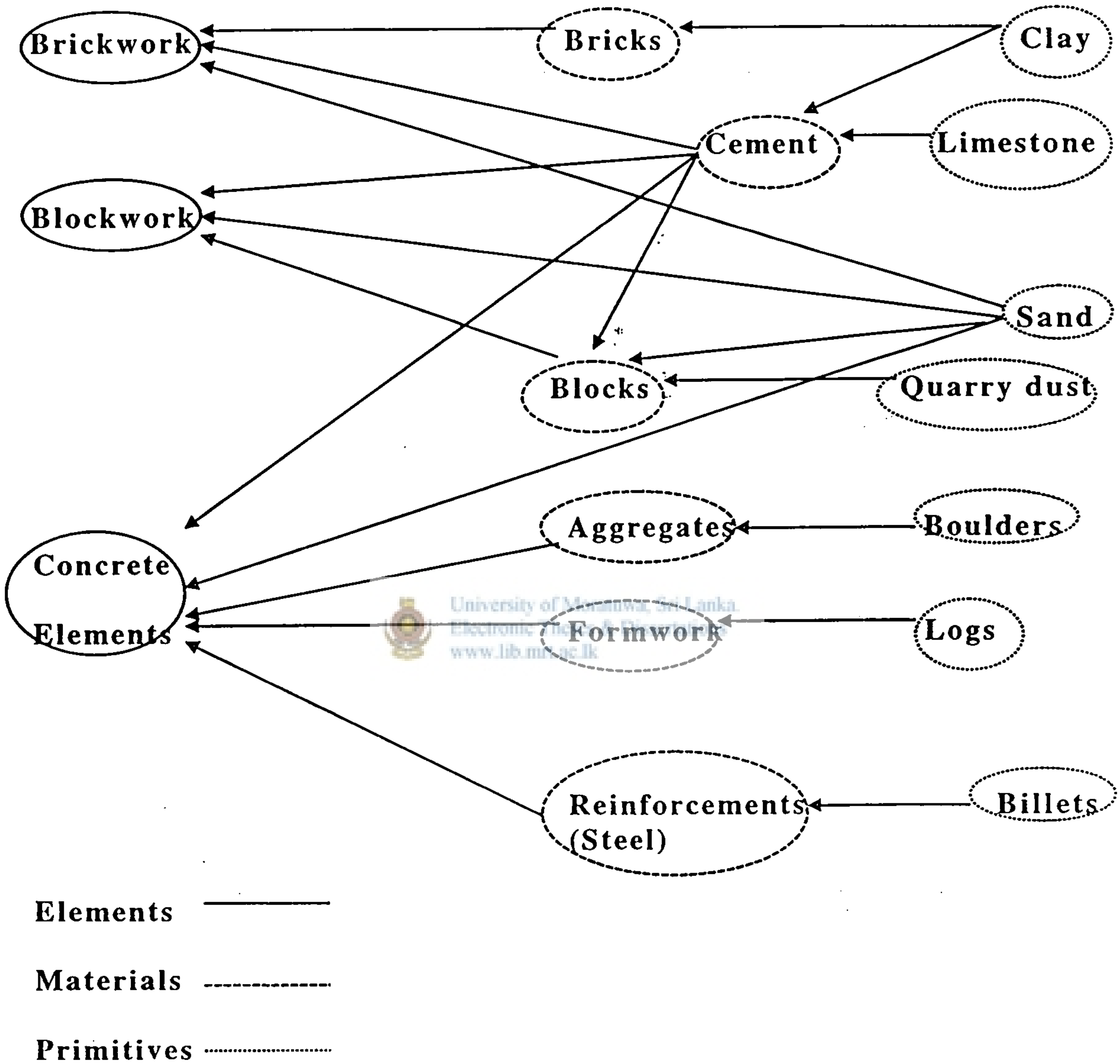


Figure 3.2 - Examples of Hierarchical Arrangements for Major Building Elements

4. ENERGY CONTENTS AND CARBON COEFFICIENTS OF BUILDING MATERIALS

4.1. General

As described in Section 3.3, the distinction between elements, materials and primitives is blurred, since all building elements (e.g. brick wall) and materials (e.g. bricks, clay etc.) can be placed in an aggregation-decomposition hierarchy, where each stage of a building material (e.g. brickwall, bricks, clay, etc.) can be considered to have both proximate and remote energy inputs.

The energy contents and carbon coefficients of primitives, materials and elements that contribute to make a building are described in this chapter. Some elements described under this chapter are aggregated via the Building Schedule of Rates (BSR), and hence are not based on surveyed samples. Some building elements will only be found in Bill of Quantities (BOQ) for example doors and windows of different sizes. These items (which can be called customised elements) are not included in the database. They are described briefly in Section 4.5.

Apart from the above BSR and BOQ items, the data required to estimate the embedded energies were collected from building material manufacturers, since process analysis has been used for the estimating of energy inputs, as described in Chapter 3. Although in some cases approximately 10 manufacturers were surveyed (e.g. for bricks) in other cases it was possible to survey only a few and in some cases only one (e.g. for steel). Nevertheless, the energy for a given material was assigned a minimum, maximum and an average value based on the survey results. In some cases a result was rejected as being unreliable or an outlier. For imports (e.g. steel billets) energy contents defined in the literature calculated by overseas researchers were used. In this analysis imported raw materials were considered as primitives.

In this research it is assumed that the final building is located in the City of Colombo for purposes of determining transport energies. The estimates carried out in this research in general, do not include material transport to the site from within the Colombo District itself (which is considered negligible); in some cases transport of imported raw material from the harbour to a factory are accounted for. For materials transported from remote areas, and in the cases where transport energy is significant within the Colombo City limits (depending on the road condition, type of vehicle etc.) the round trip energy requirement was taken. For some items based on the BSR and BOQ, although no surveyed samples were available, transport distances had different values in some cases. Hence maximum and minimum distances were used in the transport energy calculations of raw materials to find a range for the final embedded energies.

The Carbon Coefficients were based on fuel utilisation as described in Section 3.2.2, but also accounted for situations where carbon is liberated by a process or locked up in a material. To obtain carbon coefficients based on fuel utilisation, the energy values are multiplied by factors given in Table 4.1. This table was derived according to information given in Section 3.2.2. In the following detailed process descriptions, no special mention is made of carbon flows via fuels used in the production and transport stage unless there is a particular emission or "locking up" associated with that process. Burning of wood (fire wood) emits carbon dioxide, but no more than was absorbed when the tree was growing, so wood fuels are sustainable, giving a net value of zero kg carbon per MJ of energy.

A database was designed to store all these data and to perform the calculations. This will be discussed in Chapter 5. Previously published estimates of the energy contents of the main building materials together with the final outputs of this research are presented in Table 4.2. A similar table for carbon coefficients is given in Table 4.3. The above tables also indicate the number of samples surveyed or whether the item breakdown was obtained from the BSR. Some of the values from the present study in Table 4.2 are comparatively low, because some of the previously established values are only 1983 values, and since some minor energy consuming processes may not have been captured in the present study.

4.2. Primitives

4.2.1. Sand

Sand is used in cement mortar and concrete for building construction. It is mixed with cement and acts as an inert filler. Sand is extracted from rivers and streams and available all over the country.

This material cannot be divided further, and is therefore a primitive.

In Sri Lanka sand is extracted from rivers by using human labour. In this research human energy is neglected. Therefore total embedded energy is taken as zero.

Survey data was not required since embedded energy was taken as zero.

4.2.2. Clay

Clay is used as a raw material for many building materials (e.g. bricks. calicut tiles, cement etc.)

This material cannot be divided further, and is therefore a primitive.

Clay extraction is done using dozers. The embedded energy of clay consists only of the energy involved for the extraction process. This fossil fuel requirement is calculated from dozer hours used for a tractor load. It is assumed that 5 litres of diesel is being used for 1 dozer hour. According to the calculations the total embedded energy of clay is around 1-11 MJ/m^3.

Data was obtained from 5 places.

4.2.3. Boulders

This is the raw material being used for the extraction of aggregates.

This material cannot be divided further, and is therefore a primitive.

Extraction of boulders is being done by blasting of quarries.

For quarrying done on a large scale energy required to win boulders consists of drilling holes for blasting, chemical energy in the blasting itself which is ignored, and breaking the blasted rock using hydraulic excavators. These data were obtained from the fuel consumption data (fossil fuel) available for the blasting process together with the production. According to the calculations the embedded energy of boulders is around 34-41 MJ/ MT.

Data required for these calculations were obtained from 2 places.

4.2.4. Limestone

Limestone is being used as a raw material mainly for cement and lime manufacture.

This material cannot be divided further, and is therefore a primitive.

Limestone is extracted from corals or by quarrying miocene limestone or magnesium based dolomite. The energy required to win limestone from corals is considered as zero, since extraction is done using human labour where human energy is neglected in this research. To win limestone from magnesium based dolomite, a similar process as for extraction of boulders is used. Therefore in this research, as a conservative approach, the energy required to win limestone from magnesium based dolomite is used. This energy is likely to be greater than that for quarrying miocene limestone.

These data were obtained from the fuel consumption data (fossil fuel) available for the blasting process together with the production data available for boulders. Although data required for these calculations were obtained from data available for the extraction of boulders, since one needs less energy to win limestone than for boulders, only the lower limit of the embedded energy of boulders is used. Therefore the embedded energy of limestone is around 34 MJ/ MT.

4.2.5. Logs

This is the raw material used for the production of all timber products. Logs can be of two types, (i) very short life span, i.e. logs used for formwork, and the portion wasted when producing timber products such as planks and purlins, and (ii) long life span logs i.e. the portion of the logs used for roof timber, doors, windows etc.

This material cannot be divided further, and is therefore a primitive.

Extraction of timber logs consists of cutting of trees and removing of the excess part. The embedded energy of logs consists of the energy involved in the cutting and removing of the excess part. This data was obtained from the fuel consumption data for the process. According to the calculations the total embedded energy of both types of logs is around 166 MJ/m^3.

Timber used in construction is considered to "lock up" carbon and contributes a negative carbon coefficient equal to 250 kg of carbon per cubic metre of wood. Such locking up is not ascribed to short life span logs, which will release carbon to the atmosphere fairly soon by decay or other means.

Data required for the calculations was obtained from only 1 place due to the lack of data.

4.2.6. Steel Billets

This is the raw material being used for the production of steel in Sri Lanka.

This material cannot be divided further for purpose of this study, as it is imported, and is hence considered a primitive.

These billets are being imported from Russia, India and South Africa. The energy embedded in billets was extracted from published data overseas. Therefore a value of 29,000 MJ/MT (Baird and Chan 1983) was taken as the embedded energy of steel billets.

This data was extracted from only one source (i.e. published data).

4.2.7. Aluminium Billets

This is the raw material used for the production of Aluminium extrusions in Sri Lanka.

This material cannot be divided further for purpose of this study, as it is imported, and is hence considered a primitive.

These billets are being imported. The energy embedded in billets was obtained from published data in the literature. Therefore a value of 129,500 MJ/MT (Baird and Chan 1983) was taken as the embedded energy of aluminium billets.

The aluminium production process releases 130 kgC/MT of aluminium produced.

This data was extracted from only one source (i.e. published data).

4.2.8. Asbestos Fibre

This is the raw material being used for the production of asbestos sheets used for roofing in Sri Lanka.

This material cannot be divided further for purpose of this study, as it is imported, and is hence considered a primitive.

These fibres are being imported from South Africa, Canada, Greece, Russia, etc.

The energy embedded in asbestos fibre was obtained from published data in the literature. Therefore a value of 15,680 MJ/MT (Baird and Chan 1983) extracted from the data available for the production of asbestos cement was taken as the embedded energy of asbestos fibre (this value was derived assuming 12% asbestos fibre content in asbestos cement).

This data was obtained from only one source (i.e. published data).

4.2.9. PVC Resin

This is the raw material being used for the production of PVC products used for water supply and drainage in Sri Lanka.

This material cannot be divided further, and is therefore a primitive.

This resin is being imported. The energy embedded in PVC resin was obtained from published data in the literature. Therefore a value of 92,000 MJ/MT (Baird and Chan 1983) extracted from the data available for the production of PVC was taken as the embedded energy of PVC resin.

This data was extracted from only one source (i.e. published data).

4.2.10. Raw Material for Paint

This consists of the raw material (mostly water and pigments, i.e. around 80%) being used for the production of emulsion and enamel paint.

This material cannot be divided further, and is therefore a primitive.

These are being imported. The energy embedded in these raw materials were extracted from published data in the literature. Therefore a value of 53 MJ/l for the embedded energy of raw material of emulsion and a value of 124 MJ/l for the raw material for enamel (Baird and Chan 1983) were extracted from the data available for the production of paint.

This data was extracted from only one source (i.e. published data).

4.3. Materials

4.3.1. Cement

Cement is the major component used in building construction. It has cementitious properties so that it can form a good bond with other materials. It solidifies when mixed with water. It is the most active binding medium and is perhaps the most scientifically controlled component in concrete.

Cement is produced by burning a mixture of limestone, clay, dolomite, gypsum and iron ore. The clinker so obtained is cooled and powdered to the required fineness. The product so obtained is called cement. It is assumed that 1.7 MT of limestone and 4% of clay are being used to get 1 MT of cement, other minor materials being ignored.

Energy analysis of cement production consists of processing energy and raw material transport energy and embedded energy.

Limestone is transported in tippers by rail track from a distance of around 40 km, with 22 MT per load. Clay is transported in tippers by rail track from a distance of around 40 km, with 30 MT per load. The fuel consumption of a tipper is 1 ltr. of diesel per 8 km.

The electricity and furnace oil requirement for the production were obtained from monthly production reports obtained from the manufacturer. To produce 1 kg of clinker they need 3993 kJ from furnace oil (1 MT of cement requires 0.9 MT of clinker), together with 104 kWh of electricity to produce 1 MT of cement. According to the calculations the total embedded energy is around 4282 MJ/MT compared to the range 3400-6100 MJ/MT in the literature (Perera 1992).

Carbon dioxide is released to the atmosphere via chemical reactions in the cement production. Therefore a figure of 142 kg of carbon per tonne of cement has been added to the carbon coefficient (see Section 2.3.2.1).

The data required for these energy calculations were obtained from the single cement manufacturer who produces cement from raw material available in Sri Lanka.

4.3.2. Timber

Usage of timber as a building material is very common all over the country. Timber is used for roof frames, doors, windows, ceiling frames, formwork and sometimes for floor construction.

Timber is obtained in the form of purlins and planks. The raw materials for these are timber logs where the wastage lies between 10-40%. Therefore it is assumed that these timber products are made out of both long life span and short life span logs, where the wasted percentage is assumed to be made out of short life logs, while rest is assumed to be made out of long life logs. Planks used for formwork (planks-formwork) are assumed to be made out of short life span logs. Planks used in permanent construction are assumed to be made out of long life span logs.

Processing of timber is mainly done in the Moratuwa area, close to Colombo City. The embedded energy of timber can be considered to consist of three main components:

(i) Raw material (i.e. logs) embedded energy

(ii) Raw material transport energy

(iii) Processing energy for sawing and planing

Around 250-300 m^3 of timber are transported by "1210" lorries. Fuel consumption for a "1210" lorry is 1 ltr. of diesel per 8 km. Extraction of timber is mainly from Anuradhapura, Wellawaya and Hambantota.

Energy for the process of sawing and planing was obtained by daily production data (i.e. from production rate and energy consumption based on machine capacity and working hours). To produce 1 m^3 of purlins (2"x4") one needs around 152 kWh and to produce 1 m^3 of planks (3/4" or 1/2" thickness) one needs around 211 kWh. The calculated total embedded energy lies in the range of 1292-1995 MJ/m^3 for planks and 1191-2026 MJ/m3 for purlins compared to a value of 714 MJ/m^3 for rough timber in the literature (Baird and Chan 1983).

For the manufacture of purlins, data were obtained from 7 manufacturers, whereas for planks, data were obtained from 3 manufacturers.

4.3.3. Air Dry Treated Timber

Seasoning (either air or kiln drying) and wood preservation serve two purposes, i.e. by increasing the life of wood it increases the effective productivity of forests and it eliminates the labour cost of replacing wooden members. Wood preservation should be done only if economies can be effected by the use of treated wood. In temporary work such as formwork treated wood is unnecessary.

The raw material used are rough timber and preservatives. The transport distances of these raw materials are ignored since they are negligible.

There are several different ways by which wood can be dried. The most common is air drying and kiln drying. For timber used in house construction only air drying is being used. Therefore no energy is involved in the seasoning process.

Methods used for applying preservatives are brush coating (for doors, windows etc.) and dipping, where no energy is involved; and pressure impregnation, a method by which controlled quantities of preservatives are introduced into the wood. Only roof timber is being preserved using this method.

The embedded energy in wood preservatives itself is negligible. For pressure impregnation, 10 m^3 of timber requires around 8 kWh of the pressure motor, 7.5 kWh of the vacuum motor, 1.65 kWh to pump the chemicals to the storage tank and fossil fuel for the fork lift to input and output timber. These data were obtained from daily production data (i.e. energy consumption rate, production etc.). According to the calculations the total embedded energy is in the range of 1312-2028 MJ/m^3 for air dry treated planks and1424-1433 MJ/m^3 for air dry treated purlins compared to the range of 2370-3714 MJ/m^3 in the literature (Baird and Chan 1983).

The data required for the energy calculations were obtained only from two factories, as there are only few such factories.

4.3.4. Plywood

The advantages of plywood as compared to solid timber are almost similar strength properties in all directions, greater resistance to cracking and splitting, better dimensional stability with changes in moisture content, and the fact that large sheets can be produced. These are used for flush doors.

The basic principle of plywood is the gluing together of thin sheets of wood (plies) with the grain of successive sheets at right angle to each other. The number of plies is usually an odd number e.g. 3,5,7 etc. The sheets used for the production of flush doors are of 12 mm thickness. The raw material for this is timber logs of both long and short life span since the wastage during the production is around 30%.

The embedded energy of plywood can be considered to consists of raw material embedded energy and transport energy and the processing energy for plywood sheets.

The transport of the raw material (i.e. wood) is from Ratnapura and Pelmadulla and it is transported by lorries. Around 250-300 m^3 of timber are transported by "1210" lorries. Fuel consumption for a "1210" lorry is 1 ltr. of diesel per 8 km.

Preservative treatment is done using dipping where no energy is involved. The energy required for the manufacture consists of the production of these plies, applying of glue and the pressing. The data required for this production process were obtained from the average daily production (i.e. production, fuelwood used for the boiler and units of electricity used per day). To produce 1 m^3 one needs around 1.1 yd^3 of firewood and 28 units (kWh) of electricity. According to the calculations the total embedded energy is around 12,090 MJ/m^3 compared to the value 9500 MJ/m^3 in the literature (Baird and Chan 1983).

Most of the plywood sheets being used are imported sheets. Local manufacturing is done only in few places. Therefore data required to perform the energy calculations were obtained from only one major plywood sheet manufacturer in Sri Lanka.

4.3.5. Steel Products

Steel is very commonly used for buildings and structures due to its high strength in both tension and compression, high material stiffness and high strength/weight ratio. Steel is used for factory buildings, frames for multi-story buildings, reinforced concrete, prestressed concrete and roof structures.

The raw materials used for the production of steel products is steel billets.

Energy analysis of steel consists of three components:
(i) Processing energy of steel.
(ii) Raw material (i.e. billets) transport energy.
(iii) Raw material embedded energy (energy embedded in billets).

These billets are being imported from Russia, India and South Africa and are transported to the manufacturer from the harbour by "1210" lorries (20 MT per load). Fuel consumption of a lorry is 1 ltr. of diesel per 8 km.

Production of steel is done by melting of these steel billets and data required for these energy calculations were obtained from monthly production data (i.e. monthly fuel consumption). To produce 1 MT of steel one requires around 67 ltr. of heavy diesel (fuel oil) and 180 kWh of electricity. Energy embedded in billets (i.e. 29,000 MJ/MT) had to be extracted from published data (Baird and Chan 1983). According to our calculations the total energy for steel products is 32,686 MJ/MT compared to the range 30,000-50,000 MJ/MT in overseas (Spence and Cook 1983).

The amount of 0.002 kilogram storage of carbon is neglected, since it is negligible compared to what is released in the manufacture via fuels (Honey and Buchanan 1992).

In Sri Lanka steel production is mainly done at the Athurugiriya Steel Corporation. Therefore data were obtained from only this manufacturer.

4.3.6. Bricks

Clay bricks have been used as walling units from the earliest times of human civilization. This is due to its excellent durability (when they are selected and used correctly), high compressive strength, and lasting aesthetic properties.

The raw material used for the production of bricks is clay. Approximately 1.87 m^3 of clay is used to produce 1000 bricks.

Energy embedded in bricks consists of raw material embedded and transport energy, and heating energy for bricks.

In Sri Lanka bricks production is very popular mainly in the Dankotuwa, Negombo and Hanwella areas due to availability of raw material. Clay is transported by tractors (around 3/4 cubes per load) from a distance of about 1-18 km. The fuel consumption of a tractor is 10 km per ltr. of diesel.

Clay bricks are made by pressing a prepared clay sample in to a mould, extracting the formed unit immediately and then heating it in order to sinter the clay. Bricks production is done by using manpower. Hence energy requirement for production of bricks is neglected. Firewood requirement for heating is around 550 kg (coconut posts of 1' diameter and coconut husks) per 1000 bricks. According to the calculations the total energy embedded in bricks is around 5,307-10,605 MJ per 1000 bricks compared to the value 9,300-10,000 MJ per 1000 bricks in the literature (Baird and Chan 1983).

The data required for these energy calculations were obtained from 5 manufacturers located in the Hanwella and Dankotuwa areas.

4.3.7. Calicut Tiles

In Sri Lankan house construction, calicut tile roof covering is very common all over the country. It is mainly due to low construction cost, availability of raw materials, and good appearance.

The raw material used for the production of calicut tiles is clay. Approximately 1.5 m^3 of clay is used to produce 1000 tiles.

Energy embedded in tiles consists of raw material embedded and transport energy and the tile forming and heating energy.

Production of tiles is done in the Dankotuwa and Negombo areas due to availability of raw material. Raw material (i.e. clay) for the production is transported from 16 km to 40 km distances by tractors (around 3/4 cubes per load). The fuel consumption of a tractor is 10 km per ltr. of diesel.

Calicut tiles are made by pressing the prepared clay in to a mould, extracting the formed unit and then heating it in order to sinter the clay. Wire cutting and pressing of tiles is done using electrical power. To form 1000 tiles it requires around 59 kWh of electricity and to heat the tiles around 1400 kg of firewood. According to these calculations the embedded energy of calicut tiles lies between 20,274-33,384 MJ per 1000 calicut tiles.

The data required for these energy calculations were obtained from 5 manufacturers located in the Waikkala, Dankotuwa and Thamborawilla areas.

4.3.8. Cement Blocks

Hollow cement blocks are mainly used as light load bearing structures, infill panels or parapet walls. The main advantages are in terms of saving in material and saving in time and labour while maintaining a higher strength for a lower weight than conventional clay brick. Both these result in savings in cost.

The raw materials used for the production of cement blocks are cement, sand and quarry dust.

Energy analysis of cement blocks consists of

(i) Raw material embedded energy (i.e. embedded energy in cement, sand and quarry dust)

(ii) Raw material transport energy

(iii) Block production energy

Cement is assumed to be transported directly from the harbour and from Puttalam Cement Company, by "1210" lorries (200 bags per load). Sand is transported from Alawwa by ELF lorries (1.8 cubes per load), quarry dust from a distance of around 16-18 km by ELF lorries (1.8 cubes per load). The fuel consumption of each vehicle is 8 km per ltr. of diesel.

Cement sand blocks are produced using machines. These machines are powered by electrical energy. There are 3 sizes of blocks (4"x8"x16", 6"x8"x16" and 8"x8"x16") produced in 3 different machines in which energy consumption is different, but machines such as mortar mixer, mortar elevator, mortar vibrator and hydraulic jack are used in common for the 3 sizes of blocks. Data required to perform the production energy calculations were obtained from batch data (i.e. energy consumption for each machine used for each batch). To produce 1000 blocks it requires around 68 kWh of electricity. According to the calculations the embedded energy of 1000 blocks lies in the range of 3,855-4,140 MJ for 4" thickness and 5,879-6,397 MJ for 6" thickness and 6,070-6,612 MJ for 8" thickness, compared to the value of 4,615 MJ in the literature (Baird and Chan

1983).

The data required to do these calculations were obtained from the two major manufacturers in Colombo.

4.3.9. Slaked Lime

Slaked lime is widely used in building construction, as a binding material for plastering and for painting. Application of a mixture of lime with water in internal walls of a building would give a fine smooth surface and attractive appearance.

Raw material used for lime production is limestone which is a primitive. Slaked lime manufacturing is very popular in the Matale District and in coastal areas mainly due to availability of raw material. Limestone is extracted both from corals and from magnesium based dolomite as described in Section 4.2.4, where embedded energy in limestone extracted from corals is zero. To produce slaked lime from magnesium based dolomite, one needs more energy than slaked lime produced using corals. Therefore in these calculations a conservative approach is being used. It is assumed that slaked lime is produced using magnesium based dolomite as the raw material. To get 1 MT of slaked lime around 3.5 MT of limestone needs to be burnt.

Slaked lime is produced by burning limestone in kilns using firewood as fuel. Therefore the energy analysis of slaked lime consists of energy for burning and raw material transport and embedded energy.

These raw materials (i.e. limestone) are being transported from a distance of 1 to 6 km by tractors (1 cube per load), The fuel consumption of a tractor is 1 ltr. of diesel per 10 km.

Data required to perform the production energy calculations were obtained from batch data (i.e. by fuel wood used for each batch). To get 1 MT of slaked lime, one needs around 2500 kg of firewood for heating. According to the calculations the embedded energy of slaked lime lies in the range of 35,607-36,364 MJ/MT.

The data required to do these calculations were obtained from 3 manufacturers located in Palapathwella (in Matale district) and 2 located in Akurala. As described above, only data obtained from Palapathwella area (where magnesium based limestone is available) is used, in order to be conservative.

4.3.10. Aggregates and Quarry Dust

Aggregates (strictly coarse aggregates) are used as the major space filling inert material in concrete, whereas quarry dust is mainly used as a raw material for cement blocks.

Aggregates are obtained mainly from hard-rock quarries. Therefore boulders are the raw materials for aggregates. To get 1 m^3 of aggregates around 1.4 MT of boulders are required and to get 1 m^3 of quarry dust around 1.8 MT of boulders are required.

Energy analysis of aggregates and quarry dust production consists of processing energy and raw material transport and embedded energy.

These raw materials (i.e. boulders) are transported to the crushing plant by trucks from a distance of 1 to 9 km and around 2 cubes per load are transported. The fuel consumption of these trucks is around 1 ltr. of diesel per 4 km due to the poor conditions of the trucks and rugged roads being used.

The production of aggregates and quarry dust is done at the crushing plant. In Sri Lanka diesel generators are used for major metal crushing plants since they are located close to quarries in remote areas to avoid local nuisance such as noise, vibration etc.; hence main electricity lines are not available. Metal crushing plants are also carried out on a small scale using electricity, but sufficient data are not available for these calculations since only part of the owner's house hold electricity is being used for the crushing plant. To produce 1 MT of aggregates one needs around 0.67 l of diesel for the generator.

According to these calculations the embedded energy of aggregates lies in the range of 87-111 MJ/m^3, with 100-130 MJ/m^3 for quarry dust, compared to the range of 29-115 MJ/m^3 in the literature (Clough and Martyn 1995).

Though data were obtained from 4 manufacturers, only data from 2 places were used for the calculations due to the unreliability of the other data.

4.3.11. Asbestos Sheets

In Sri Lanka asbestos sheets are used mainly for roofing purposes. The sheets, typically of 5 mm thickness are light and easy to lay and have a much better thermal performance than either steel or aluminium sheets. On the other hand they are somewhat brittle, and thus liable to be damaged during and after laying.

Asbestos cement sheets are made from a mixture of cement and asbestos fibre. To produce 1 MT of asbestos sheets around 0.1 MT of fibre is required.

The energy analysis of asbestos cement sheets consists of embedded energy in its raw material (i.e., asbestos fibre and cement), transport of these raw materials to the factory and the energy for the production of sheets.

These asbestos fibres are imported from Zimbabwe, Canada, Brazil, Russia, South Africa etc. These fibres are transported from the harbour by 20' truck containers (16-18 tonnes per load) where fuel consumption is 1 ltr. of diesel per 3 km.. Cement is transported either from Puttalam or from the harbour by "1210" lorries (200 bags per load) where fuel consumption is 1 ltr. of diesel per 8 km.

The embedded energy of asbestos fibre is extracted from other published data (Baird and Chan 1983). To produce 1 MT of sheets one needs around 62 ltr. of diesel and 119 kWh of electricity. According to these calculations the embedded energy of asbestos sheets lies between 4,359-4,594 MJ/MT compared to 8200 MJ/MT (for IFIAS level 4 analysis) for asbestos-cement in the literature (Baird and Chan 1983).

These data for the production stage were obtained from the 2 major manufacturers in Sri Lanka.

4.3.12. Glass

The general trend in recent building has been to use glass much more than in the past, both in the form of larger windows and also for decorative purposes.

The major raw materials required for the production are sand, dolomite, feldspar, calcite, and soda which are locally available. Some of the minor materials are imported in negligible quantities.

The energy analysis of glass consists of the embedded energy in raw materials (which is neglected since mineral extraction is done using human energy), energy for the transport of these raw materials to the factory and the energy for the production of sheet glass.

Sand is being transported from Natandiya, dolamite and feldspar from Kandy, calcite from Matale and soda from the harbour (since imported). These raw materials are transported by "1210" lorries (10 tonnes per load) where fuel consumption is 1 ltr. of diesel per 8 km.

The basic raw materials for glass manufacture are melted in a furnace. After the melting, refining and forming, which depends on the final end use of the product, is carried out. In these calculations only embedded energy of sheet glass is calculated. Around 157 ltr. of heavy diesel and 18.13 kg of LPG are used in the kiln to produce 1 MT of glass where an additional 20% is included for sheet glass. Around 4 kWh is required for the conveyer for 1 MT of glass. In these calculations the density of sheet glass was taken as 2500-2560 kg/m^3. According to the calculations the total embedded energy of glass is around 8342 MJ/MT compared to the range of 13,900-22,100 MJ/MT in the literature (Baird and Chan

1983).

These data were obtained from only 1 manufacturer due to the lack of data.

4.3.13. Paint

Emulsion paint is used for interior masonry surfaces of both new buildings and maintenance coatings of old buildings, and it provides a matt finish. Enamel paint is used for interior and exterior surfaces of both metal and wood and gives a gloss finish.

Paints consist of the following ingredients namely, water and other solvents, pigments, binder and other additives. Depending on the type of paint and thus the chemical constituents, the energy requirement for manufacture can vary considerably.

The energy analysis of paint consists of embedded energy in raw materials, transport of these raw materials and the energy for the mixing.

Pigments are transported from the harbour (since they are imported) using 20' containers (20 tonnes per load) where fuel consumption is 1 ltr. of diesel per 4 km. The binder is transported from a distance of 11 km, using lorries (5 tonnes per load) where fuel consumption is 1 ltr. of diesel per 6 km. Transport energies of other materials are ignored (since they are negligible).

In Sri Lanka the basic paint making chemicals are imported. Only the less energy intensive stage of "mixing" is done in Sri Lanka. The mixing needs around 0.06 kWh per 1 ltr. of paint. The embedded energy of the raw material is extracted from other published data (Baird and Chan 1983). According to the calculations the embedded energy of paint lies in the range of 53-125 MJ/ltr., compared to the range of 20-150 MJ/ltr. indicated in the literature (Baird and Chan 1983).

These data were obtained from 3 major paint manufacturers in Sri Lanka.

4.3.14. PVC Products

These PVC products are mainly used in building construction for gutters and fittings, sewerage fittings, down pipes and fittings, conduit pipes and fittings etc.

The raw material used for the production of these PVC products is the PVC resin. It is assumed that to get 1 MT of PVC product, 1 MT of resin is being used.

The energy analysis of PVC products consists of embedded energy in raw materials, transport of these raw materials and the energy for the product fabrication stage.

PVC resin is transported from the harbour to the manufacturer (since it is imported) by 20' truck containers (16-18 tonnes per load), where fuel consumption is 1 ltr. of diesel per 8 km. The distance involved lies between 11-22 km.

The manufacture of polymer falls into four major steps,

(i) acquisition of feedstock

(ii) manufacture of the monomer and other inputs to polymerisation.

(iii) polymerization

(iv) product fabrication.

The monomer production and polymerisation process appear to be the more energy intensive processes. All the Sri Lankan manufacturers in the PVC industry only carry out the less energy intensive product fabrication stage. The embedded energy of the resin is extracted from other published data, i.e. a value of 92,000 MJ/MT was taken (Baird and Chan 1983). Around 634 kWh is required to produce 1 MT of PVC from the resin. Therefore according to these calculations the total embedded energy of PVC products lies in the range of 94,204-98,590 MJ/MT compared to the range of 81,000 -96,000 MJ/MT in the literature (Baird and Chan 1983).

The data required for this product fabrication stage were obtained from 3 major manufacturers in Sri Lanka.

4.3.15. Aluminium Extrusions

Aluminium extrusions are very commonly used in Sri Lanka for windows, partitions, curtain walls, ceilings etc., due to their easy maintenance and easy assembly.

In Sri Lanka the raw material used for the production of aluminium extrusion is aluminium billets. It is assumed that to get 1 MT of aluminium extrusions, 1 MT of aluminium billets is required.

Energy analysis of Aluminium extrusions consists of three components.
(i) The embedded energy in its raw material (i.e. in Aluminium billets)
(ii) Energy for the transport of this raw material to the factory (from the harbour)
(iii) Energy for the production of Aluminium extrusions

These billets are transported from the harbour (since imported) by open lorries (20 tonnes per load), where the fuel consumption is 1 ltr. of diesel per 8 km.

The embedded energy of these billets is extracted from other published data, i.e. a value of 129,500 MJ/MT (Baird and Chan 1983). Energy for the extrusion production stage was calculated using the data available for the number of electricity units being used for the monthly production. To produce 100 MT of aluminium extrusions one requires around 310,870 kWh. According to these calculations the total embedded energy of Aluminium extrusions is around 147,478 MJ/MT compared to the value of 145,000 MJ/MT in the literature (Baird and Chan 1983).

Energy data for the production of Aluminium extrusions was obtained from only 1 major manufacturer in Sri Lanka due to the lack of data.

4.3.16. GI Wire Mesh

In Sri Lanka GI wire mesh is used, among others, for precast slab construction.

Raw material used for the mesh is GI wires. It is assumed that the density of the 2"x2" mesh is 2.44 Kg/m^2.

The energy analysis of the GI wire mesh consists of the embedded energy in the raw material (GI wires), transport of these raw materials and energy for welding the mesh.

These GI wires are transported from the harbour (since they are imported), but the energy involved in this stage is ignored as it is negligible.

Production of the wire mesh consists of welding the mesh using imported GI wires. Energy embedded in GI wires is obtained from published data, i.e. a value of 35.5 MJ/kg (Baird and Chan 1983). The data for the energy calculations for welding of the mesh was obtained from electricity units used for the monthly production. To do the welding one requires around 29 kWh per 1 MT of GI wires. According to these calculations the total embedded energy is around 87 MJ/m^2 for a 2"x2" mesh compared to a value of 40 MJ/m^2 of 50 mm x 50 mm GI wire mesh reported in the literature (Baird and Chan 1983).

Energy for welding of the mesh stage was obtained from only 1 manufacturer due to the lack of data.

4.3.17. Concrete Manufactured on Site

Concrete can be used in construction by being manufactured and poured on site or as concrete that are manufactured off site and delivered to site for pouring. Concrete can be used for foundations, and structural or non structural superstructure elements of the final product.

The basic raw materials for concrete production are cement, aggregates and sand. For the concrete manufactured on site, the quantities of raw material required depend on the grade of concrete and are based on the BSR quantities.

The energy analysis of concrete consists of the embedded energy in its raw material, energy for the transport of these raw materials, the energy for the production of concrete (i.e. the mixing stage), and energy for the laying of the concrete.

Since BSR quantities are being used for the calculations, samples were not required. Therefore it is assumed that raw materials are being transported from both maximum distances (i.e. cement from Puttalam, sand from Alawwa and aggregates from Kalutara) and minimum distances (i.e. cement from the harbour, sand from Kelaniya and aggregates from Kahatuduwa) to Colombo City in order to find a range for the total embedded energy. It is assumed that cement is transported by "1210" lorries (200 bags per each load) and sand by ELF lorries (1.8 cubes per load), where fuel consumption in each case is 1 ltr. of diesel per 8 km, and aggregates by tractors (3 cubes per load) where fuel consumption is 1 ltr. of diesel per 3.25 km.

The machinery allowed for in this analysis is the concrete mixer and the vibrator. In these embedded energy calculations energy upto the laying of the concrete is included (i.e. energy for the vibrator). Generally for the mixer to produce 1 cube of concrete it needs around 2 ltr. of diesel, and the vibrator needs around 1 ltr. of kerosine to vibrate 1 cube of concrete. According to the calculations the total embedded energy is around 1558-1770 MJ/m^3 for 1:2:4 concrete manufactured on site, compared to a range of 1950-4434 MJ/m^3 in the literature (Baird and Chan 1983), whereas it is around 1179-1390 MJ/m^3 for 1:3:6

concrete, compared to the range of 1324-1840 MJ/m^3 in the literature (Baird and Chan 1983). Embedded energy of 1:1:2 concrete is around 2641 MJ/m^3.

4.3.18. Ready Mix Concrete

Ready mix (RMIX) concrete which is manufactured in a plant and transported to site is being used widely especially in the Colombo District.

The basic raw materials for concrete production are cement, aggregates and sand and admixtures in the case of RMIX concrete.

The energy analysis of ready mix concrete is made only upto the production stage. Therefore embedded energy consists of the embedded energy in its raw materials (here admixtures are ignored since only a small amount is used) transport of the raw materials and the energy involved in the production stage.

Cement is being transported from a distance of around 5 km to 17 km using 15 to 25 tonnes capacity bowsers (fuel consumption is 1 ltr. of diesel per 3.22 km). Sand is transported from a distance of 19 km to 85 km (3.8 cubes per load) and aggregates are transported from a distance of around 15 km to 18 km using trucks (3 cubes per load) where fuel consumption in both cases is 1 ltr. of diesel per 8 km. Transport of admixture is neglected since the amount used is negligible.

The data for the production stage were obtained from monthly electricity units being used and the production volumes. To produce 1 m^3 of concrete one needs around 2.43 kWh at the batching plant. According to the calculations the total embedded energy of ready mix concrete is around 1471-1764 MJ/m^3 for grade 25 concrete compared to a value of 3560 MJ/m^3 for IFIAS level 4 analysis in the literature (Baird and Chan 1983).

RMIX data for production energy calculations (i.e. plant data) were collected from 2 leading RMIX companies in Sri Lanka.

4.4. Elements

4.4.1. Brickwork

The material used in the construction of walls is important from the point of view of permanency and durability of housing units. Brickwork is one of the most widely used structural materials in Sri Lanka.

The raw material required to construct a brickwall are bricks, cement and sand. The quantities of these raw materials for different wall thicknesses are based on the BSR quantities. A 9" thick brick wall of 10 m^2, needs 1173 nos. bricks, 0.16 MT of cement and 0.59 m^3 of sand. A 4 1/2" thick brick wall of 10 m^2 needs 592 nos. bricks, 0.07 MT of cement and 0.3 m^3 of sand.

For the construction of the wall only human energy is involved and hence it is neglected. Therefore the embedded energy of the wall consists of embedded energy in its raw material used for the construction and the energy involved in transporting these raw materials to the site.

For the maximum transport distances, it is assumed that bricks are being transported from Kochchikade, cement from Puttalam and sand from Alawwa. For the minimum transport distances it is assumed that bricks are being transported from Kaduwela, cement from the harbour and sand from Kelani ganga.

It is assumed that, to transport Bricks (7,000-10,000 per load) and cement (200 bags per load) "1210" lorries are used. The fuel consumption of a "1210" lorry is around 1 ltr. of diesel per 8 km.

According to the above calculations the total embedded energy of a 9" thick brick wall lies in the range of 6,968-13,364 MJ/10m^2, whereas for a 4 1/2" thick wall this value lies between 3471-6698 MJ/10 m^2.

Since BSR quantities are being used for the calculations no samples are required.

4.4.2. Blockwork

Blockwork is also one of the most widely used structural materials in Sri Lanka. Blockwork is preferred due to low cost compared to other materials except brickwork, faster construction due to bigger size of blocks and better dimensional tolerances.

The raw materials required to construct a blockwall are blocks, cement and sand. The quantities of these raw materials for different wall thicknesses are based on the BSR quantities. A 4" thick block wall of 10 m^2 needs 120 nos. blocks, 0.02 MT cement and 0.09 m^3 of sand. 6" thick block wall of 10 m^2 needs 120 nos. blocks, 0.03 MT of cement and 0.14m^3 of sand. 8" thick block wall of 10 m^2 needs 120 nos. of blocks, 0.04 MT of cement and 0.18 m^3 of sand.

For the construction of the wall only human energy is involved and hence it is neglected. Therefore embedded energy of the wall consists of embedded energy in its raw material used for the construction and the energy involved in transporting these raw materials to the site.

For the maximum transport distances, it is assumed that cement is transported from Puttalam and sand from Alawwa. For the minimum transport distances it is assumed that cement is transported from the harbour and sand from Kelani Ganga. In both calculations it is assumed that blocks are being produced at the site itself or in Colombo where the transport component is negligible. It is assumed that cement is transported by "1210" lorries (200 bags per load) where fuel consumption is 1 ltr. of diesel per 8 km, and sand is transported by tractors (3/4 cubes per load) where fuel consumption is 1 ltr. of diesel per 10 km.

According to these calculations the total embedded energy of a 8" thick brick wall lies in the range of 910-994 MJ/10m^2. For a 6" wall this value lies between 841-918 MJ/10 m^2, and for a 4" thick wall it lies in the range of 519-597 MJ/10 m^2.

Since BSR quantities are being used for the calculations no samples are required.

4.4.3. Random Rubble Masonry

The main applications of random rubble masonry are in elements where aesthetic considerations govern, or in plinth walls of foundations, due to its superior durability in comparison to brickwork or blockwork.

The raw materials used for the construction of a rubble masonry wall are rubble, cement and sand. The quantities required are based on the BSR quantities. For 1 m^3 of random rubble masonry work, one needs 1.3 m^3 of rubble (boulders), 0.09 MT of cement and 0.3 m^3 of sand.

For the construction of the wall only human energy is involved and hence it is neglected. Therefore embedded energy of the wall consists of embedded energy in its raw material used for the construction and the energy involved in transporting these raw materials to the site.

For the maximum transport distances it is assumed that rubble (boulders) are transported from Kalutara, cement from Puttalam and sand from Alawwa. For the minimum transport distances it is assumed that boulders are transported from Kahatuduwa, cement from the harbour and sand from the Kelani Ganga. It is assumed that rubble is transported by trucks (2 cubes per load), where diesel consumption is 1 ltr. of diesel per 4 km; cement by "1210" lorries (200 bags per load) where fuel consumption is 1 ltr. of diesel per 8 km; and sand by tractors (3/4 cubes per load) where fuel consumption is 1 ltr. of diesel per 10 km.

According to these calculations the total embedded energy of 1 m^3 of random rubble masonry lies in the range of 618-806 MJ/m^3.

Since BSR quantities are being used for the calculations no samples are required.

4.4.4. Plastering

Plastering is the process of applying a soft mixture of lime, cement and sand for coating walls. The mixture used can change according to the type of surface finish required (rough or smooth), exposure conditions (interior or exterior walls), type of structure (e.g. walls above or below ground level, water tanks, etc.). A 15 mm thick 1 cement : 1 lime : 5 sand plaster is used for exposed faces of exterior walls. A 15 mm thick 1 cement : 1 lime : 5 sand plaster with setting coat of lime putty is applied for interior faces of exterior walls and faces of interior walls. A 15 mm thick 1 cement : 3 sand plaster with a setting coat of neat cement slurry is applied for exposed faces of a plinth wall below the DPC level.

The raw material quantities used are different for different mixtures. These quantities are based on the BSR quantities. A 15 mm thick 1 cement : 1 lime : 5 sand plaster needs 0.04 MT of cement, 0.02 MT of slaked lime and 0.21 m^3 of sand. A 15 mm thick 1 cement : 1 lime : 5 sand plaster with setting coat of lime putty needs 0.04 MT of cement, 0.03 MT of slaked lime, and 0.21 m^3 of sand. A 15 mm thick 1 cement : 3 sand plaster with a setting coat of neat cement slurry needs 0.06 MT of cement and 0.15 m^3 of sand.

The embedded energy in plaster comes from two stages i.e. transport of the raw material and plastering of the wall. For the plastering itself only human energy is involved which is neglected. Therefore embedded energy of the wall plastering consists of embedded energy in its raw material used for the plastering and the energy involved in transporting these raw materials to the site.

For the maximum transport distances it is assumed that cement is being transported from Puttalam, sand from Alawwa and slaked lime from Matale. For the minimum transport distances it is assumed that cement is being transported from the harbour, sand from the Kelani Ganga and slaked lime from Akurala. It is assumed that cement is transported by

"1210" lorries (200 bags per load), where fuel consumption is 1 ltr. of diesel per 8 km; sand by tractors (3/4 cubes per load), where fuel consumption is 1 ltr. of diesel per 10 km; and slaked lime by lorries (4 MT per load), where fuel consumption is 1 ltr. of diesel per 8 km.

According to these calculations the total embedded energy of 15 mm thick 1 cement : 1 lime : 5 sand plaster is 912-976 $MJ/10m^2$. For 15 mm thick 1 cement : 1 lime : 5 sand plaster with setting coat of lime putty it is 1271-1343 $MJ/10m^2$ and for a 15 mm thick 1 cement : 3 sand plaster with a setting coat of neat cement slurry it is around 501-543 $MJ/10m^2$.

Since BSR quantities are being used for the calculations no samples are required.

4.4.5. Painting

Painting is done on interior masonry surfaces of new buildings, while maintenance coatings are applied on old buildings. It is also applied on interior and exterior surfaces of both metal and wood.

According to the BSR quantities for painting in walls, to apply one coat of alkali resistant primer and two coats of emulsion paint to 10 m^2 of a wall one needs 0.97 ltr. primer and 1.5 ltr. of emulsion paint. Painting of 10 m^2 wood work with primer and 2 coats enamel paint requires 0.8 ltr. primer, and 2.7 ltr. of enamel paint.

For the painting of the wall only human energy is involved and is hence neglected. Therefore embedded energy of the wall painting consists of embedded energy in its raw material used for the painting and the energy involved in transporting these raw materials to the site.

The transport energy of the raw materials is neglected because they are negligible.

According to these calculations the total embedded energy of paint on a wall is 202 MJ/10 m^2 , and paint on wood is 438 MJ/10 m^2.

Since BSR quantities are being used for the calculations no samples are required.

4.4.6. Prestressed Concrete Purlins

Prestressing is the technique of introducing compressive stress in the concrete before it is subjected to load. The introduction of prestress has to a large extent removed the disadvantages which a conventional reinforced concrete element has, when comparing it with a similar steel element. Two sizes of frequently used purlins are included in the database,

(i) with 3 m span and cross-section of 60mm x 120 mm (with 3 Nos. 6 mm diameter high tensile wires) which can carry a udl of 1 kN/m,

(ii) with 3.5 m span and cross-section of 60 mm x 160 mm (with 5 Nos. 6 mm diameter high tensile wires) which can carry a udl of 1.18 kN/m.

The raw materials used for prestressed concrete purlins are steel and grade 40 concrete.

The energy analysis of prestressed concrete units consists of

(i) Raw material embedded energy (i.e. embedded energy in steel, cement, aggregates and sand)

(ii) Raw material transport energy

(iii) Production energy- Energy for wire drawing (tensioning), concreting, vibrating and for the lifting and placement of the prestressed components.

Cement is transported from the harbour, 200 bags per truck. Sand is transported from Alawwa, 1.8 cubes per ELF truck load. Aggregates are transported around 4.5 miles from Piliyandala. Steel is transported from the harbour or from Athurugiriya (10 tonnes per load). The fuel consumption of each vehicle used is 1 ltr. of diesel per 8 km .

When a beam is prestressed (i.e. stressed before the working loads are applied) generally the whole section is put into compression. This compressive force is obtained by tensioned wires within the beam which are bonded to the concrete throughout the length of the beam. According to the calculations the embedded energy of a 3 m span purlin is 120 MJ, while it is 236 MJ for a purlin of 3.5 m span.

The data required to do these calculations were obtained from three manufacturers.

4.4.7. Formwork

The economical design and construction of formwork is of great importance since its cost may be one-third, or even more, of the whole concrete element. The formwork should be sufficiently rigid and tied to prevent loss of grout or motar from the concrete and should take due account of the method of placing and compacting.

For 1 m^2 of column, beam and slab formwork one needs 0.03 m^3, 0.027 m^3 and 0.028 m^3 of planks-formwork respectively. It is assumed that all forms are used twice in BOQ calculations.

The energy analysis of formwork consists of embedded energy in planks-formwork, transport of these raw material to the site which is negligible and the energy for the construction of forms.

According to these calculations the embedded energy of columns, beams and slab formwork are 50 MJ/m^2, 45 MJ/m^2 and 47 MJ/m^2 respectively.

4.5. Customised Elements

These items are not in the database, as their raw material input quantities will depend on the type and size of element. They are described briefly here qualitatively. Most of them are also dealt with in Chapter 7, where alternative forms of construction are compared. At that stage, quantitative analyses are performed.

4.5.1. Concrete Elements

Most of the load bearing elements in a building e.g. slabs, beams and columns are made out of reinforced concrete.

The raw materials required to construct a concrete element are concrete, steel (reinforcements) and formwork (rough timber). The raw material quantities required vary according to the type of structure (i.e. columns, slabs, beams etc.).

For the construction of the element only human energy is involved and this is neglected (since energy involved in concrete production and in the laying is embedded in concrete). Therefore embedded energy of the element consists of embedded energy in its raw material used for the construction and the energy involved in transporting these raw materials to the site.

It is assumed that concrete is manufactured on site and the transport energy for formwork and steel (reinforcements) are neglected. Therefore the transport energy component is zero.

4.5.2. Calicut Tile Roofing

One of the most predominant types of roofing material used in buildings is calicut tiles. It is mainly due to lower price, aesthetic reasons and comfort.

The raw materials required to construct a roof are calicut tiles and treated timber. The raw material quantities required vary according to the span of the roof.

For the construction of the roof only human energy is involved and this is neglected. Therefore embedded energy of the roof consists of embedded energy in its raw material used for the construction and the energy involved in transporting these raw materials to the site.

For the maximum transport distances it is assumed that calicut tiles are being transported from Waikkala and Dankotuwa and for the minimum transport distances it is assumed that they are transported from Hanwella. Transport energy of treated timber is neglected as it is considered to be within the Colombo District. It is assumed that calicut tiles are transported by ELF lorries (2000 per load) where fuel consumption is 1 ltr. of diesel per 8 km.

4.5.3. Asbestos Roofing

Another predominant type of roofing material used in construction is asbestos sheets. The increasing popularity of this sheet roofing is not the result of improved appearance or user preference, but rather one of practical necessity. A growing scarcity of structural grade timber and its high price has forced industry to economise on timber by reducing the size and number of structural members and to simplify roof design.

The raw materials required to construct a roof are asbestos sheets and treated timber. The raw material quantities required vary according to the span of the roof.

For the construction of the roof only human energy is involved and this is neglected. Therefore embedded energy of the roof consists of embedded energy in its raw material used for the construction and the energy involved in transporting these raw materials to the site.

For the maximum transport distances it is assumed that asbestos sheets are being transported from Ekala and for the minimum transport distances it is assumed that they are transported from Ratmalana. Transport energy of treated timber is neglected as transport is considered to be within the Colombo District. It is assumed that asbestos sheets are transported by open lorries (10 MT per load), where fuel consumption is 1 ltr. of diesel per 8 km.

4.5.4. Doors

A door is a movable barrier to an opening in a building. Doors may be hung to swing, or made to slide, to fold or to revolve. A door consists of three main elements, i.e. door frame, door shutter and the ironmongery.

The raw material used for a door can be treated timber (planks and purlins) or plywood, and the material used for ironmongery. The raw material required varies according to the size and type of door.

For the making and fixing of the door only human energy is involved and this is neglected. Therefore embedded energy of the door consists of embedded energy in its raw material used (here the embedded energy of ironmongery is ignored since it is negligible) and the energy involved in transporting these raw materials to the site.

The transport energy components of these raw materials are neglected as transport is considered to be within the Colombo District.

4.5.5. *Windows*

A window is an opening designed primarily to let air and light into a building. A window consists of three main elements, i.e. window frame, window shutter and the ironmongery.

The raw material used for a window can be treated timber (planks and purlins) or Aluminium extrusions, glass and the material used for ironmongery. The raw material required varies according to the size and type of window.

For the making and fixing of the window (using its raw material) only human energy is involved and this is neglected. Therefore embedded energy of the window consists of embedded energy in its raw material used (here the embedded energy of ironmongery is ignored since it is negligible) and the energy involved in transporting these raw materials to the site.

The transport energy components of these raw materials are neglected as transport is considered to be within the Colombo District.

Table 4.1 - Factors Used for Carbon Coefficient Calculations in The Database

Energy Source	CO_2 Emission Rate (kgC/MJ)	Reference
Fossil Fuel	20.3/1000	Turbott et al. 1991
Biomass (actual) Biomass (effective)	15/1000 0*	Turbott et al. 1991 Honey and Buchanan 1992
Electricity (based on 34% thermal)	18.36/1000	Turbott et al. 1991
Imports	0.02	Honey and Buchanan 1992

* - Value adopted

Table 4.2 - Comparison of Energy Contents of Building Items with Previously Published Estimates

Items	Number of Samples	Qtty	Total Energy(MJ)			Other Researchers	
			Min.	Avg.	Max.	Values (MJ)	Reference
Aggregates	2(4)	1 m^3	87	99	111	28.78-115.12	Clough & Martyn 1995
Asbestos Sheets	2	1 MT	4,359	4,476	4,594		
Asbestos-Cement						8,130	Baird & Chan 1983
Blocks 4"x8"x16"	2	1000 Nos	3,571	3,855	4,140		
Blocks 6"x8"x16"			5,879	6,136	6,397	4,615	Baird & Chan 1983
Blocks 8"x8"16"			6,070	6,341	6,612		
Bricks	5	1000 Nos	5,307	8,576	10,605	9,300-10,000	Baird & Chan 1983
Cement	1	1 MT	4,282	4,282	4,282	3,400-6,100	Clough & Martyn 1995
Concrete (1:2:4)	(BSR)	1 m^3	1,558	1,664	1,770	1,766-4,434	Baird & Chan 1983
Concrete(1:3:6)	(BSR)	1 m^3	1,179	1,284	1,390	1,324-1,840	Baird & Chan 1983
Glass	1	1 MT	8,342	8,342	8,342	13,900-22,100	Baird & Chan 1983
Paints-Emulsion	3	1 l	53	54	54	20-150	Baird & Chan 1983
Paints-Primer	3	1 l	124	125	125		
Timber rough Purlins	7	1 m^3	1,191	1,402	2,026	714	Baird & Chan 1983
Timber rough Planks	3	1 m^3	1,292	1,696	1,995		
PVC	3	1 MT	94,204	95,685	98,590	81,000-96,000	Baird & Chan 1983
Steel	1	1 MT	32,686	32,686	32,686	30,000-50,000	Spence & Cook 1983
Al extrusions	1	1 MT	147,478	147,478	147,478	145,000	Baird & Chan 1983
Plywood	1	m^3	12,090	12,090	12,090	9,500	Baird & Chan 1983
Brickwork 41/2"	(BSR)	10 m^2	3,471	5,452	6,698	10,000-11,920	Baird & Chan 1983
Brickwork 9"	(BSR)	10 m^2	6,968	10,893	13,364		
Slaked lime	5	1 MT	35,607	36,038	36,364	3,000-5,000	Spence & Cook 1983
Soil(Clay)	5	1 m^3	1	4	11	0-100	Spence & Cook 1983
AirdryTrea.Tim -Purlins	(BSR)	1 m^3	1,211	1,429	2,059	2,370-3,714	Baird & Chan 1983
AirdryTrea.Tim -Planks	(BSR)	1 m^3	1,312	1,722	2,028		

Table 4.3 - Comparison of Carbon Coefficients of Building Items with Previously Published Estimates

Item	Number of Samples	Qtty	Carbon Coefficient	Other Researchers Quoted by Baird & Chan (1983)	
			Net value (kgC/Qty)	Range(MJ)	IFIAS Level
Aggregates	2(4)	1 m^3	2.00	5.45	4
Asbestos Sheets	2	1 MT	189.90		
Asbestos-Cement				160.00	4
Cement	1	1 MT	227.75	311.04	4
Concrete (1:2:4)	(BSR)	1 m^3	78.85	118.11	4
Concrete(1:3:6)	(BSR)	1 m^3	58.46		
Glass	1	1 MT	166.05	610.00	4
Paints-Emulsion	3	1 l	1.07	0.19-0.23	4
Paints-Primer	3	1 l	2.49		
Timber rough Purlins	7	1 m^3	-280.77	-234.41	4
Timber rough Planks	3	1 m^3	-258.31		
PVC	3	1 MT	1907.69	1680.00	2
Steel	1	1 MT	652.81	610.00	4
Al extrusions	1	1 MT	3050.00	2530.00	2
Plywood	1	m^3	-347.28	-72.67	4
Soil(Clay)	5	1 m^3	0.09	3.83	2
AirdryTreated -Purlins	(BSR)	1 m^3	-280.27	-228.00	4
Airdry Treated -Planks	(BSR)	1 m^3	-257.81		

5. DATABASE DESIGN

5.1. Introduction

As outlined in Section 2.4, in order that designers and those involved in building construction become aware of the energy related consequence of their designs, an accurate database has to be developed to store all the energy related data of building materials and elements and to retrieve data when needed. Baird and Chan (1983) recommended the setting up of such a database in a readily accessible form as an extension of their study. The database design carried out in this study is described in this chapter.

In order to computerise this database of energy inputs and carbon emissions, two major requirements need to be fulfilled. First it must be possible for the common scheme to be applied to all materials at any level (in the hierarchical structure defined in Chapter 3), and also for user defined materials to be added. Although the scheme would be common, the list length of component raw materials would be different from one material to another. Hence, computer implementation must support list processing.

The second requirement, where the materials are concerned, is that the list entries would not merely be "text" type entries. The entry would not merely be a description, but would also be a material in its own right. This suggests that an object oriented implementation would be required.

Since the figures of the various energy values in many cases would be average values obtained from a number of establishments, the database must be capable of storing the original primary data, and also calculating the summary statistics, of which the mean (and, as described later the minimum and maximum values as well) would be used in the energy computations. The ability to create many instances of a class object in the object oriented paradigm once again makes it suitable for adoption in the computerisation of this database.

5.2. Design of the Database

The database was implemented using a relational database management system (RDBMS), i.e. Microsoft Access, to satisfy the above requirements. The data required for the various embedded energy and carbon coefficient calculations, i.e. in terms of the different fuel types on the one hand and process stages on the other hand (as discussed in Chapter 3) were obtained as described in Chapter 4.

5.2.1. Structure of The Database

There are three tables used to structure the database namely, (i) data table; (ii) samples table; and (iii) relations table.

The data table is used to define the items (i.e., primitives, materials and elements) in the database. The structure of the table is shown in Table 5.1 and part of the table actually used in the database is shown as Table 5.2. Here the items are defined with (i) a serial code to identify the items, (ii) a BOQ code (used to export data to a spread sheet - discussed in Section 5.3), (iii) description of item, (iv) quantity description (i.e. the standard unit of the item), (v) price of a unit quantity in SL Rupees, (vi) an indication as to whether the material is a primitive or not and (vii) type of material (i.e. whether cement, aluminium, wood or other), used for the calculation of process related carbon "lock up" or release (described later in Section 5.2.2. and 5.2.3).

Since energy data of the materials were available from several sources (or samples), there was a need to capture this information. Each item can have data from many sources (i.e. from a number of manufacturers). These are defined in the samples table. The structure of the table is shown in Table 5.3 and part of the table actually used in the database is shown as Table 5.4. Here samples are related to the data table by the item code, where each item can have several samples. This samples table consists of a sample number and description with all its relevant data such as,

(i) Energy for the production stage with respect to different fuel types (PEBiomass, PEFossilFuel, PEElectricity), together with the total production energy (TotProduction).

(ii) Energy for the transport in terms of different fuel types (TEBiomass,TEFossilFuel, TEElectricity), together with average total transport energy (TotTransport).

(iii) Average, minimum and maximum embedded energies of the sample raw materials in terms of different fuel types (EEBiomass,EEMinBiomass,EEMaxBiomass, EEFossilFuel, EEMinFossilFuel, EEMaxFossilfuel, EEElectricity, EEMinElectricity, EEMaxElectricity, EEOther, EEMinOther, EEMaxOther), together with average, minimum and maximum total embedded energies of its raw material (TotEmbedded, MinTotEmbedded, MaxTotEmbedded).

(iv) Average, minimum and maximum energy totals of different fuels (TBiomass, TMinBiomass, TMaxBiomass, TFossilfuel, TMinFossilfuel, TMaxFossilfuel, TEElectricity, TMinElectricity, TMaxElectricity, TOther, TMinOther, TMaxOther).

(v) Average, maximum & minimum total energies (TotalEnergy, MaxTotalEnergy, MinTotalEnergy).

(vi) Whether an additional carbon calculation has to be performed for process related "lock up" or release.

In the above definitions "other" is used to define imports, and "Analysis" is used to indicate the type of analysis (i.e. whether calculations are based on energy or other considerations - e.g. price).

The components that make up a given sample (for example blocks, cement and sand in the case of blockwork) are defined in the relations table. The structure of the table is shown in Table 5.5 and part of the actual table used in the database is shown as Table 5.6. Here the relations table is related to the samples table by (i) a sample (serial) number, (ii) quantities of its raw materials that are required and (iii) transport energy for a standard unit of those raw materials in terms of different fuels (TEBiomass, TEFossilfuel, TEElectricity). Different quantities of raw materials may be needed by different manufacturers, and indeed even different types of raw materials; such variations can be accommodated in this scheme.

There are one to many relationships between the data and samples tables and also between the samples and relations table (see Figure 5.1). The advantage of this structure is that one item can accommodate a multiple number of samples. One disadvantage is that the relations have to be defined for each sample. This "disadvantage" however does allow the flexibility of defining different relations for different samples, although the need for that may be infrequent.

Another feature of this structure is that the calculated values will not strictly represent a particular manufacturer. For example, even though a certain manufacturer of bricks obtains clay with a particular value of embedded energy, the embedded energy of clay used for the calculation of the embedded energy of his bricks will be an average value for the embedded energy of clay and not his particular value (see Figure 5.2). The database calculations are also performed based on maximum and minimum values of embedded energy, which are also combined with the maximum and minimum transport energies as well. In this way the ranges obtained for embedded energies are likely to include most of the possibilities. This means that the ranges for items higher up in hierarchies will be wider.

5.2.2. Data entry

Screen forms are used to customise the way in which the data from records in tables or queries are displayed on the screen. Queries are used to view, change, and analyse data in different ways. Their main purpose is to provide a user-friendly interface for the entry of new records or for editing existing records. Three form layouts were used to enter data into the tables, namely (i) data form; (ii) primitives form; and (iii) samples form.

The data form is used to enter the initial (basic) descriptions of all the data items (i.e. primitives, materials or elements) excluding energy related data (see Figure 5.3). This allows the user to define the items as primitives or non primitives and the type of material (i.e. whether a wood product, cement, aluminium, imports or other). The type of material classification is used for the carbon coefficient calculations which will be discussed further in Section 5.2.3. The data form also allows the user to define the quantity description and the price, together with a code (i.e. BOQ Code) to export data to a spread sheet, in order to synthesise data. This will be discussed later under Section 5.3.

The primitives form is used to enter data for primitives (see Figure 5.4). Here the primitives are defined as the raw materials which cannot be decomposed further, and have only production energy (with no embedded or transport energy of raw materials). Therefore they will have only a total energy component in terms of different fuel types (TBiomass, TFossilfuel and TElectricity). For convenience, imports are also defined as primitives.

Finally the samples data form is used to enter data for samples (see Figure 5.5). This allows the user to enter the components (sub items) of the sample and production energy in terms of different fuel types (PEBiomass, PEFossilfuelDir, PEElectricity). This form also allows the user to enter transport energy per unit quantity of each sub item together with the quantities of the sub items required. In this example given (i.e. in Figure 5.4), to get 1 m^3 of ready mix concrete one needs, among other sub items, 0.3 MT of cement with a transport energy component of 15.13 MJ (fossil fuel) per 1 MT of cement.

5.2.3. Calculations

Queries were used to perform simple summary type calculations, i.e. to summarise all sample data into average, minimum and maximum values (e.g. Table 5.7). The calculations were done by the implementation of a recursive algorithm, which stops when it reaches the basic raw materials (i.e. primitives). This was developed using Visual Basic. The recursive algorithm used for energy calculations is depicted in Figure 5.6. Once a data entry (i.e. data from several sources for a particular item) is done, the average, maximum and minimum energies of that item are calculated. If the item is a primitive the calculations are stopped and the final result is given as the total embedded energy. If the item is not a primitive a recursive calculation is performed. It will calculate each sub item of that item (for example in the case of brickwork, the sub items are bricks, cement and sand), and again if a sub item is a primitive (e.g. sand), it will stop the calculations and will give the final result, and if it is not a primitive (say bricks), it will again search for its sub items (i.e. clay). This process continues until all the sub items are primitives, and finally results in the aggregation of the average, minimum and maximum total embedded energies of the initial item.

For carbon coefficient calculations the average energy values entered will be multiplied by factors given in Table 4.1. These values were derived according to information given in Chapter 3. These calculations were performed using a query. In addition to these fuel consumption based calculations for carbon coefficients, an additional amount is added or deducted for certain types of materials (as discussed in Chapters 2 and 3), accounting for locking up or releasing of carbon directly by the production process. The same recursive algorithm (used for energy calculations) is adopted to find the carbon coefficients of non primitive materials.

5.2.4. Outputs

Reports were used to show summary information relating to the data. These reports summarise the embedded energy of each item for a defined quantity in terms of,

(i) different fuel types, i.e. biomass, fossil fuel, electricity and imports (see Table 5.8), and

(ii) process, i.e. production, transport of raw material and the energy embedded in raw materials (see Table 5.9).

In both reports these different energy categories are shown as minimum, average and maximum valus, and the total minimum, average and maximum embedded energies of each item are given in the last column.

They also give the carbon coefficients (see Table 5.10), consisting of the carbon emissions from (i) all the fuels, i.e. biomass, fossil fuel, electricity, (ii) imports and (iii) particular carbon liberations or locking up, i.e. from "material". Finally, the net value of each item for a defined quantity is given.

5.3. Use of the Database

The relational database developed using a recursive algorithm can be used to represent the embedded energies and carbon coefficients of building materials and elements that are hierarchically arranged, such that some materials are raw materials of others. It can also handle multiple sources of data and perform the calculations to give the energies corresponding to average, maximum or minimum values.

The database outputs can be exported to a spreadsheet that contains the bill of quantities (BOQ) of a building. In this way, the variations in energy for alternative types of building material types (e.g. use of a blockwall instead of a brickwall) can also be studied. This is further discussed in Chapter 7. The embedded energy of an entire building can be computed using the complete BOQ. This is discussed further in Chapter 8, where this embedded energy is also compared with operational energy.

The data in the database can also be used for other energy related analyses such as energy quality and energy price studies. These are described in Chapter 6.

As discussed in Chapter 4, it is assumed that the final building is located in Colombo City for the purpose of determining transport energies. However, as seen in Table 5.11, the contribution from transport is low except in the cases of quarry products (i.e. aggregates, Random rubble, quarry dust,) timber products, cement blocks and concrete where the contributions are from 10-20%. Hence, it should be possible, with some care, to use the embedded energy coefficients in this database for construction even outside of the Colombo City and District, as the transport energy components appear to be small.

Table 5.1 - Data Table Structure

Field Name	Data Type	
Code	AutoNumber	Code No of Item
BoqCode	Text	BoQ Code No
Description	Text	Description of Item
QtyDescription	Text	Qty e.g. 10m^2
Primitive	Yes/No	
Price	Number	Unit Price
Type	Text	Type of Material

Table 5.2 - Part of the Data Table Actually Used

Code	BoqCode	Description	QtyDescripti	Primitive	Price	Type
1	1Cl	Clay	1 m^3	Yes		Other
2	1Li	Limestone	1 MT	Yes		Other
3	2Sa	Sand	1 m^3	Yes	420	Other
4	2Ce	Cement	1 MT	No	6400	Cement
5	2Br	Bricks	1000 Nos	No	1400	Other
7	3Br9	Brickwork	10m^2	No	4678	Cement
8	1Lo	Logs	1 m^3	Yes		Wood Product
9	2Pu,R	Purlins-	1 m^3	No	30000	Wood Product
10	2Pl,R	Planks-	1 m^3	No	200	Wood Product

Table 5.3 - Sample Table Structure

Field Name	Data Type	
SampleNo	AutoNumber	Sample No
SampleDescription	Text	Sample Description
Code	Number	Code No of Item
TotalEnergy	Number	Total Energy
PEBiomass	Number	Production Biomass
PEFossilFuelIn	Number	Production FossilFuel InDirect
PEFossilFuelDir	Number	Production FossilFuel Direct
PEElectricity	Number	Production Electricity
TotProduction	Number	Total Production
TEBiomass	Number	Transport Biomass
TEFossilFuel	Number	Transport Fossil Fuel
TEElectricity	Number	Transport Electricity
TotTransport	Number	Avg Total Transport
EEBiomass	Number	Avg Embedded Biomass
EEFossilFuel	Number	Avg Ebbedded Fossil Fuel
EEElectricity	Number	Avg Embedded Electricity
EEOther	Number	Avg Embedded Other
TotEmbedded	Number	Avg Total Embedded
Analysis	Number	Whether Data is based on Energy
TBiomass	Number	Avg Total Biomass
TFossilfuel	Number	Avg Total FossilFuel
TElectricity	Number	Avg Total Electricity
TOther	Number	Avg Total Other
Calculated	Yes/No	Calculated Yes/No
TMinBiomass	Number	Total Min Biomass
TMinFossilfuel	Number	Total Min Fossilfuel
TMinElectricity	Number	Total Min Electricity
TMinOther	Number	Total Min Other
TMaxBiomass	Number	Total Max Biomass
TMaxFossilFuel	Number	Total Max FossilFuel
TMaxElectricity	Number	Total Max Electricity
TMaxOther	Number	Total Max Other
EEMinBiomass	Number	Min Embedded Energy Biomass
EEMinFossilFuel	Number	Min Embedded Energy Fossil Fuel
EEMinElectricity	Number	Min Embedded Energy Electricity
EEMinOther	Number	Min Embedded Energy Other
EEMaxBiomass	Number	Max Embedded Energy Bimass
EEMaxFossilFuel	Number	Max Embedded Energy Fossil Fuel
EEMaxElectricity	Number	Max Embedded Energy Electricity
EEMaxOther	Number	Max Embedded Energy Other
MinTotEmbedded	Number	Min Total Embedded
MinTotalEnergy	Number	Min Total Energy
MaxTotEmbedded	Number	Max Total Embedded
MaxTotalEnergy	Number	Max Total Energy
AdditionalCarbon	Number	Additional Carbon

Table 5.4 - Part of the Sample Table Actually Used

Sam	SampleD	Code	TotalE	PEBio	PEFos	PEElect	TotProd	TEBiom
2	Clay2	Clay	3.48	0	0	0	0	0
3	Clay3	Clay	3.86	0	0	0	0	0
4	Clay4	Clay	10.86	0	0	0	0	0
5	Clay5	Clay	1.45	0	0	0	0	0
6	Limeston	Lime	34	0	0	0	0	0
7	Sand1	Sand	0	0	0	0	0	0
8	Puttlam	Cem	4281.7	0	0	601.12	4194.82	0
9	Bricks1	Brick	8801.7	8774.84	0	0	8774.84	0
10	Bricks2	Brick	9503.1	9449.5	0	0	9449.5	0
11	Bricks3	Brick	10564.	10524.3	0	0	10524.3	0
12	Bricks4	Brick	9811.6	9740.48	0	0	9740.48	0
13	Bricks5	Brick	8355.1	8307.22	0	0	8307.22	0
14	Bricks6	Brick	9110.3	9062.43	0	0	9062.43	0
15	Bricks7	Brick	7127.9	7080.02	0	0	7080.02	0

Table 5.5 - Relations Table Structure

Field Name	Data Type	
SampleNo	Number	Sample No in Sample Table
SubCode	Number	Sub Code of Item in Data Table
Amount	Number	Amount Needed
TEBiomass	Number	Transport Biomas Component
TEFossilFuel	Number	Transport Fossil Fuel Component
TEElectricity	Number	Transport Electricity Component
Analysis	Number	Type of Analysis

Table 5.6 - Part of the Relations Table Actually Used

SampleNo	SubItemCod	Amount	TEBiomas	TEFossilFu	TEElectric
Blocks1 4"x8"x16"	Cement	0.69	0	120.93	0
Blocks1 4"x8"x16"	Sand	4.92	0	131.13	0
Blocks1 4"x8"x16"	Quarry Dust	1.42	0	32.48	0

Table 5.7 - Part of an Average Data Query Output Used

Code	Analysis	FirstOfDescripti	FirstOfQtyDe	AvgOfTotal	AvgOfPEBio	AvgOfPEFossil
1	0	Clay	1 m^3	4.37	0.00	0
2	0	Limestone	1 MT	34.00	0.00	0
3	0	Sand	1 m^3	0.00	0.00	0
4	0	Cement	1 MT	4281.77	0.00	0
5	0	Bricks	1000 Nos	8576.14	8528.17	0
7	0	Brickwork (9")	10m^2	10893.42	0.00	0
8	0	Logs	1 m^3	165.73	0.00	0

Table 5.8 - Energy Breakdown By Fuel Type (MJ/Qty)

Description	Qty	Biomass			Fossil Fuel			Electricity			Imported			Total Energy		
		Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
Aggregates	1 m^3	0	0	0	86.71	98.73	110.75	0.00	0.00	0.00	0	0	0	87	99	111
Air-drytr.TimbPurlin	1 m^3	0	0	0	244.06	331.70	396.50	966.48	1097.05	1662.46	0	0	0	1211	1429	2059
Air-dryTr.TimPlank	1 m^3	0	0	0	236.46	296.88	342.64	1075.24	1425.23	1684.92	0	0	0	1312	1722	2028
Al-Billets	1 MT	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	129500	129500	129500	129500	129500	129500
Aluminium Extrusio	1 MT	0	0	0	9.23	9.23	9.23	17968.28	17968.28	17968.28	129500	129500	129500	147478	147478	147478
Asbestos fibre	I MT	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	15680	15680	15680	15680	15680	15680
Asbestos Sheets	1 MT	0	0	0	2270.63	2297.62	2324.68	677.07	689.14	701.20	1411	1490	1568	4359	4476	4594
Beam Formwork	1 m^2	0	0	0	7.72	7.72	7.72	37.35	37.35	37.35	0	0	0	45	45	45
Blocks(4"x8"x16")	1000 Nos	0	0	0	2941.94	3220.15	3498.42	628.63	634.99	641.35	0	0	0	3571	3855	4140
Blocks(6"x8"x16")	1000 Nos	0	0	0	4902.43	5160.40	5418.48	976.82	977.78	978.75	0	0	0	5879	6138	6397
Blocks(8"x8"x16")	1000 Nos	0	0	0	4902.36	5160.37	5418.48	1167.56	1180.57	1193.57	0	0	0	6070	6341	6612
Blockwork 4"	10 m^2	0	0	0	431.59	469.69	507.81	87.46	88.22	88.98	0	0	0	519	558	597
Blockwork 6"	10 m^2	0	0	0	706.13	744.21	782.30	135.25	135.37	135.48	0	0	0	841	880	918
Blockwork 8"	10 m^2	0	0	0	745.42	785.84	826.27	164.15	165.71	167.27	0	0	0	910	952	994
Boulders	1 MT	0	0	0	34.36	37.72	41.07	0.00	0.00	0.00	0	0	0	34	38	41
Bricks	1000 Nos	5286	8528	10524	20.75	47.97	80.34	0.00	0.00	0.00	0	0	0	5307	8576	10605
Brickwork (9")	10m^2	6201	10004	12345	670.95	793.71	922.52	96.18	96.18	96.18	0	0	0	6968	10893	13364
Brickwork(41/2")	10 m^2	3130	5049	6230	299.28	361.02	425.82	42.08	42.08	42.08	0	0	0	3471	5452	6698
Calicut tiles	1000 Nos	19792	24817	32366	267.47	402.89	525.83	215.50	356.60	492.58	0	0	0	20274	25576	33384
Cement	1 MT	0	0	0	3680.56	3680.65	3680.84	601.12	601.12	601.12	0	0	0	4282	4282	4282

Table 5.8 (Cont.)

Description	Qty	Biomass			Fossil Fuel			Electricity			Imported			Total Energy		
		Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
Clay	1 m^3	0	0	0	1.45	4.37	10.86	0.00	0.00	0.00	0	0	0	1	4	11
Column Formwork	1 m^2	0	0	0	8.57	8.57	8.57	41.50	41.50	41.50	0	0	0	50	50	50
Concrete(1:1:2)	1 m^3	0	0	0	2192.08	2310.16	2428.29	330.62	330.62	330.62	0	0	0	2523	2641	2759
Concrete(1:2:4)	1 m^3	0	0	0	1365.64	1471.84	1578.07	192.36	192.36	192.36	0	0	0	1558	1664	1770
Concrete(1:3:6)	1 m^3	0	0	0	1040.94	1146.09	1251.27	138.26	138.26	138.26	0	0	0	1179	1284	1390
GI Welded Mesh2"	1 m^2	0	0	0	0.00	0.00	0.00	0.41	0.41	0.41	87	87	87	87	87	87
GI Wires	1 MT	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	35500	35500	35500	35500	35500	35500
Glass	1 MT	0	0	0	6648.40	6648.40	6648.40	1693.26	1693.26	1693.26	0	0	0	8342	8342	8342
Glazing(3mm)	1 m^2	0	0	0	51.06	51.06	51.06	13.00	13.00	13.00	0	0	0	64	64	64
Glazing(4-5mm)	1 m^2	0	0	0	76.72	76.72	76.72	19.54	19.54	19.54	0	0	0	96	96	96
Limestone	1 MT	0	0	0	34.00	34.00	34.00	0.00	0.00	0.00	0	0	0	34	34	34
Logs	1 m^3	0	0	0	0.00	0.00	0.00	165.73	165.73	165.73	0	0	0	166	166	166
Logs-short term	1 m^3	0	0	0	0.00	0.00	0.00	165.73	165.73	165.73	0	0	0	166	166	166
Painting walls	10 m^2	0	0	0	0.11	0.16	0.22	0.85	1.61	3.14	200	200	200	201	202	204
Painting wood	10 m^2	0	0	0	0.18	0.24	0.32	1.20	2.28	4.45	435	435	435	437	438	440
Paints-Emulsion	1 l	0	0	0	0.01	0.01	0.02	0.34	0.65	1.27	53	53	53	53	54	54
Paints-Primer	1 l	0	0	0	0.01	0.01	0.02	0.34	0.65	1.27	124	124	124	124	125	125
Pcon(3)	1 Nos	0	0	0	44.35	44.54	44.72	9.00	9.00	9.00	67	67	67	120	120	120
Pcon(3.5)	1 Nos	0	0	0	74.85	75.14	75.43	15.85	15.85	15.85	145	145	145	236	236	236
Planks-Formwork	1 m^3	0	0	0	285.83	285.83	285.83	1383.41	1383.41	1383.41	0	0	0	1669	1669	1669
Plywood	1 m^3	11548	11548	11548	142.47	142.47	142.47	399.24	399.24	399.24	0	0	0	12090	12090	12090
Purlins-Formwork	1 m^3	0	0	0	320.65	320.65	320.65	1043.87	1043.87	1043.87	0	0	0	1365	1365	1365

Table 5.8 (Cont.)

Description	*Qty*	*Biomass*			*Fossil Fuel*			*Electricity*			*Imported*			*Total Energy*		
		Min	*Avg*	*Max*	*Min*	*Avg*	*Max*	*Min*	*Avg*	*Max*	*Min*	*Avg*	*Max*	*Min*	*Avg*	*Max*
PVC -MT	1 MT	0	0	0	16.41	21.55	31.84	2188.07	3663.10	6557.68	92000	92000	92000	94204	95685	98590
PVC El.Conduits	1 m	0	0	0	0.00	0.00	0.00	0.19	0.32	0.57	8	8	8	8	8	9
PVC Resin	1 MT	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	92000	92000	92000	92000	92000	92000
PVC-110-T400	1 m	0	0	0	0.02	0.03	0.04	3.09	5.17	9.26	130	130	130	133	135	139
PVC-20-T1000	1 m	0	0	0	0.00	0.00	0.00	0.25	0.43	0.77	11	11	11	11	11	12
PVC-32-T1000	1 m	0	0	0	0.00	0.01	0.01	0.62	1.03	1.85	26	27	28	27	28	29
PVC-40-T600	1 m	0	0	0	0.00	0.01	0.01	0.64	1.07	1.91	28	28	28	28	29	30
PVC-63-T400	1 m	0	0	0	0.01	0.01	0.01	1.02	1.71	3.06	43	43	43	44	45	46
PVC-90-T400	1 m	0	0	0	0.02	0.02	0.03	2.10	3.51	6.29	88	88	88	90	92	95
PVC-Down Pipe	1 m	0	0	0	0.01	0.01	0.01	1.01	1.68	3.02	42	42	42	43	44	45
PVC-Gutters	1 m	0	0	0	0.01	0.01	0.02	1.31	2.20	3.93	55	55	55	57	57	59
Quarry Dust	1 m^3	0	0	0	99.51	114.52	129.52	0.00	0.00	0.00	0	0	0	100	115	130
Random Rubble	1 m^3	0	0	0	564.23	657.97	751.72	54.10	54.10	54.10	0	0	0	618	712	806
Raw(Emulsion)	1 l	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	53	53	53	53	53	53
Raw(Enamel)	1 l	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	124	124	124	124	124	124
Raw(Glass)	1 MT	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0	0
Render 5/8"(1:1:5)	10 m^2	705	713	718	181.50	206.61	232.26	25.85	25.85	25.85	0	0	0	912	945	976
Render5/8"(1:1:5)S	10 m^2	1057	1069	1077	187.45	213.39	240.13	25.85	25.85	25.85	0	0	0	1271	1308	1343
Rendering1/2"(1:3)	10 m^2	0	0	0	229.21	247.77	266.34	36.07	36.07	36.07	0	0	0	265	284	302
Rendering3/4"(1:3)	10 m^2	0	0	0	344.59	373.92	403.25	54.10	54.10	54.10	0	0	0	399	428	457
Rendering3/8"1:3li	10 m^2	303	307	309	171.60	189.82	208.28	25.85	25.85	25.85	0	0	0	501	522	543
Rmix Conc.	1 m^3	0	0	0	1273.98	1404.93	1536.23	197.22	212.73	228.23	0	0	0	1471	1618	1764

Table 5.8 (Cont.)

Description	*Qty*	*Biomass*			*Fossil Fuel*			*Electricity*			*Imported*			*Total Energy*		
		Min	*Avg*	*Max*	*Min*	*Avg*	*Max*	*Min*	*Avg*	*Max*	*Min*	*Avg*	*Max*	*Min*	*Avg*	*Max*
Roofing(Asbestos)	10 m^2	0	0	0	364.33	368.80	373.28	108.33	110.26	112.19	226	238	251	698	717	736
Roofing(calicut)	10 m^2	2672	3350	4369	61.02	80.85	99.01	29.09	48.14	66.50	0	0	0	2762	3479	4535
Sand	1 m^3	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0	0
Slab formwork	1 m^2	0	0	0	8.00	8.00	8.00	38.74	38.74	38.74	0	0	0	47	47	47
Slaked lime	1 MT	35243	35640	35905	363.99	397.93	458.91	0.00	0.00	0.00	0	0	0	35607	36038	36364
Steel	1 MT	0	0	0	2648.23	2648.23	2648.23	1037.78	1037.78	1037.78	29000	29000	29000	32686	32686	32686
Steel-Billets	1 MT	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	29000	29000	29000	29000	29000	29000
Tim.Planks-rough	1 m^3	0	0	0	226.46	285.83	330.54	1065.33	1409.93	1664.23	0	0	0	1292	1696	1995
Tim.Purlins-rough	1 m^3	0	0	0	234.06	320.65	384.40	956.57	1081.75	1641.78	0	0	0	1191	1402	2026

Table 5.9 - Energy Breakdown By Process (MJ/Qty)

Description	Qty	Production			Transport of Raw Mat.			Embedded in Raw Mat.			Total Energy		
		Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
Aggregates	1 m^3	35.56	35.65	35.74	1.67	8.77	15.87	49.48	54.31	59.14	87	99	111
Air-drytr.TimbPurlin	1 m^3	22.01	26.35	30.69	0.00	0.00	0.00	1190.63	1402.40	2026.18	1211	1429	2059
Air-dryTr.TimPlanks	1 m^3	22.01	26.35	30.69	0.00	0.00	0.00	1291.79	1695.75	1994.78	1312	1722	2028
Al-Billets	1 MT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	129500	129500	129500
Aluminium Extrusions	1 MT	17968.28	17968.28	17968.28	9.23	9.23	9.23	129500.00	129500.00	129500.00	147478	147478	147478
Asbestos fibre	1 MT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15680	15680	15680
Asbestos Sheets	1 MT	298.37	346.75	395.13	5.75	6.72	7.69	4108.66	4122.89	4137.18	4359	4476	4594
Beam Formwork	1 m^2	0.00	0.00	0.00	0.00	0.00	0.00	45.07	45.07	45.07	45	45	45
Blocks(4"x8"x16")	1000 Nos	213.86	220.22	226.57	261.05	517.88	774.72	3095.67	3117.03	3138.47	3571	3855	4140
Blocks(6"x8"x16")	1000 Nos	375.70	376.66	377.63	798.94	993.05	1187.17	4704.62	4768.47	4832.42	5879	6138	6397
Blocks(8"x8"x16")	1000 Nos	566.44	579.45	592.45	798.87	993.02	1187.17	4704.62	4768.47	4832.42	6070	6341	6612
Blockwork 4"	10 m^2	0.00	0.00	0.00	4.94	9.66	14.38	514.10	548.25	582.41	519	558	597
Blockwork 6"	10 m^2	0.00	0.00	0.00	7.43	14.54	21.66	833.96	865.04	896.13	841	880	918
Blockwork 8"	10 m^2	0.00	0.00	0.00	9.91	19.37	28.82	899.66	932.18	964.72	910	952	994
Boulders	1 MT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	34	38	41
Bricks	1000 Nos	5286.45	8528.17	10524.39	17.70	39.84	64.92	2.06	8.13	22.81	5307	8576	10605
Brickwork (9")	10m^2	0.00	0.00	0.00	57.73	148.54	239.35	6910.41	10744.89	13124.46	6968	10893	13364
Brickwork(41/2")	10 m^2	0.00	0.00	0.00	29.35	74.98	120.60	3441.58	5376.80	6577.74	3471	5452	6698
Calicut tiles	1000 Nos	20139.32	25466.08	33269.56	79.19	104.01	132.84	1.67	6.28	17.27	20274	25576	33384
Cement	1 MT	4194.82	4194.82	4194.82	29.02	29.02	29.02	57.84	57.93	58.13	4282	4282	4282

Table 5.9 (Cont.)

Description	*Qty*	*Production*			*Transport of Raw Mat.*			*Embedded in Raw Mat.*			*Total Energy*		
		Min	*Avg*	*Max*	*Min*	*Avg*	*Max*	*Min*	*Avg*	*Max*	*Min*	*Avg*	*Max*
Clay	1 m^3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	4	11
Column Formwork	1 m^2	0.00	0.00	0.00	0.00	0.00	0.00	50.08	50.08	50.08	50	50	50
Concrete(1:1:2)	1 m^3	0.00	0.00	0.00	84.53	191.02	297.51	2438.17	2449.75	2461.40	2523	2641	2759
Concrete(1:2:4)	1 m^3	30.73	30.73	30.73	80.82	176.42	272.01	1446.44	1457.05	1467.69	1558	1664	1770
Concrete(1:3:6)	1 m^3	30.73	30.73	30.73	83.91	177.98	272.05	1064.56	1075.64	1086.74	1179	1284	1390
GI Welded Mesh2"x2"	1 m^2	0.41	0.41	0.41	0.00	0.00	0.00	86.62	86.62	86.62	87	87	87
GI Wires	1 MT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	35500	35500	35500
Glass	1 MT	8281.40	8281.40	8281.40	60.26	60.26	60.26	0.00	0.00	0.00	8342	8342	8342
Glazing(3mm)	1 m^2	0.00	0.00	0.00	0.00	0.00	0.00	64.06	64.06	64.06	64	64	64
Glazing(4-5mm)	1 m^2	0.00	0.00	0.00	0.00	0.00	0.00	96.26	96.26	96.26	96	96	96
Limestone	1 MT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	34	34	34
Logs	1 m^3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166	166	166
Logs-short term	1 m^3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	166	166	166
Painting walls	10 m^2	0.00	0.00	0.00	0.08	0.13	0.17	201.18	201.96	203.50	201	202	204
Painting wood	10 m^2	0.00	0.00	0.00	0.14	0.19	0.25	436.48	437.57	439.76	437	438	440
Paints-Emulsion	1 l	0.34	0.65	1.27	0.01	0.01	0.02	53.00	53.00	53.00	53	54	54
Paints-Primer	1 l	0.34	0.65	1.27	0.01	0.01	0.02	124.00	124.00	124.00	124	125	125
Pcon(3)	1 Nos	1.03	1.03	1.03	2.73	2.73	2.73	116.30	116.48	116.66	120	121	120
Pcon(3.5)	1 Nos	1.65	1.65	1.65	4.32	4.32	4.32	229.74	230.03	230.32	236	236	236
Planks-Formwork	1 m^3	1217.68	1217.68	1217.68	285.83	285.83	285.83	165.73	165.73	165.73	1669	1669	1669
Plywood	1 m^3	11710.25	11710.25	11710.25	142.47	142.47	142.47	237.00	237.00	237.00	12090	12090	12090
Purlins-Formwork	1 m^3	878.14	878.14	878.14	320.65	320.65	320.65	165.73	165.73	165.73	1365	1365	1365

Table 5.9 (Cont.)

Description	*Qty*	*Production*			*Transport of Raw Mat.*			*Embedded in Raw Mat.*			*Total Energy*		
		Min	*Avg*	*Max*	*Min*	*Avg*	*Max*	*Min*	*Avg*	*Max*	*Min*	*Avg*	*Max*
PVC -MT	1 MT	2188.07	3663.10	6557.68	16.41	21.55	31.64	92000.00	92000.00	92000.00	94204	95685	98590
PVC El.Conduits	1 m	0.00	0.00	0.00	0.00	0.00	0.00	8.20	8.32	8.53	8	8	9
PVC Resin	1 MT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	92000	92000	92000
PVC-110-T400	1 m	3.09	5.17	9.26	0.02	0.03	0.04	129.72	129.78	[illegible]	133	135	139
PVC-20-T1000	1 m	0.25	0.43	0.77	0.00	0.00	0.00	11.04	11.04	11.04	11	11	12
PVC-32-T1000	1 m	0.62	1.03	1.85	0.00	0.01	0.01	25.94	27.05	27.60	27	28	29
PVC-40-T600	1 m	0.64	1.07	1.91	0.00	0.01	0.01	27.60	27.60	27.60	28	29	30
PVC-63-T400	1 m	1.02	1.71	3.06	0.01	0.01	0.01	42.87	42.87	42.87	44	45	46
PVC-90-T400	1 m	2.10	3.51	6.29	0.02	0.02	0.03	88.32	88.32	88.32	90	92	95
PVC-Down Pipe	1 m	1.01	1.58	[illegible]	0.01	0.01	0.01	42.32	42.32	42.32	43	44	45
PVC-Gutters	1 m	0.00	0.00	0.00	0.00	0.00	0.00	56.52	57.41	59.15	57	57	59
Quarry Dust	1 m^3	35.56	35.65	35.74	2.11	10.98	19.85	61.85	67.89	73.93	100	115	130
Random Rubble	1 m^3	0.00	0.00	0.00	108.94	190.56	272.18	509.39	[illegible]	533.64	618	712	806
Raw(Emulsion)	1 l	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	53	53	53
Raw(Enamel)	1 l	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	124	124	124
Raw(Glass)	1 MT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0
Render 5/8"(1:1:5)SR	10 m^2	0.00	0.00	0.00	15.96	40.38	64.81	896.25	904.88	911.40	912	945	976
Render5/8"(1:1:5)SL	10 m^2	0.00	0.00	0.00	18.27	43.18	68.09	1252.32	1265.26	1275.03	1271	1308	1343
Rendering1/2"(1:3)	10 m^2	0.00	0.00	0.00	8.38	26.93	45.49	256.90	256.91	256.92	265	284	302
Rendering3/4"(1:3)	10 m^2	0.00	0.00	0.00	13.34	42.66	71.98	385.35	385.36	385.38	399	428	457
Rendering3/8"1:3lime	10 m^2	0.00	0.00	0.00	10.20	28.13	46.06	490.33	494.04	498.85	501	522	543

Table 5.9 (Cont.)

Description	*Qty*	*Production*			*Transport of Raw Mat.*			*Embedded in Raw Mat.*			*Total Energy*		
		Min	*Avg*	*Max*	*Min*	*Avg*	*Max*	*Min*	*Avg*	*Max*	*Min*	*Avg*	*Max*
Rmix Conc.	1 m^3	11.23	14.06	16.88	108.25	117.09	125.93	1346.07	1486.51	1627.30	1471	1618	1764
Roofing(Asbestos)	10 m^2	0.00	0.00	0.00	1.03	1.18	1.33	697.42	716.20	735.02	698	717	736
Roofing(calicut)	10 m^2	0.00	0.00	0.00	24.91	26.46	28.02	2737.05	3452.81	4506.87	2762	3479	4535
Sand	1 m^3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0
Slab formwork	1 m^2	0.00	0.00	0.00	0.00	0.00	0.00	46.74	46.74	46.74	47	47	47
Slaked lime	1 MT	35464.18	35885.09	36237.29	5.91	33.45	70.84	119.00	119.45	120.36	35607	36038	36364
Steel	1 MT	3674.48	3674.48	3674.48	11.53	11.53	11.53	29000.00	29000.00	29000.00	32686	32686	32686
Steel-Billets	1 MT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	29000	29000	29000
Tim.Planks-rough	1 m^3	869.76	1217.68	1478.62	226.46	285.83	330.54	185.62	192.25	195.56	1292	1696	1995
Tim.Purlins-rough	1 m^3	768.65	878.14	1365.01	234.06	320.65	384.40	183.96	203.61	276.77	1191	1402	2026

Table 5.10 - Carbon Calculations (kgC/Qty)

Description	*Qty*	*From Fuel*	*From Imports*	*From Material*	*Net Value*
Aggregates	1 m^3	2.00	0.00	0.00	2.00
Air-drytr.TimbPurlin	1 m^3	26.88	0.00	-307.14	-280.27
Air-dryTr.TimPlanks	1 m^3	32.19	0.00	-290.00	-257.81
Al-Billets	1 MT	0.00	2590.00	130.00	2720.00
Aluminium Extrusions	1 MT	330.09	2590.00	130.00	3050.09
Asbestos fibre	I MT	0.00	313.60	0.00	313.60
Asbestos Sheets	1 MT	59.29	29.79	100.82	189.90
Beam Formwork	1 m^2	0.84	0.00	0.00	0.84
Blocks(4"x8"x16")	1000 Nos	77.03	0.00	97.98	175.01
Blocks(6"x8"x16")	1000 Nos	122.71	0.00	142.00	264.71
Blocks(8"x8"x16")	1000 Nos	126.43	0.00	142.00	268.43
Blockwork 4"	10 m^2	11.15	0.00	14.60	25.75
Blockwork 6"	10 m^2	17.59	0.00	21.30	38.89
Blockwork 8"	10 m^2	18.99	0.00	22.72	41.71
Boulders	1 MT	0.77	0.00	0.00	0.77
Bricks	1000 Nos	0.97	0.00	0.00	0.97
Brickwork (9")	10m^2	17.88	0.00	22.72	40.60
Brickwork(41/2")	10 m^2	8.10	0.00	9.94	18.04
Calicut tiles	1000 Nos	14.73	0.00	0.00	14.73

Table 5.10 (Cont.)

Description	*Qty*	*From Fuel*	*From Imports*	*From Material*	*Net Value*
Cement	1 MT	85.75	0.00	142.00	227.75
Clay	1 m^3	0.09	0.00	0.00	0.09
Column Formwork	1 m^2	0.94	0.00	0.00	0.94
Concrete(1:1:2)	1 m^3	52.97	0.00	78.10	131.07
Concrete(1:2:4)	1 m^3	33.41	0.00	45.44	78.85
Concrete(1:3:6)	1 m^3	25.80	0.00	32.66	58.46
GI Welded Mesh2"x2"	1 m^2	0.01	1.74	0.00	1.75
GI Wires	1 MT	0.00	710.00	0.00	710.00
Glass	1 MT	166.05	0.00	0.00	166.05
Glazing(3mm)	1 m^2	1.28	0.00	0.00	1.28
Glazing(4-5mm)	1 m^2	1.92	0.00	0.00	1.92
Limestone	1 MT	0.69	0.00	0.00	0.69
Logs	1 m^3	3.04	0.00	-250.00	-246.96
Logs-short term	1 m^3	3.04	0.00	0.00	3.04
Painting walls	10 m^2	0.03	4.00	0.00	4.03
Painting wood	10 m^2	0.05	8.70	0.00	8.75
Paints-Emulsion	1 l	0.01	1.06	0.00	1.07
Paints-Primer	1 l	0.01	2.48	0.00	2.49
Pcon(3)	1 Nos	1.07	1.34	1.32	3.73
Pcon(3.5)	1 Nos	1.82	2.90	2.13	6.85
Planks-Formwork	1 m^3	31.20	0.00	0.00	31.20
Plywood	1 m^3	10.22	0.00	-357.50	-347.28
Purlins-Formwork	1 m^3	25.67	0.00	0.00	25.67

Table 5.10 (Cont.)

Description	*Qty*	*From Fuel*	*From Imports*	*From Material*	*Net Value*
PVC -MT	1 MT	67.69	1840.00	0.00	1907.69
PVC El.Conduits	1 m	0.01	0.16	0.00	0.17
PVC Resin	1 MT	0.00	1840.00	0.00	1840.00
PVC-110-T400	1 m	0.10	2.60	0.00	2.70
PVC-20-T1000	1 m	0.01	0.22	0.00	0.23
PVC-32-T1000	1 m	0.02	0.55	0.00	0.57
PVC-40-T600	1 m	0.02	0.56	0.00	0.58
PVC-63-T400	1 m	0.03	0.86	0.00	0.89
PVC-90-T400	1 m	0.06	1.76	0.00	1.82
PVC-Down Pipe	1 m	0.03	0.84	0.00	0.87
PVC-Gutters	1 m	0.04	1.10	0.00	1.14
Quarry Dust	1 m^3	2.32	0.00	0.00	2.32
Random Rubble	1 m^3	14.35	0.00	525.40	539.75
Raw(Emulsion)	1 l	0.00	1.06	0.00	1.06
Raw(Enamel)	1 l	0.00	2.48	0.00	2.48
Raw(Glass)	1 MT	0.00	0.00	0.00	0.00
Render 5/8"(1:1:5)SR	10 m^2	4.67	0.00	6.11	10.77
Render5/8"(1:1:5)SL	10 m^2	4.81	0.00	6.11	10.91
Rendering1/2"(1:3)	10 m^2	5.69	0.00	8.52	14.21
Rendering3/4"(1:3)	10 m^2	8.58	0.00	12.78	21.36
Rendering3/8"1:3lime	10 m^2	4.33	0.00	6.11	10.43
Rmix Conc.	1 m^3	32.43	0.00	46.93	79.36
Roofing(Asbestos)	10 m^2	9.51	4.76	16.13	30.40

Table 5.10(Cont.)

Description	*Qty*	*From Fuel*	*From Imports*	*From Material*	*Net Value*
Roofing(calicut)	10 m^2	2.53	0.00	0.00	2.53
Sand	1 m^3	0.00	0.00	0.00	0.00
Slab formwork	1 m^2	0.87	0.00	0.00	0.87
Slaked lime	1 MT	8.08	0.00	0.00	8.08
Steel	1 MT	72.81	580.00	0.00	652.81
Steel-Billets	1 MT	0.00	580.00	0.00	580.00
Tim.Planks-rough	1 m^3	31.69	0.00	-290.00	-258.31
Tim.Purlins-rough	1 m^3	26.37	0.00	-307.14	-280.77

Table 5.11 - Contribution From Raw Material Transport Energy Component To Embedded Energies

Description	Qtty.	Average Transport	Average Total Energy	Transport %
Aggregates	1 m^3	8.77	99	8.88
Aluminium Extrusions	1 MT	9.23	147478	0.01
Blocks(4"x8"x16")	1000 Nos	517.88	3855	13.43
Blocks(6"x8"x16")	1000 Nos	993.05	6138	16.18
Blocks(8"x8"x16")	1000 Nos	993.02	6341	15.66
Bricks	1000 Nos	39.84	8576	0.46
Cement	1 MT	29.02	4282	0.68
GI Welded Mesh2"x2"	1 m^2	0.00	87	0.00
Glass	1 MT	60.26	8342	0.72
Paints-Emulsion	1 l	0.01	54	0.02
Paints-Primer	1 l	0.01	125	0.01
Air-dryTr.TimPlanks	1 m^3	0.00	1722	0.00
Planks-rough	1 m^3	285.83	1696	16.86
Planks-Formwork	1 m^3	285.83	1669	17.12
Air-drytr.TimbPurlin	1 m^3	0.00	1429	0.00
Purlins-rough	1 m^3	320.65	1402	22.86
Purlins-Formwork	1 m^3	320.65	1365	23.50
Quarry Dust	1 m^3	10.98	115	9.59
Asbestos Sheets	1 MT	6.72	4476	0.15
Calicut tiles	1000 Nos	104.01	25576	0.41
Rmix Conc.	1 m^3	117.09	1618	7.24
Slaked lime	1 MT	33.45	36038	0.09
Steel	1 MT	11.53	32686	0.04
Beam Formwork	1 m^2	0.00	45	0.00
Blockwork 4"	10 m^2	9.66	558	1.73
Blockwork 6"	10 m^2	14.54	880	1.65
Blockwork 8"	10 m^2	19.37	952	2.04
Brickwork(41/2")	10 m^2	74.98	5452	1.38
Brickwork (9")	10m^2	148.54	10893	1.36
Concrete(1:1:2)	1 m^3	191.02	2641	7.23
Concrete(1:2:4)	1 m^3	176.42	1664	10.60
Concrete(1:3:6)	1 m^3	177.98	1284	13.86
Column Formwork	1 m^2	0.00	50	0.00
Glazing(3mm)	1 m^2	0.00	64	0.00
Glazing(4-5mm)	1 m^2	0.00	96	0.00
PVC-32-T1000	1 m	0.01	28	0.02
PVC-40-T600	1 m	0.01	29	0.02
PVC-63-T400	1 m	0.01	45	0.02
PVC-Down Pipe	1 m	0.01	44	0.02
PVC-110-T400	1 m	0.03	135	0.02
PVC-90-T400	1 m	0.02	92	0.02
PVC-20-T1000	1 m	0.00	11	0.02
Painting walls	10 m^2	0.13	202	0.06
Painting wood	10 m^2	0.19	438	0.04
Pcon(3)	1 Nos	2.73	121	2.27
Pcon(3.5)	1 Nos	4.32	236	1.83
PVC El.Conduits	1 m	0.00	8	0.00
PVC-Gutters	1 m	0.00	57	0.00
Plywood	1 m^3	142.47	12090	1.18
PVC -MT	1 MT	21.55	95685	0.02
Roofing(Asbestos)	10 m^2	1.18	717	0.16
Roofing(calicut)	10 m^2	26.46	3479	0.76
Render 5/8"(1:1:5)SR	10 m^2	40.38	945	4.27
Render5/8"(1:1:5)SL	10 m^2	43.18	1308	3.30
Rendering1/2"(1:3)	10 m^2	26.93	284	9.49
Rendering3/4"(1:3)	10 m^2	42.66	428	9.97
Rendering3/8"1:3lime	10 m^2	28.13	522	5.39
Random Rubble	1 m^3	190.56	712	26.76
Slab formwork	1 m^2	0.00	47	0.00

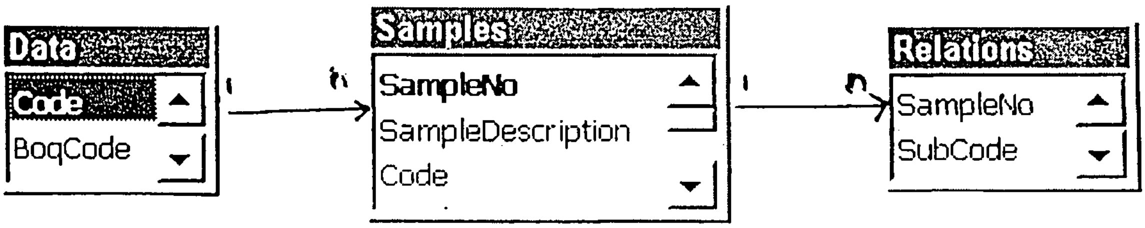
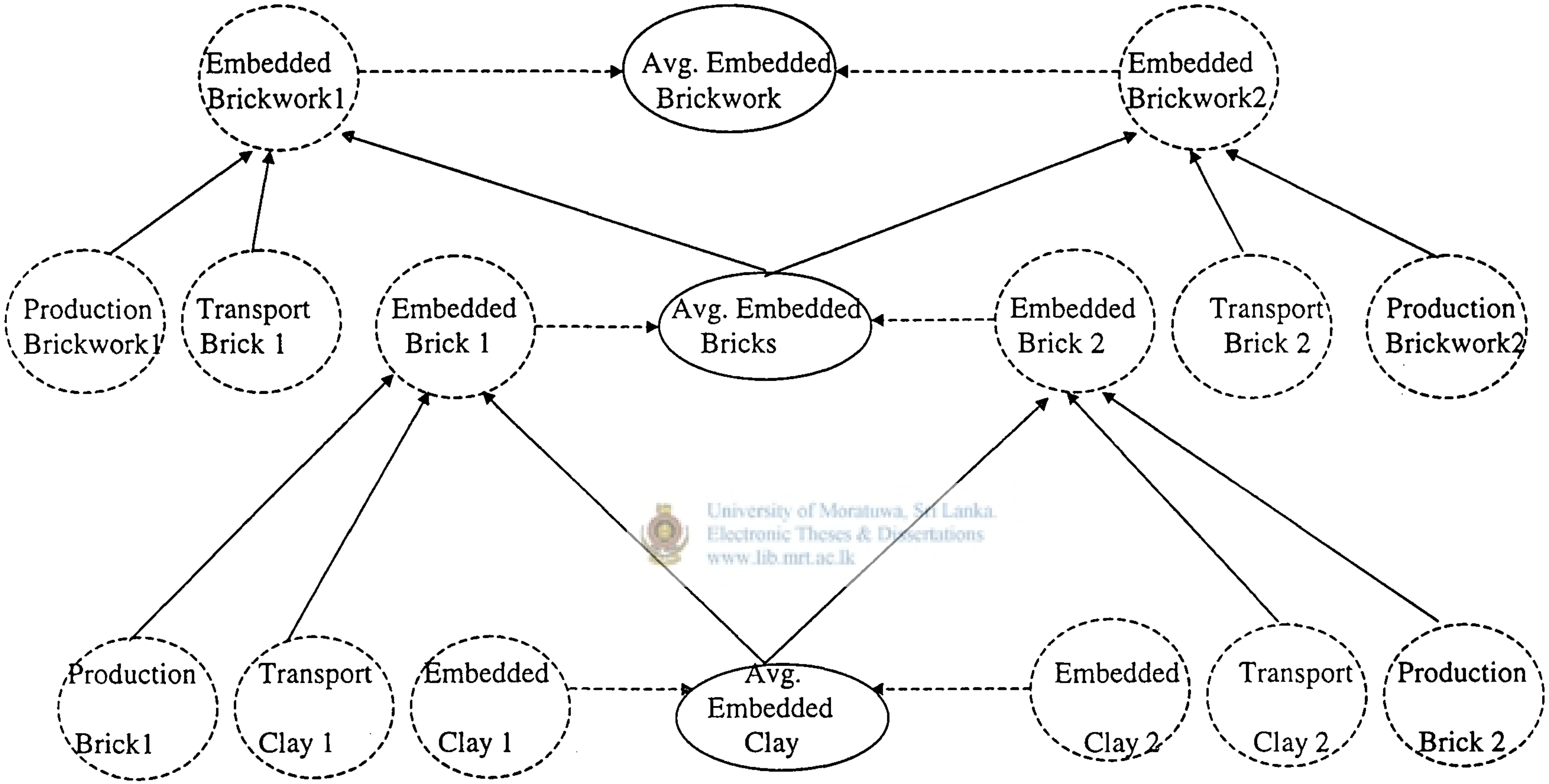


Figure 5.1 - Relationship between Tables



Actual Sample data

Summary data

Indirect Calculations

Direct Calculations

Figure 5.2 Implications of the Database Structure

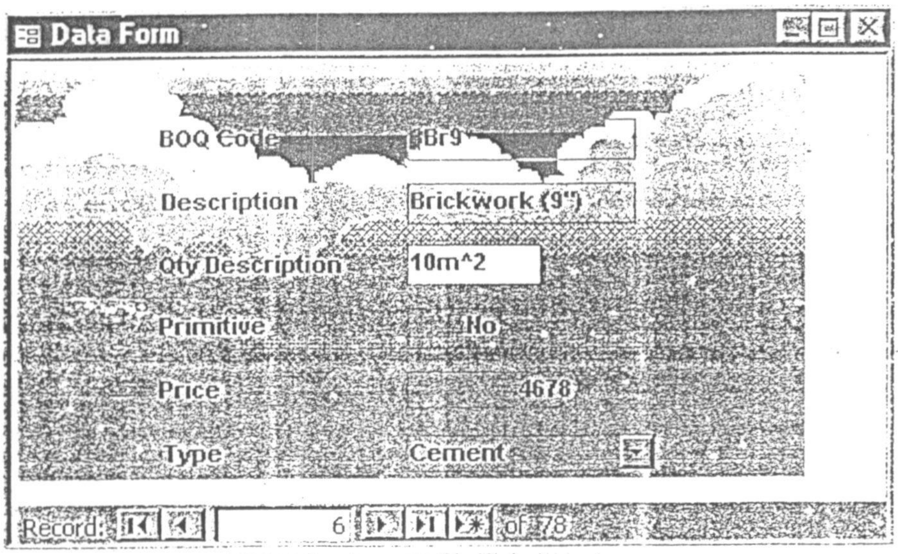


Figure 5.3 - Data Form

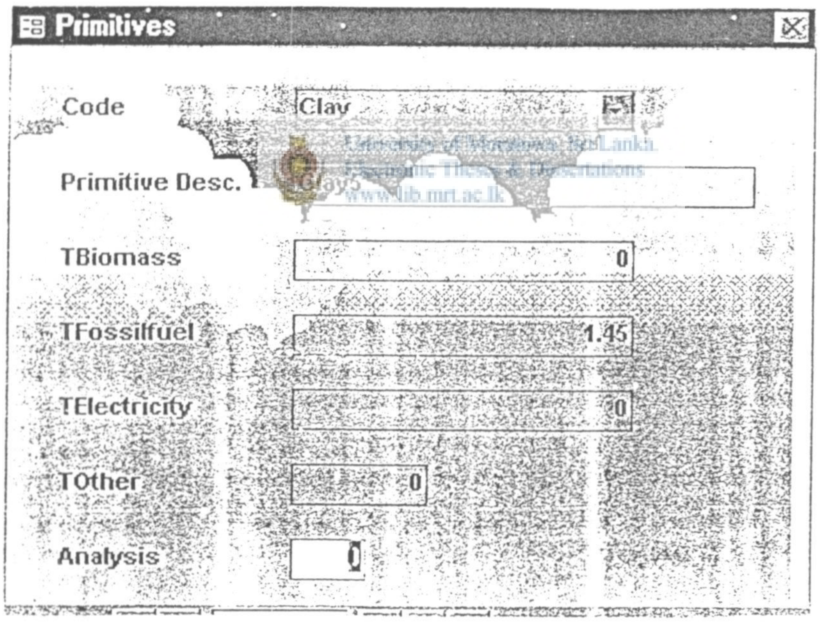


Figure 5.4 - Primitives Form

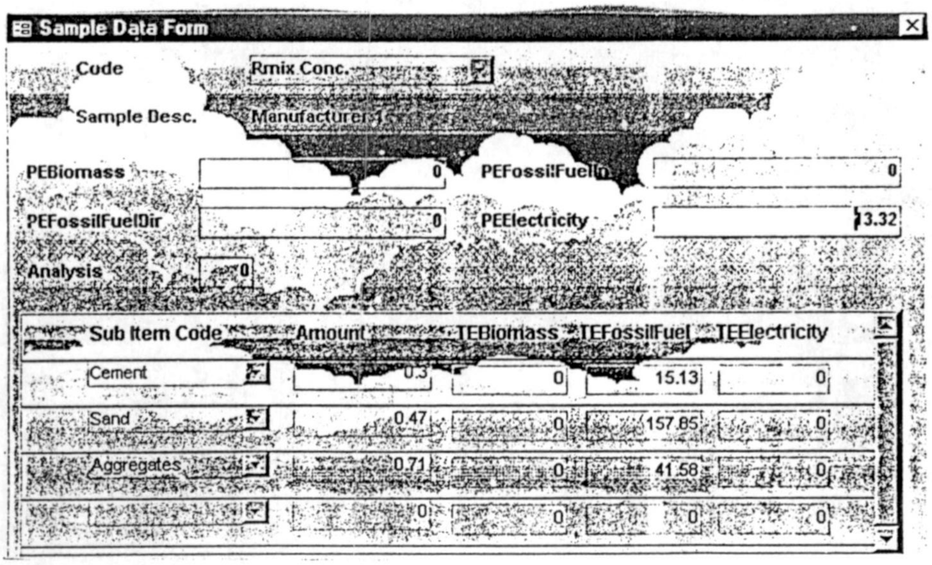


Figure 5.5 - Samples Form

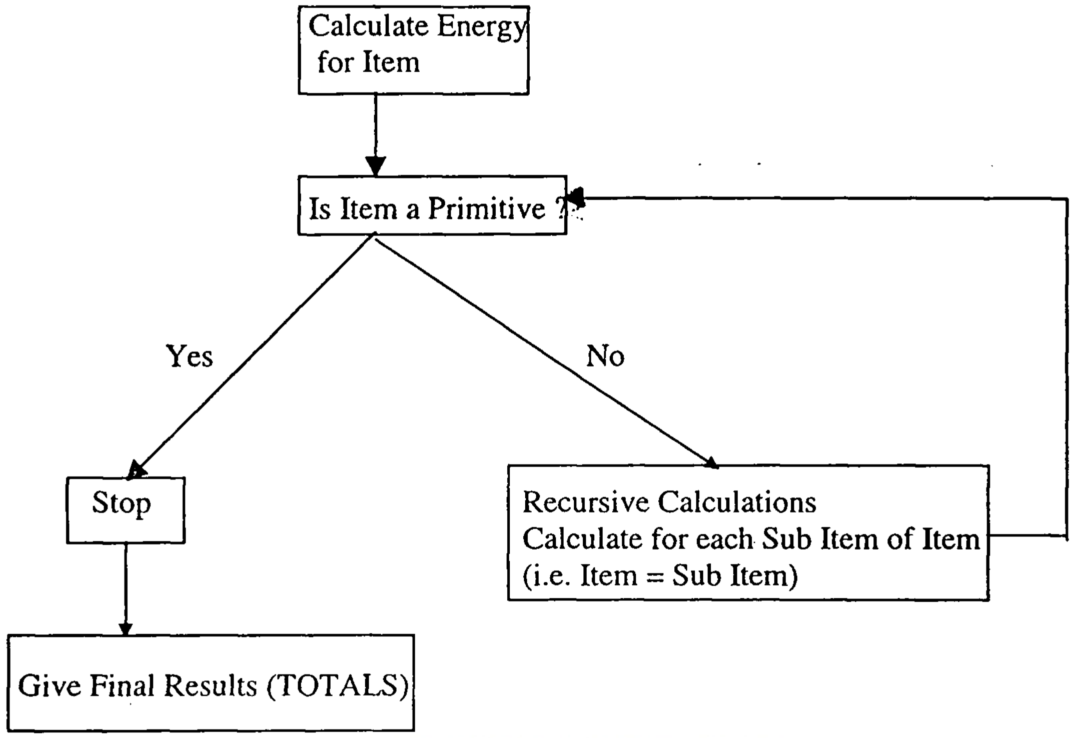


Figure 5.6. - Recursive Calculation Procedure for Embedded Energies

6. ENERGY QUALITY AND PRICE

6.1. Energy Quality Analysis

6.1.1. Introduction

Though it appears that least energy intensive material is the preferred option, there are however other issues that have to be considered. One of the main issues is regarding the differences in energy quality.

As described in Section 2.6, it is possible for a variety of interpretations to be given to the term "quality of energy". For the purpose of this study the concept that "a high quality energy or energy source can be used for a variety of end-uses with relative ease" will be generally accepted (Perera 1992). An approximate guide of classification of different types of energy according to their quality class is shown in Table 2.11 (Perera 1981).

As suggested in Section 2.6, the next step should be to find a methodology for comparing different energy qualities. One approach to this could be to assess the amount of the lower quality energy that is required to obtain a given quantity of the higher quality energy via established processes. The following processes were considered :

(i) thermal electricity generation

(ii) obtaining electricity by burning firewood (dendro-electricity)

(iii) use of producer gas in shaft power applications and direct heat applications.

All the energy requirements can then be compared on the basis of the total equivalent amount of lowest quality energy (i.e. biomass energy). The analyses carried out in this study are discussed below. The resulting energy values are termed "bio-equivalent energy" units. It must be appreciated that the above analyses are essentially efficiency based analyses. The disparity between the quantities of biomass, fossil fuel and electricity based energy is likely to be greater than reflected by these efficiency calculations. For example Odum (1971) values a unit of electrical energy at 4 times that of fossil fuel energy, whereas a purely efficiency based approach will result in a factor of only 2.78 (see Section 6.1.2 below). This study adopts the efficiency based approach, since it has a clean basis and since it will not distort the original energy values too much.

Since electricity has the highest energy quality, it is used as a reference, and assigned an "efficiency" of 100%, whatever the primary fuel used for its generation; this is similar to the ideas associated with assigning a TOE value for hydro-electricity (see Section 3.2.1)

6.1.2. Relationship between Fossil Fuel and Electricity

In obtaining thermal electricity the thermal efficiency is assumed as 36%.

Therefore,
2.78 GJ of fossil fuel energy = 1 GJ of electrical energy

6.1.3. Relationship between Biomass and Electricity

The process of obtaining electricity by burning firewood (dendro-electricity) can be used to find the relationship between electricity and biomass.

Fuel-wood farming, a new form of agriculture, of quick growing, and trees grown by farmers specially for fuel, has become one of the fastest developing and most environmentally friendly sources of energy in the United States, Scandinavia, Europe, China, etc. It is taking over from disbanded coal, oil and nuclear-fueled thermal electricity generation plants all over the world as not only a more viable and economic way to generate power but also to conserve the environment. Not surprisingly, it is proving to be even better suited to the tropical regions of the world. While fossil-fuelled generators always and continuously emit large volumes of CO_2 and SO_2 into the air to cause irreparable damage, the CO2 exhaust from wood-fueled generators is totally re-absorbed for the growing of the trees. Thus it is well proven to be totally CO_2 neutral.

When 10 million tonnes of fuel wood is used, 10,000 GWh of electricity could be generated (Joseph 1998).

Therefore, 1 MT of fire-wood = 1 MWh

But, 1 MT of Fire-wood at bone dry condition = 0.43 TOE

Therefore,

1 Mwh = 0.43 TOE
= 0.43 x 41.84 GJ
= 18 GJ

For electricity that is 100% efficient,

1 Mwh = 0.086 TOE
= 3.6 GJ

Therefore, 1 GJ of electrical energy = 18/3.6 GJ of biomass energy
= 5 GJ of biomass energy

However it should be noted that the values for electricity based energy that have been calculated in Tables 5.9 and 5.10 are based on a 34% thermal and 66% hydro mix. Hence, as described in Section 3.2.2,

1 MWh = (0.66)(3.6) + (0.34)(10.0) GJ
= 5.78 GJ

Hence in order to convert the electricity based energy in Table 5.9 to Bio-equivalent energy, they have to be factored, not by 5 but by 18/5.78 = 3.11

6.1.4. Relationship between Biomass and Fossil Fuel

Producer gas which is a combustible gas is generated as the product of partial combustion of solid fuels such as firewood in a gassifier. This partial combustion process, called gassification, is accomplished by restricting the supply of air in burning.

The uncleaned gas may contain tar-like matter, water vapour, ash, dust and volatile substances. Although it is not a high quality fuel, producer gas can be used effectively in a variety of applications. These can be divided into two main categories: shaft-power applications where very clean gas is required to run engines; and direct-heat applications, where it is burnt directly in a boiler, furnace or kiln to provide heat.

After retrofitting a wood gassifier to an existing oil-fired boiler it was found that fuel oil consumption of 29 kg/GJ is equivalent to 100 kg/GJ of wood consumption (Foley and Barnard 1983).

Therefore,

29 kg/ GJ of fuel oil = 100 kg/GJ of wood

But,

1 MT of fire-wood (at 30% moisture content) = 0.38 TOE
= 0.38 x 41.84 GJ
= 15.9 GJ

Therefore,
100 kg of fire wood = 1590 GJ

Now,
1 MT of fuel oil = 0.98 TOE
= 0.98 x 41.84 GJ
= 41 GJ

Therefore,

29 kg of fossil fuel = 1189 MJ

Therefore, 1 GJ of fossil fuel energy = 1.34 GJ of biomass energy

6.1.5. Consistency of the Bio Equivalent System

According to our calculations, 1 GJ of electricity is equivalent to 5 GJ of biomass energy, and 1 GJ of fossil fuel energy is equivalent to 1.31 GJ of biomass energy. In addition, 1 GJ of electricity is equivalent to 2.78 GJ of fossil fuel energy based on 36% efficiency. These results are depicted in Figure 6.1.

For the system to be mutually consistent, the fossil fuel to electricity factor is maintained at 2.78 (based on 36% efficiency of thermal electricity), as it is fairly well established. The biomass to fossil fuel factor is increased from 1.31 to 1.8 in order to increase this "quality gap" rather than reducing the "quality gap" between biomass and electricity. These relationships are depicted in Figure 6.2.

To find the bio equivalent energy content of all the building items, energy contents based on TOE values in terms of different fuel types are multiplied by the factors given in Table 6.1. In addition, as described in Section 3.2.3, it is assumed that the imports are made out of fossil fuel. It should be noted that the electricity based energy is factored by 3.11 and not 5, because the TOE based values already account for a mix of 34% thermal and 66% hydro (see Section 6.1.3). The final database outputs of embedded energies of all the building items in terms of bio equivalent units are shown in Table 6.2.

The study adopted in this research is an efficiency based approach essentially using the first law of thermodynamics. A thermodynamic system always receives energy in one or several forms and it gives out an equal amount of energy in another one or several forms. In complying with this fact one might define an energy efficiency as unity, which is logical. On the other hand, one may define an energy efficiency as the ratio of useful energy to energy input or consumed. Thus, the value of this efficiency may vary from case to case as the two terms 'useful' and 'consumed' are case dependent. That is, the first law is incapable of properly characterising the thermodynamic losses in a process. As a result the necessity of a more universal index of characterising a thermodynamic system performance arises. The solution to this is the introduction of an efficiency in terms of thermodynamic quality of energy streams rather than the quantities. The inability of the first law to characterise thermodynamic losses can be compensated by introducing a parameter called exergy through the combination of first and second laws. The exergy analysis resulting from the combination of first and second laws provides a measure of the maximum work that can be extracted from a certain thermodynamic system during a process; in other words, a way of quantifying the thermodynamic potential of the system. In practice, the work recoverable from a system in a given process is always less than this maximum amount represented as exergy because of irreversibilities causing degradation of this potential. Irreversibilities arise due to friction (molecular & sliding), heat transfer across finite temperature difference, chemical reactions etc. (Attalage 1997).

Therefore it is seen that due to the irreversibilities the efficiency based on exergy is less than the traditional energy efficiencies. Thus, exergy analysis can play an important role in finding exact relationships between efficiency based systems. Such analysis however, is outside the scope of this work, but could be undertaken as an extension of it.

6.2. Relationship between Selling Prices of Building Materials and Fuel Types

6.2.1. Introduction

The relationship between the selling prices of building materials and their embedded energies as described by different authors is given in Section 2.8.

As described under Section 2.8, though the market price does not reflect the actual energy embedded in a product, a relationship can be found between price per unit energy source based on actual prices of products and compared with the actual price per unit of different energy sources. The analysis carried out in this study is described below.

6.2.2. Analysis

Embedded energies in building products, in terms of different fuel types, together with their actual prices, were used to perform a regression analysis to find a relationship between price per unit energy source based on prices of products. This analysis is done making use of two sets of data, namely (i) with only local products, ignoring items which are imports or have imports as raw materials and (ii) considering all items including imported raw materials.

It is difficult to get costs, since they are not easily quantifiable in the informal sector and due to confidentiality in the formal sector. Therefore in this analysis, prices are used as opposed to costs although it is somewhat of a drawback. Where building elements are concerned (i.e. those that are aggregates of priced raw materials), a markup of 25% is used.

Only part of the database items was used for the analysis. Timber products except for formwork and roof timber (air-dry treated timber) are ignored, since prices vary according to the grade of timber. Most of the primitives are also ignored due to the lack of of data regarding prices.

The regression model used is as follows:

$$\text{Product Price} = \text{Constant} + P_1 \left| \begin{matrix} \text{Biomass} \\ \text{Energy} \end{matrix} \right| + P_2 \left| \begin{matrix} \text{Fossil Fuel} \\ \text{Energy} \end{matrix} \right| + P_3 \left| \begin{matrix} \text{Electrical} \\ \text{Energy} \end{matrix} \right| + P_4 \left| \begin{matrix} \text{Imported} \\ \text{Energy} \end{matrix} \right|$$

where P_1, P_2, P_3, P_4 are factors in the linear multiple regression model that reflect energy prices, and energy is based on TOE values.

Another model was used without the P_4 and imported energy terms.

6.2.3. Results

The results of these analyses are shown in Tables 6.3 and 6.4.

It is seen that in both cases, the values of price per unit of energy of biomass, fossil fuel and electrical energy is very similar, being around 0.03 Rs./MJ for biomass, 2.3 Rs./MJ for fossil fuel and 10.7 Rs./MJ for electricity. This gives confidence in the regression modelling, because the addition or removal of imports causes only very minor changes in the prices of other energy sources. According to the degree of freedom of 37 in case 1 and 26 in case 2, the t-value at a level of significance of 5% should be greater than 2. In both case 1 and 2 the constant and P_1 (coefficient for biomass) are less than 2 and the 95% confidence interval varies from a negative value to a positive value; thus suggesting that the constant and P_1 should be removed from the model.

Analysis was done again ignoring those 2 components, i.e. the constant and the biomass energy (Table 6.5a and Table 6.5b). It is seen that the changes in the coefficients of fossil fuel (P_2) and electricity (P_3) are negligible.

As regards recent actual prices, fuel wood is around Rs. 1,500 per tonne, fossil fuel is around Rs. 10 per litre (based on the prices of furnace oil and diesel, since they are the most frequently used fossil fuels in the industry), and electricity is around Rs. 5.20 per kWh in general for industry (Central 1998).

Hence,

1 MT of fuel wood = Rs. 1,500

1 MT of fuel wood = 0.38 TOE

= 15.9 GJ

Therefore,

1 MJ of biomass energy = Rs. 0.09

Also,

1 litre of fossil fuel = Rs. 10

For the range of oil based fossil fuels we can assume that

1 MT of fossil fuel = 1 TOE

let density of oil based fossil fuel be 900 kg/m^3 ,

Thus,

1 litre of fossil fuel = $0.9 \times 10^{-3} \times 1 \times 41.84$ GJ

= 37.66 MJ

Therefore,

1 MJ of fossil fuel energy = Rs. 0.27

Finally,

1 kWh of electricity = Rs. 5.20

Based on 34% thermal and 66% hydro mix

1 MWh of electricity = (0.66)(3.6) + (0.34)(10) GJ

1 kWh of electricity = 5.78 MJ

Therefore,

1 MJ of electrical energy = Rs. 0.90

These final results are shown in Table 6.6.

Although the the price per unit of biomass energy based on the actual prices of the products is not a reliable value because of its low t-value in the regression analysis, it is found to be only one third of the actual price per unit of biomass energy. This is because biomass is readily available for tropical countries like Sri Lanka. This is the least cost fuel and processes using such wood fuel are less costly. Manufacturing using wood fuel is done mostly in remote areas where raw materials and human energy sources are widely available and where capital investment and overheads are low (e.g. brick manufacturing). Therefore in general it is possible for the price of products to be close to the actual price of energy.

For fossil fuel and electricity, the actual price of products is much higher than the actual price of the energy source. The ratios between the regression analysis results and the actual prices are 8.5 for fossil fuel and 11.9 for electricity. This may be due to the high initial cost of the machinery required and their maintenance costs and other overheads. It is also probably reflecting the fact that there is greater value addition in processes that use fossil fuel and electricity as energy sources.

Table 6.1 - Bio Equivalent Units of Different Fuel Types

Fuel Type	Bio Equivalent Units
Biomass	1
Fossil Fuel	1.8
Electricity	5.0 (3.11)
Imports	1.8

Table 6.2 - Energy Breakdown -using BioEq (MJ/Qty)

Description	*Qty*	*Biomass*	*Fossil Fuel*	*Electricity*	*Imported*	*Total Energy(BioEq)*	*Total Energy(TOE)*
Aggregates	1 m^3	0.00	177.71	0.00	0.00	177.71	98.73
Air-drytr.TimbPurlin	1 m^3	0.00	597.06	3411.83	0.00	4008.89	1428.75
Air-dryTr.TimPlank	1 m^3	0.00	534.38	4432.45	0.00	4966.83	1722.10
Al-Billets	1 MT	0.00	0.00	0.00	233100.00	233100.00	129500.00
Aluminium Extrusio	1 MT	0.00	16.61	55881.36	233100.00	288997.97	147477.52
Asbestos fibre	I MT	0.00	0.00	0.00	28224.00	28224.00	15680.00
Asbestos Sheets	1 MT	0.00	4135.71	2143.21	2681.10	8960.02	4476.25
Beam Formwork	1 m^2	0.00	13.89	116.16	0.00	130.06	45.07
Blocks(4"x8"x16")	1000 Nos	0.00	5796.26	1974.82	0.00	7771.08	3855.14
Blocks(6"x8"x16")	1000 Nos	0.00	9288.72	3040.91	0.00	12329.63	6138.18
Blocks(8"x8"x16")	1000 Nos	0.00	9288.66	3671.56	0.00	12960.22	6340.93
Blockwork 4"	10 m^2	0.00	845.45	274.37	0.00	1119.81	557.91
Blockwork 6"	10 m^2	0.00	1339.58	420.99	0.00	1760.57	879.58
Blockwork 8"	10 m^2	0.00	1414.50	515.37	0.00	1929.87	951.55
Boulders	1 MT	0.00	67.89	0.00	0.00	67.89	37.72

Table 6.2 (Cont.)

Description	*Qty*	*Biomass*	*Fossil Fuel*	*Electricity*	*Imported*	*Total Energy(BioEq)*	*Total Energy(TOE)*
Bricks	1000 Nos	8528.17	86.35	0.00	0.00	8614.51	8576.14
Brickwork (9")	10m^2	10003.54	1428.67	299.12	0.00	11731.33	10893.42
Brickwork(41/2")	10 m^2	5048.67	649.84	130.86	0.00	5829.38	5451.77
Calicut tiles	1000 Nos	24816.89	725.20	1109.03	0.00	26651.12	25576.38
Cement	1 MT	0.00	6625.17	1869.48	0.00	8494.65	4281.77
Clay	1 m^3	0.00	7.87	0.00	0.00	7.87	4.37
Column Formwork	1 m^2	0.00	15.43	129.07	0.00	144.51	50.08
Concrete(1:1:2)	1 m^3	0.00	4158.28	1028.22	0.00	5186.50	2640.77
Concrete(1:2:4)	1 m^3	0.00	2649.30	598.23	0.00	3247.54	1664.19
Concrete(1:3:6)	1 m^3	0.00	2062.97	429.98	0.00	2492.95	1284.35
GI Welded Mesh2"	1 m^2	0.00	0.00	1.27	156.60	157.87	87.41
GI Wires	1 MT	0.00	0.00	0.00	63900.00	63900.00	35500.00
Glass	1 MT	0.00	11967.12	5266.04	0.00	17233.16	8341.66
Glazing(3mm)	1 m^2	0.00	91.91	40.44	0.00	132.35	64.06
Glazing(4-5mm)	1 m^2	0.00	138.10	60.77	0.00	198.87	96.26
Limestone	1 MT	0.00	61.20	0.00	0.00	61.20	34.00

Table 6.2 (Cont.)

Description	*Qty*	*Biomass*	*Fossil Fuel*	*Electricity*	*Imported*	*Total Energy(BioEq)*	*Total Energy(TOE)*
Logs	1 m^3	0.00	0.00	515.42	0.00	515.42	165.73
Logs-short term	1 m^3	0.00	0.00	515.42	0.00	515.42	165.73
Painting walls	10 m^2	0.00	0.29	5.02	360.00	365.31	201.78
Painting wood	10 m^2	0.00	0.43	7.10	783.00	790.53	437.52
Paints-Emulsion	1 l	0.00	0.02	2.02	95.40	97.45	53.66
Paints-Primer	1 l	0.00	0.02	2.02	223.20	225.25	124.66
Pcon(3)	1 Nos	0.00	80.16	28.00	120.60	228.77	120.54
Pcon(3.5)	1 Nos	0.00	135.25	49.30	261.00	445.55	235.99
Planks-Formwork	1 m^3	0.00	514.49	4302.41	0.00	4816.90	1669.24
Plywood	1 m^3	11548.00	256.45	1241.64	0.00	13046.09	12089.71
Purlins-Formwork	1 m^3	0.00	577.17	3246.45	0.00	3823.62	1364.52
PVC -MT	1 MT	0.00	38.80	11392.24	165600.00	177031.04	95684.65
PVC El.Conduits	1 m	0.00	0.00	0.99	14.40	15.39	8.32
PVC Resin	1 MT	0.00	0.00	0.00	165600.00	165600.00	92000.00
PVC-110-T400	1 m	0.00	0.05	16.08	234.00	250.14	135.20
PVC-20-T1000	1 m	0.00	0.00	1.33	19.80	21.14	11.43

Table 6.2 (Cont.)

Description	*Qty*	*Biomass*	*Fossil Fuel*	*Electricity*	*Imported*	*Total Energy(BioEq)*	*Total Energy(TOE)*
PVC-32-T1000	1 m	0.00	0.01	3.21	49.20	52.42	28.37
PVC-40-T600	1 m	0.00	0.01	3.32	50.40	53.74	29.08
PVC-63-T400	1 m	0.00	0.02	5.31	77.40	82.72	44.72
PVC-90-T400	1 m	0.00	0.04	10.92	158.40	169.36	91.53
PVC-Down Pipe	1 m	0.00	0.02	5.24	75.60	80.86	43.69
PVC-Gutters	1 m	0.00	0.02	6.84	99.00	105.86	57.21
Quarry Dust	1 m^3	0.00	206.13	0.00	0.00	206.13	114.52
Random Rubble	1 m^3	0.00	1184.34	168.25	0.00	1352.59	712.07
Raw(Emulsion)	1 l	0.00	0.00	0.00	95.40	95.40	53.00
Raw(Enamel)	1 l	0.00	0.00	0.00	223.20	223.20	124.00
Raw(Glass)	1 MT	0.00	0.00	0.00	0.00	0.00	0.00
Render 5/8"(1:1:5)	10 m^2	712.80	371.90	80.39	0.00	1165.09	945.26
Render5/8"(1:1:5)S	10 m^2	1069.20	384.09	80.39	0.00	1533.68	1308.44
Rendering1/2"(1:3)	10 m^2	0.00	445.99	112.17	0.00	558.16	283.84
Rendering3/4"(1:3)	10 m^2	0.00	673.05	168.25	0.00	841.31	428.02
Rendering3/8"1:3)	10 m^2	306.50	341.68	80.39	0.00	728.57	522.17

Table 6.2 (Cont.)

Description	*Qty*	*Biomass*	*Fossil Fuel*	*Electricity*	*Imported*	*Total Energy(BioEq)*	*Total Energy(TOE)*
Rmix Conc.	1 m^3	0.00	2528.87	661.58	0.00	3190.45	1617.65
Roofing(Asbestos)	10 m^2	0.00	663.84	342.91	428.40	1435.15	717.06
Roofing(calicut)	10 m^2	3350.28	145.54	149.72	0.00	3645.54	3479.28
Sand	1 m^3	0.00	0.00	0.00	0.00	0.00	0.00
Slab formwork	1 m^2	0.00	14.41	120.47	0.00	134.87	46.74
Slaked lime	1 MT	35640.06	716.28	0.00	0.00	36356.34	36037.99
Steel	1 MT	0.00	4766.81	3227.48	52200.00	60194.30	32686.01
Steel-Billets	1 MT	0.00	0.00	0.00	52200.00	52200.00	29000.00
Tim.Planks-rough	1 m^3	0.00	514.49	4384.87	0.00	4899.36	1695.75
Tim.Purlins-rough	1 m^3	0.00	577.17	3364.25	0.00	3941.42	1402.40

Table 6.3 - Regression Analysis for Fuel Prices with Imports

Item	Qtty.	Total(MJ)	Biomass	Fossil Fuel	Electricity	Imports	Price(Rs.)
Aggregates	1 m^3	99	0	99	0	0	950
Blocks(4"x8"x16")	1000 Nos.	3855	0	3220	635	0	15,000
Blocks(6"x8"x16")	1000 Nos.	6138	0	5160	978	0	24,000
Blocks(8"x8"x16")	1000 Nos.	6341	0	5160	1181	0	30,000
Bricks	1000 Nos.	8576	8528	48	0	0	1,400
Cement	1 MT	4282	0	3681	601	0	5,800
GI Welded Mesh2"x2"	1 m^2	87	0	0	0	87	112
Paints-Emulsion	1 l	54	0	0	1	53	250
Paints-Primer	1 l	125	0	0	1	124	300
Air-dry,tr.Timber(Planks)	1 m^3	1722	0	297	1425	0	1,180
Air-dry,tr.Timber(Purlin)	1 m^3	1429	0	332	1097	0	30,880
Calicut tiles	1000 Nos	25576	24817	403	357	0	7,000
Rmix Conc.	1 m^3	1618	0	1405	213	0	4,800
Sand	1 m^3	0	0	0	0	0	420
Slaked lime	1 MT	36038	35640	398	0	0	5,000
Steel	1 MT	32686	0	2648	1038	29000	36,000
Beam Formwork	1 m^2	45	0	8	37	0	432
Blockwork 4"	10 m^2	558	0	470	88	0	3,528
Blockwork 6"	10 m^2	880	0	744	135	0	5,158
Blockwork 8"	10 m^2	952	0	786	166	0	6,340
Brickwork(41/2")	10 m^2	5452	5049	361	42	0	2,347
Brickwork (9")	10 m^2	10893	10004	794	96	0	4,678
Concrete(1:2:4)	1 m^3	1664	0	1472	192	0	4,510
Concrete(1:3:6)	1 m^3	1284	0	1146	138	0	3,908
column Formwork	1 m^2	51	0	9	42	0	450
Glazing(3mm)	1 m^2	64	0	51	13	0	192
Glazing(4-5mm)	1 m^2	96	0	77	20	0	265
PVC-32-T1000	1 m	28	0	0	1	27	63
PVC-40-T600	1 m	29	0	0	1	28	98
PVC-63-T400	1 m	45	0	0	2	43	127
Painting walls	10 m^2	202	0	0	2	200	927
Painting wood	10 m^2	438	0	0	2	435	1,412
Pcon(3)	1 Nos	121	0	45	9	67	407
Pcon(3.5)	1 Nos	236	0	75	16	145	548
Roofing(Asbestos)	10 m^2	717	0	369	110	238	3,922
Roofing(calicut)	10 m^2	3479	3350	81	48	0	1,512
Render 5/8"(1:1:5)SR	10 m^2	945	713	207	26	0	905
Render5/8"(1:1:5)SL	10 m^2	1308	1069	213	26	0	1,555
Rendering1/2"(1:3)	10 m^2	284	0	248	36	0	1,409
Rendering3/4"(1:3)	10 m^2	428	0	374	54	0	1,426
Random Rubble Masonry	1 m^3	712	0	658	54	0	2,198
Slab formwork	1 m^2	47	0	8	39	0	435

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.884[a]	.781	.757	4346.1011

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	521.378	815.002		.640	.526	-1129.972	2172.729
	P_1	2.615E-02	.041	.049	.635	.529	-.057	.110
	P_2	2.271	.704	.337	3.225	.003	.844	3.697
	P_3	10.701	2.532	.458	4.225	.000	5.569	15.832
	P_4	.633	.162	.321	3.920	.000	.306	.961

Table 6.4 - Regression Analysis for Fuel Prices without Imports

Item	Qtty.	Total(MJ)	Biomass	Fossil Fue	Electricity	Price(Rs.)
Aggregates	1 m^3	99	0	99	0	950
Blocks(4"x8"x16")	1000 Nos	3855	0	3220	635	15000
Blocks(6"x8"x16")	1000 Nos	6138	0	5160	978	24000
Blocks(8"x8"x16")	1000 Nos	6341	0	5160	1181	30000
Bricks	1000 Nos	8576	8528	48	0	1400
Cement	1 MT	4282	0	3681	601	5800
Air-dry,tr.Timber(Planks)	1 m^3	1722	0	297	1425	1180
Air-dry,tr.Timber(Purlin)	1 m^3	1429	0	332	1097	30880
Calicut tiles	1000 Nos	25576	24817	403	357	7000
Rmix Conc.	1 m^3	1618	0	1405	213	4800
Sand	1 m^3	0	0	0	0	420
Slaked lime	1 MT	36038	35640	398	0	5000
Beam Formwork	1 m^2	45	0	8	37	432
Blockwork 4"	10 m^2	558	0	470	88	3528
Blockwork 6"	10 m^2	880	0	744	135	5158
Blockwork 8"	10 m^2	952	0	786	166	6340
Brickwork(41/2")	10 m^2	5452	5049	361	42	2347
Brickwork (9")	10 m^2	10893	10004	794	96	4678
Concrete(1:2:4)	1 m^3	1664	0	1472	192	4510
Concrete(1:3:6)	1 m^3	1284	0	1146	138	3908
column Formwork	1 m^2	51	0	9	42	450
Glazing(3mm)	1 m^2	64	0	51	13	192
Glazing(4-5mm)	1 m^2	96	0	77	20	265
Roofing(calicut)	10 m^2	3479	3350	81	48	1512
Render 5/8"(1:1:5)SR	10 m^2	945	713	207	26	905
Render5/8"(1:1:5)SL	10 m^2	1308	1069	213	26	1555
Rendering1/2"(1:3)	10 m^2	284	0	248	36	1409
Rendering3/4"(1:3)	10 m^2	428	0	374	54	1426
Random Rubble	1 m^3	712	0	658	54	2198
Slab formwork	1 m^2	47	0	8	39	435

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.809[a]	.654	.614	5172.0276

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	594.580	1226.943		.485	.632	-1927.438	3116.598
	P_1	2.528E-02	.050	.059	.507	.616	-.077	.128
	P_2	2.256	.847	.390	2.663	.013	.514	3.998
	P_3	10.640	3.056	.512	3.482	.002	4.359	16.921

Table 6.5a – Model Summary with Imports Ignoring Biomass and the Constant

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	P_2	2.408	.679	.356	3.545	.001	1.034	3.781
	P_3	11.027	2.441	.470	4.517	.000	6.089	15.964
	P_4	.628	.160	.279	3.936	.000	.305	.951

Table 6.5b – Model Summary without Imports Ignoring Biomass and the Constant

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	P_2	2.404	.799	.411	3.010	.005	.768	4.041
	P_3	11.012	2.872	.523	3.835	.001	5.130	16.895

Table 6.6 - Comparison of Regression Analysis Results and Actual Market Prices of Fuels

Fuel type	Price per Unit of energy Based on Regression Analysis (Rs./MJ) = A	Price per Unit of Energy Based on Actual Prices of Fuels (Rs./MJ) = B	A/B
Biomass	0.03	0.09	0.3
Fossil Fuel	2.3	0.27	8.5
Electricity	10.7	0.90	11.9
Imports	0.63	-	-

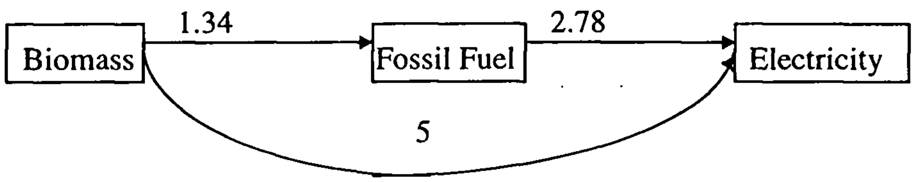
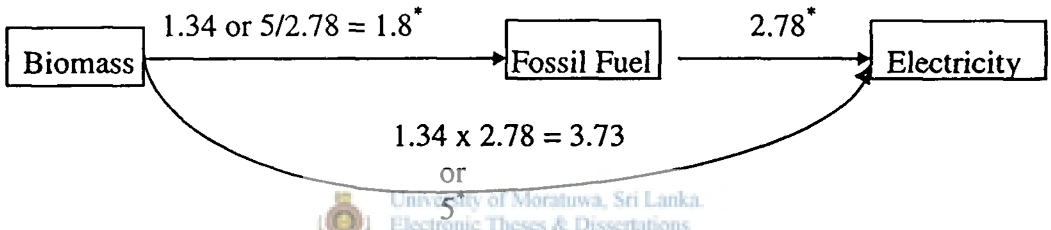


Figure 6.1 - Relationship between different fuels according to gathered data



* Final values used for the system to be consistent

Figure 6.2 - Adopted relationship between different fuels that is mutually consistent

7. COMPARISON OF ALTERNATIVE FORMS OF CONSTRUCTION

7.1. Introduction

The main objective of this analysis for alternative forms of construction is to identify materials with low energy contents and carbon coefficients, and to provide policy makers with data for possible policy measures.

Analyses carried out for alternative forms of construction described by different authors is given in Section 2.4. Alternative forms of construction relevant to Sri Lanka are discussed in this chapter.

Calculations based on energy content (in terms of TOE) and carbon emissions allow comparisons to be made between alternative materials on the basis of energy and carbon emission considerations, as opposed to financial ones. Though it may appear that the least energy intensive item is the preferred option, as described in Section 6.1, energy quality analysis too needs to be performed in order to make more realistic comparisons.

Therefore comparisons below are based on, (i) Energy contents in terms of TOE; (ii) energy contents in terms of bio-equivalent units; and (iii) carbon coefficients based on the actual fuel mix used.

In this analysis, calculations are based on average values of embedded energies and carbon coefficients. The estimates carried out in this chapter do not in general include material transport to the site from within the Colombo District, since it is negligible. The bio-equivalent energy calculations are based on concept outlined in Section 6.1. The carbon coefficients are based on fuel utilisation as described in Section 3.2.2, but also accounted for situations where carbon is liberated by a process or locked up in a material.

The detailed process descriptions for the alternatives are given in Section 4.5. The descriptions below mainly give the quantities required, based on the particular sizes and spans etc. chosen for the comparisons. Transport requirements from outside the Colombo District are also stated.

7.2. Alternative Forms of Construction for Purlins

7.2.1. Types of Purlins Considered

The energy inputs and carbon emissions corresponding to purlins made out of 3 different materials, i.e. timber, steel and prestressed concrete were analysed. The cross section of each purlin was selected so that it could carry a uniformly distributed load of 1 kN/m over a span of 3 m.

The cross section required for timber purlins is 3"x4". The raw material required for timber purlins is air-dry treated timber of 0.02 m^3.

The cross section required for steel purlins is 3"x3"x1/4" angle section. The raw material required is 0.02 MT of steel.

The cross section required for prestressed concrete purlins is 60 mm x 120 mm with 3 Nos. 6 mm diameter high tensile wires. The raw material requirement for a prestressed concrete purlin is 2.3 kg of steel, 9.3 kg of cement, 0.02 m^3 of aggregates and 0.01 m^3 of sand (i.e. grade 40 concrete).

7.2.2. Energy and Carbon Coefficient Comparisons

The energy inputs corresponding to timber, prestressed concrete and steel purlins, which have similar spans and approximately similar bending capacities, are 29 MJ, 121 MJ and 654 MJ respectively in terms of TOE, indicating that steel is around 23 times more energy intensive than timber and that prestressed concrete is around 4 times more energy intensive than timber. However on the basis of bio equivalent units the ratios are 15 and 3 respectively. These total energy input results are given in Table 7.1 and a comparison of embedded energies in terms of TOE and bio-equivalent units is depicted in Figure 7.1.

Where carbon emissions are concerned Table 7.1 indicates that 5.61 kg of carbon is stored for the timber purlin compared to 3.73 kg of carbon and 13.06 kg of carbon released to the atmosphere via prestressed concrete and steel purlins respectively (see Figure 7.2).

Therefore it appears that wood is the preferred option, and that policy measures to promote timber purlins are desirable.

7.3. Alternative Forms of Construction for Walls

7.3.1. Types of Walls Considered

The energy inputs and carbon emissions corresponding to 10 m^2 of 9" thick brickwork and 8" thick blockwork, both of which will have approximately similar strengths, are compared.

The raw material requirement for 10 m^2 of brickwork is 1173 Nos. of bricks, 0.16 MT of cement and 0.59 m^3 of sand. This is obtained from the BSR (Building 1988).

The raw material requirement for 10 m^2 of blockwork is 120 Nos. of 8"x8"x16" cement blocks, 0.04 MT of cement and 0.18 m^3 of sand. This is also obtained from the BSR (Building 1988).

7.3.2. Energy and Carbon Coefficient Comparisons

The energy inputs corresponding to 10 m^2 of brickwork and blockwork, which have approximately similar strengths,are 10.89 GJ and 0.95 GJ respectively in terms of TOE, indicating that brickwork is around 11 times more energy intensive than blockwork. However on the basis of bio equivalent units the ratio is around 6. These total energy input results are given in Table 7.2 and a comparison of embedded energies in terms of TOE and bio-equivalent units is depicted in Figure 7.3.

Where carbon emissions are concerned Table 7.2 indicates that 40.6 kg of carbon is released to the atmosphere via brickwork compared to 41.71 kg of carbon via blockwork. This puts brickwork and blockwork on a more equal footing (see Figure 7.4).

Therefore it appears that blockwork is the preferred option (based mainly on the large energy advantage it has), and that policy measures to promote blockwork are desirable.

7.4. Alternative Forms of Construction for Roofs

7.4.1. Types of Roofs Considered

The energy inputs and carbon emissions corresponding to 10 m^2 plan area of a calicut tile roof and an asbestos roof were compared.

The raw material requirement for a calicut tile roof is 0.02 m^3 of air-dry treated timber purlins, 0.06 m^3 of air-dry treated timber planks and 156 Nos. of calicut tiles. These quantities are obtained from the BSR (Building 1988). For the calicut tile transport distance an average value of 31 MJ was used (see also Section 4.5.2).

The raw material requirement for an asbestos roof is 0.11 m^3 of air-dry treated timber purlins and 12.29 m^2 of asbestos sheets. These requirements are also obtained from the BSR (Building 1988).

7.4.2. Energy and Carbon Coefficient Comparisons

The energy inputs corresponding to a calicut roof and an asbestos roof, which have a similar plan area of 10 m^2, are 4.1 GJ and 0.75 GJ respectively in terms of TOE, indicating that the calicut tile roof is around 5 times more energy intensive than an asbestos roof. However on the basis of bio equivalent units the ratio is only around 2. These total energy input results are given in Table 7.3 and a comparison of embedded energies in terms of TOE and bio-equivalent units is depicted in Figure 7.5.

Where carbon emissions are concerned Table 7.3 indicates that 18 kg of carbon is stored for the calicut tile roof compared to 6.53 kg of carbon released to the atmosphere via the asbestos roof (see Figure 7.6).

Therefore it appears that the calicut roof and the asbestos roof have competitive claims for being the preferred option, since the asbestos roof is the preferred option with respect to energy inputs while the calicut tile roof is the preferred option with respect to carbon emissions. The difference between both energy contents (at least on the basis of bio-equivalent units) and carbon emissions are also not very great.

7.5. Alternative Forms of Construction for Slabs

7.5.1. Types of Slabs Considered

The energy inputs and carbon emissions corresponding to 10 m^2 of an in-situ concrete slab and a prestressed concrete beam slab are compared. It is assumed that the slab is supported on two parallel 225 mm brick walls. The one - way span assumed is 3.5 m, and the designs were done to carry an imposed load of 2 KN/m^2.

The depth of the of in-situ concrete slab was selected as 125 mm. The entire slab is reinforced with 10 mm diameter bars at 150 mm spacing at mid span and 10 mm diameter bars at 300 mm spacing at supports. Secondary reinforcements (i.e. 10 mm diameter bars) are placed at 300 mm spacing. The raw material requirement is 1.25 m^3 of concrete (1:2:4), 0.08 MT of steel and 10 m^2 of formwork.

To construct a 10 m^2 prestressed concrete beam slab, one needs 6 nos. of 3.5 m prestressed concrete beams (with 5 nos. of 6 mm diameter high tensile wires) placed at 0.6 m spacing, GI welded mesh (50 mm x 50 mm) of 15 m^2, concrete (1:2:4) of 0.5 m^3 (for the structural concrete topping of 50 mm) and 10.5 m^2 of formwork.

7.5.2. Energy and Carbon Coefficient Comparisons

The energy inputs corresponding to an in-situ concrete slab and a prestressed concrete beam slab, which have a similar span of 3.5 m and area of 10 m^2, is 4.32 GJ and 3.75 GJ respectively in terms of TOE, indicating that the in-situ concrete slab is around 1.2 times more energy intensive than the prestressed concrete beam slab. However on the basis of bio equivalent units the ratio is around 1.1. This appears to put the in-situ concrete slab and prestressed concrete beam slab on an equal footing. These total energy input results are given in Table 7.4 and a comparison of embedded energies in terms of TOE and bio-equivalent units is depicted in Figure 7.7.

Where carbon emissions are concerned Table 7.4 indicates that 143 kg of carbon is released to the atmosphere via the in-situ concrete slab compared to 112 kg of carbon via the prestressed concrete beam slab (see Figure 7.8). Here too, the values are similar.

Therefore it appears that the prestressed concrete beam slab is the preferred option, but only marginally so.

7.6. Alternative Forms of Construction for Windows

7.6.1. Types of Windows Considered

The energy inputs and carbon emissions corresponding to aluminium and timber windows of size 1250 mm x 1550 mm with two shutters were compared.

The raw material required for an aluminium window is 15.7 kg of aluminium extrusions (7.96 kg for the frame and 7.74 kg for the shutter) and 1.9 m^2 of 3 mm thick glazing.

To construct a timber window one needs 0.04 m^3 of rough purlins for the frame, 0.01 m^3 of rough planks for the shutter, 1.5 m^2 of wood painting and 1 m^2 of 3 mm thick glazing.

7.6.3. Energy and Carbon Coefficient Comparisons

The energy inputs corresponding to an aluminium window and a timber window, which are of the same size, are 2.44 GJ and 0.20 GJ respectively in terms of TOE, indicating that the aluminium window is around 12 times more energy intensive than the timber window. On the basis of bio equivalent units the ratio is around 10. These total energy input results are given in Table 7.5 and a comparison of embedded energies in terms of TOE and bio-equivalent units is depicted in Figure 7.9.

Where carbon emissions are concerned Table 7.5 indicates that 11.22 kg of carbon is stored for the timber window compared to 50.32 kg of carbon released to the atmosphere via the aluminium window (see Figure 7.10).

Therefore it appears that timber windows are the preferred option, and that policy measures to promote timber windows are desirable.

7.7. Discussion

The analysis carried out indicates that among the more common construction materials considered, the lowest energy option appears to be the timber. For example, on the basis of TOE, timber purlins are around 23 times less energy intensive than steel purlins and 4 times less energy intensive than prestressed concrete purlins (see Section 7.2). Similarly timber windows are around 10 times less energy intensive than aluminium windows (see Section 7.6).

Wood products have a negative carbon coefficient, i.e. they store more carbon than is emitted in their use for house building, and thus give a beneficial effect towards halting global warming. For example, for purlins of 3 m span discussed in Section 7.2, 5.61 kg of carbon is stored for the timber purlin compared to 3.73 kg of carbon and 13.06 kg of carbon released to the atmosphere via prestressed concrete and steel purlins respectively. For windows of size 1250 mm x 1550 mm discussed in Section 7.6, 11.22 kg of carbon is stored for the timber window compared to 50.32 kg of carbon released to the atmosphere via the aluminium window.

Therefore to minimise adverse energy effects and to give a beneficial effect to halting global warming, policy measures to promote timber products are desirable.

However, because of the scarcity of timber, the use of timber as a raw material for building elements will result in further undesirable deforestation. The forest cover in Sri Lanka declined from around 70% in 1900 to 23.9% in 1992 according to the Forestry

Master Plan (1995). The extent deforested (clear felled) from forest plantations for the supply of timber in 1998 was 210 hectares. Although a greater area of 571 hectares were reforested by the Forest Department (Central 1998), the question still remains as to whether the local timber available can meet the increase in demand for timber.

It is also seen that materials which use timber fuels (e.g. bricks and tiles) consume more energy. However, the use of timber fuels is more competitive when compared on a bio-equivalent unit basis. For example, the energy input corresponding to a calicut tile roof and an asbestos roof, which have a similar plan area of 10 m^2, is 4.1 GJ and 0.75 GJ respectively in terms of TOE, indicating that the calicut tile roof (where timber fuels are the fuel used for the production of calicut tiles) is around 5 times more energy intensive than an asbestos roof; however on the basis of bio equivalent units the ratio is only around 2. When energy input corresponding to 10 m^2 of brick work and block work is considered, brick work (where again timber fuels are used for the production of bricks) is around 11 times more energy intensive than block work; however on the basis of bio-equivalent units the ratio is only around half that value. Furthermore, with respect to carbon emissions, wood fuels are considered to be self-sustaining, as the carbon released during burning is that which has been absorbed from the atmosphere and stored.

As Sri Lanka does not posses any fossil fuel reserves, we need to import all our fossil fuel. Though the electricity generating system in Sri Lanka is predominantly hydroelectric (i.e. hydro: thermal ratio of 66:34 in 1997), by the year 2005, if the CEB's generation plan is implemented without hindrance, this ratio of hydro:thermal will change to 37:63 (Siyambalapitiya 1997). Therefore it is observed that within about ten years the cost for thermal generation will be severe drain on Sri Lanka's net foreign exchange earnings. Therefore the need for Sri Lanka to develop its own sources of energy and raw material to meet the projected increase in demand is evident. Therefore policy measures may have to be put in place in order to reduce dependence on imported energy and raw materials.

Though the use of wood as a fuel once again raises the spectre of deforestation, fuel wood farming, a new form of agriculture of quick- growing trees grown by farmers specifically for fuel, has been shown to be one of the fastest developing and most environmentally friendly sources of energy in the United States, Scandinavia, Europe, China, etc. It is taking over from disbanded coal, oil and nuclear-fueled thermal electricity generating plants all over the world, not only as a more viable and economic way to generate power, but also to conserve the environment (Joseph 1998). Fuel-wood farming is particularly well suited to the humid-tropical region in which we live, as the growing of trees is well proven as the agriculture we do best. The distribution of land area in Sri Lanka is generally as represented in the Table 7. 6. Forests still cover 1.8 million hectares or 28% of our land, while plantation crops (tea, rubber, coconut) occupy 1 million hectares or 15% of the land. Paddy lands occupy a further half-million hectares or 8% of the country. However a further 1.5 million hectares of hitherto-under-utilised scrub and chena lands (i.e. 25% of the total land area) have been identified all over the country in the Forestry Master Plan (Joseph 1998). While unsuitable for the growing of food crops, is well suited to the farming of fast-growing fuel-wood trees.

The variety of energy sources and the consequences of raw material extraction would also result in differing environmental costs. For example, blockwork of 10 m^2 is 11 times less energy intensive than similar strength brickwork of 10 m^2 of as discussed in Section 7.3. Although the mining and transporting of river sand, which is a major raw material for blocks, may have a rather low energy cost, thus resulting in a low embedded energy for cement blocks, the environmental cost of sand mining may be high, giving rise as it does to river bed degradation and coastal erosion (National 1992). Hence, further studies must account for a comprehensive environmental costing of building materials, using the techniques of environmental economics.

The question also arises as to whether the embedded energies of imported raw materials should be given importance when making decisions regarding the choice of building materials. For example though aluminium windows are around 12 times more energy intensive than timber windows, 88% of the total embedded energy in the former is of imports (i.e. aluminium billets). Hence, on the one hand, the use of aluminium windows may be considered acceptable or even desirable, because the energy expenditure is incurred overseas, and not nationally. On the other hand a continuing shortage of world energy sources and an increasing world demand for energy will increase the market price of energy, which in turn will be reflected in the increased price of imports. Thus eventually the embedded energy of imports will play an important role in the choice of building materials.

Table 7.1 - Comparison of Purlins (3 m span & a udl of 1 kN/m)

Description	Qty.	Energy (TOE) - MJ Biomass	Fossil Fuel	Electricity	Imports	Total	Bio Equivalent Energy - MJ	Carbon Emission (KgC)
Timber	0.02 m^3	-	7	22	-	29	80	-5.6
Prestressed Concrete	1 Purlin	-	45	9	67	121	229	3.7
Steel (3"x3"x1/4")	0.02 MT	-	53	21	580	654	1,204	13.1

Table 7.2 - Comparison of Wall Construction - 10 m^2

Description	Qtty.	Energy (TOE) - MJ Biomass	Fossil Fuel	Electricity	Imports	Total	Bio Equivalent Energy -MJ	Carbon Emission (KgC)
Brickwork 9"	10 m^2	10,004	794	96	-	10,893	11,731	40.6
Blockwork 8"	10 m^2	-	786	166	-	952	1,930	41.7

Table 7.3 - Comparison of Roof Construction - 10 m^2 (Plan area)

Description	Qtty.	Energy (TOE) - MJ Biomass	Fossil Fuel	Electricity	Imports	Total	Bio Equivalent Energy - MJ	Carbon Emission (KgC)
CALICUT TILE ROOF								
Purlins	0.02 m^3	-	7	22	-	29	80	-6
Planks (Reepers)	0.06 m^3	-	18	86	-	103	298	-15
Calicut tiles	156 NOS	3,871	63	56	-	3,990	4,159	2
Transport of tiles			31					1
TOTAL ENERGY		3,871	118	163		4,122	4,592	-18
ASBESTOS ROOF								
Purlins	0.11 m^3	-	36	121	-	157	441	-30.83
Asbestos sheets	12.29 m^2	0	453	136	293	881	1,764	37.36
TOTAL ENERGY		0	490	256	293	746	2,205	6.53

Table 7.4 - Comparison of Slab Construction -10 m^2

		Energy (TOE) - MJ					Bio Equivalent	Carbon
Description	Qtty.	Biomass	Fossil Fuel	Electricity	Imports	Total	Energy - MJ	Emission (KgC)
INSITU								
Reinforcement	0.08 MT	-	212	83	2,320	2,615	4,816	52.2
Concrete (1:2:4)	1.25 m^3	-	1,840	240	-	2,080	4,059	126.2
Formwork	10 m^2	-	80	387	-	467	1,349	8.7
TOTAL ENERGY			2,132	711	2,320	5,163	10,224	187.1
PC BEAMS- SLAB								
3.5 m PC Purlins	6 Nos		451	95	870	1,321	2,673	41
GI welded mesh(50x50)	15 m^2			6	1,305	1,305	2,368	26
Concrete (1:2:4)	0.5 m^3		736	96	-	832	1,624	39
Formwork	10.5 m^2		84	407	-	491	1,416	9
TOTAL ENERGY			1,271	604	2,175	3,949	8,081	116

Table 7.5 - Comparison of Windows 1250x1550 1 NOS

		Energy (TOE) - MJ					Bio Equivalent	Carbon
Description	Qtty.	Biomass	Fossil Fuel	Electricity	Imports	Total	Energy - MJ	Emission (KgC)
ALUMINIUM								
Al extrusions	15.7kg	-	0	282	2,033	2,315	4,537	47.9
Glazing	1.9 m^2	-	97	25	-	122	251	2.4
TOTAL ENERGY			97	307	2,033	2,437	4,789	50.3
TIMBER								
Purlins	0.036 m^3	-	13	43	-	56	158	-11.2
Planks	0.01 m^3	-	3	14	-	17	49	-2.6
Painting	1.5 m^2	-	0	0	66	66	119	1.3
Glazing	1 m^2	-	51	13	-	64	132	1.3
TOTAL ENERGY		-	67	71	66	203	458	-11.2

Table 7.6 - Distribution of Land Area in Sri Lanka (Joseph 1998)

Total Land area	**6,500,000 ha.**	**100%**
Natural Forest	1,750,000 ha.	28%
Industrial Plantations (tea, rubber, coconut etc.)	1,000,000 ha.	15%
Paddy lands	500,000 ha.	8%
Scrub lands	(over) 600,000 ha.	10%*
Chena land	(over) 1,000,000 ha.	15%*
Other	1,510,000 ha.	23% (urban, housing, roads, shores, river-reservations, mountains etc.)

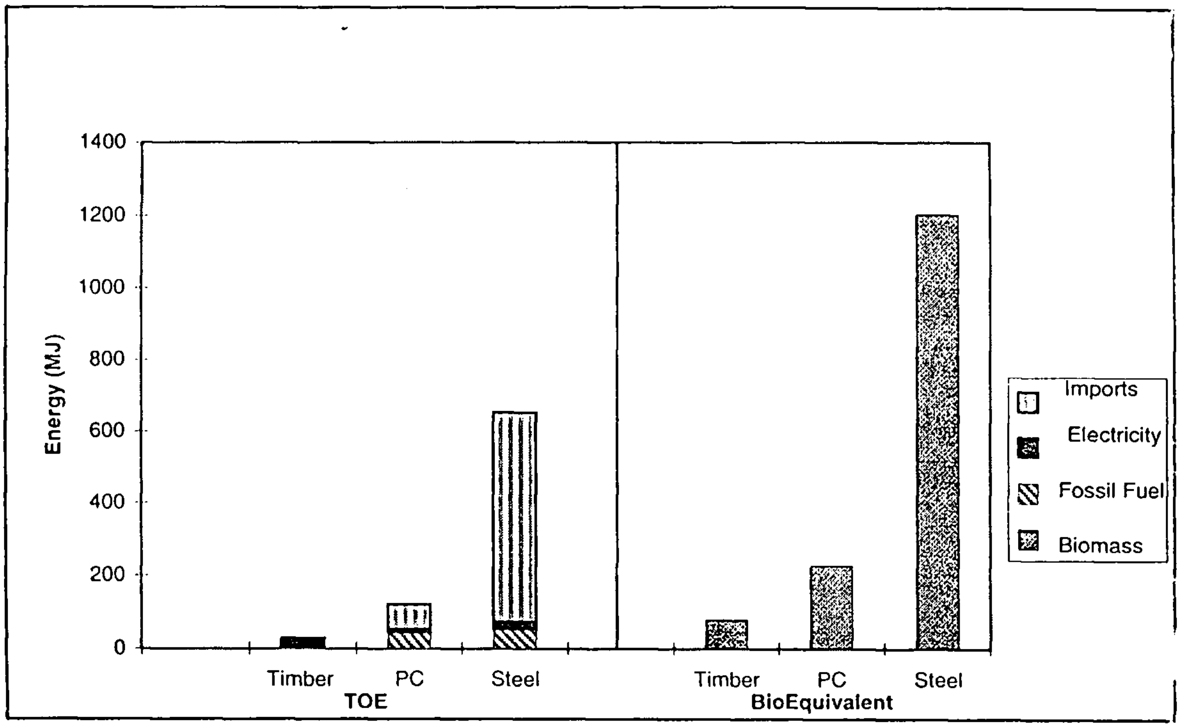


Figure 7.1 - Energy Comparison for Purlins

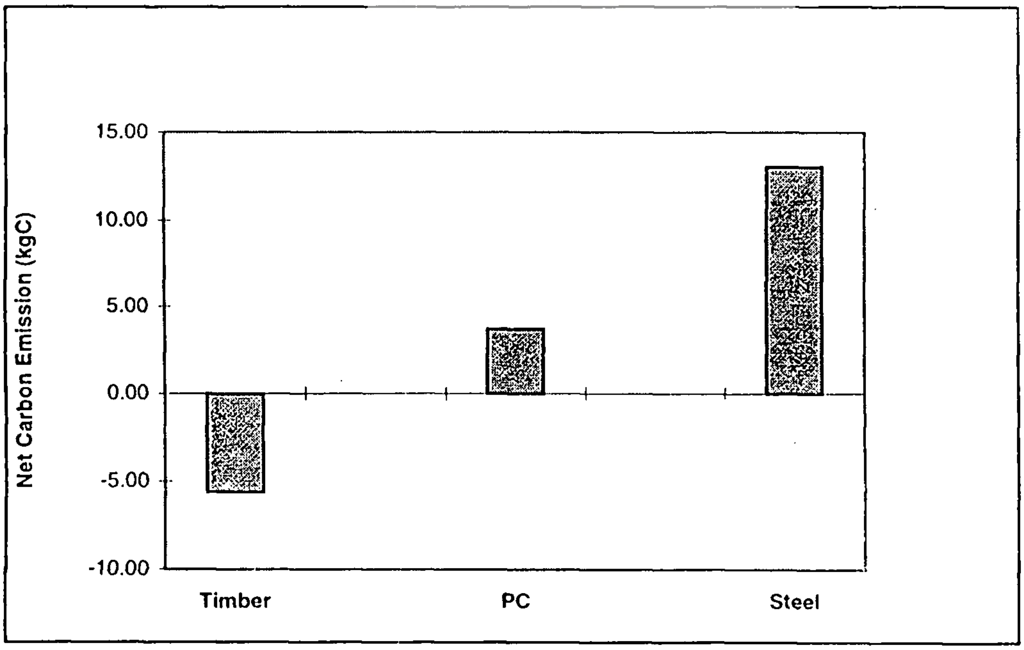


Figure 7.2 - Carbon Emission Comparison for Purlins

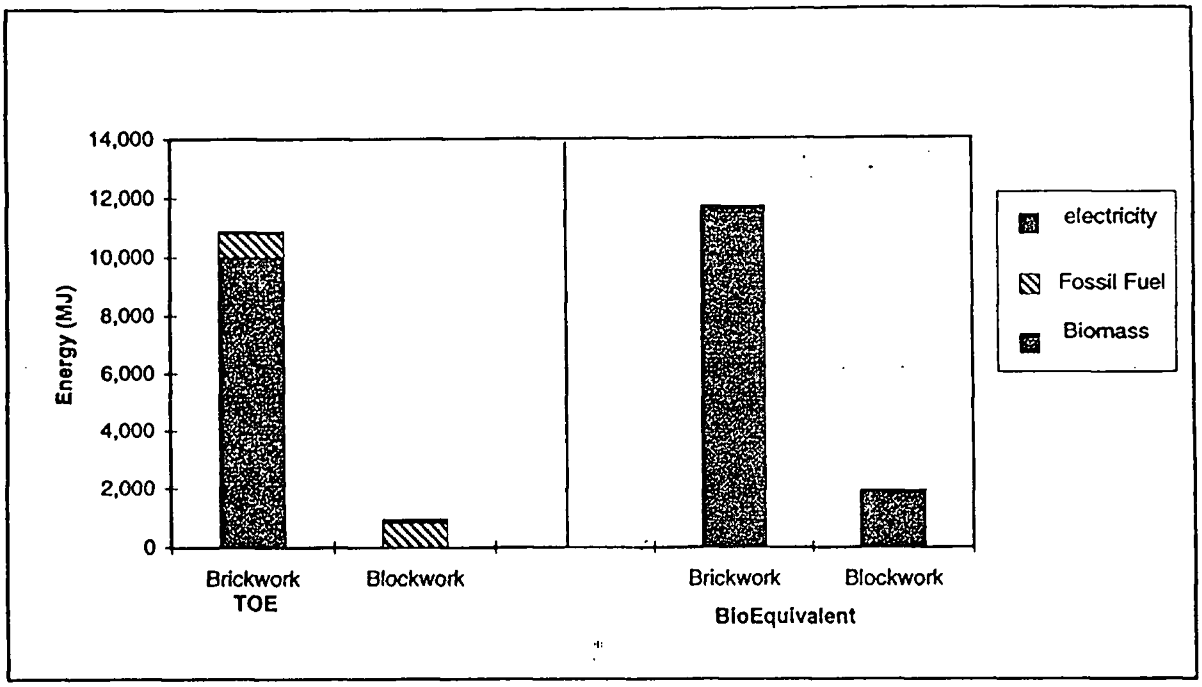


Figure 7.3 - Energy Comparison for Walls

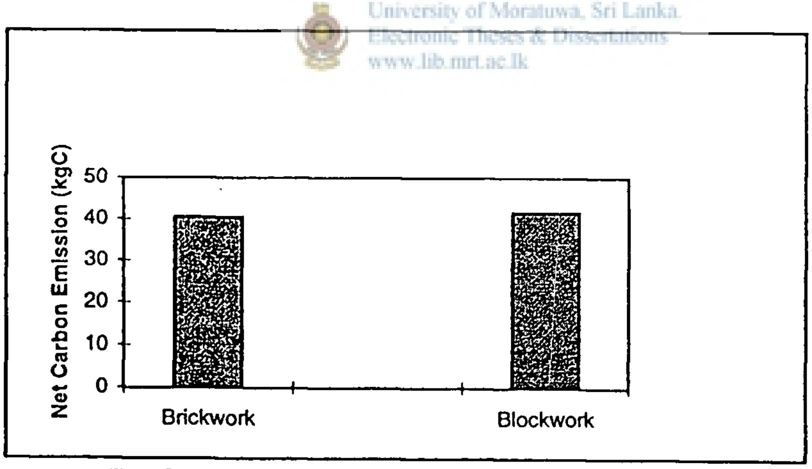


Figure 7.4 - Carbon Emission Comparison for Walls

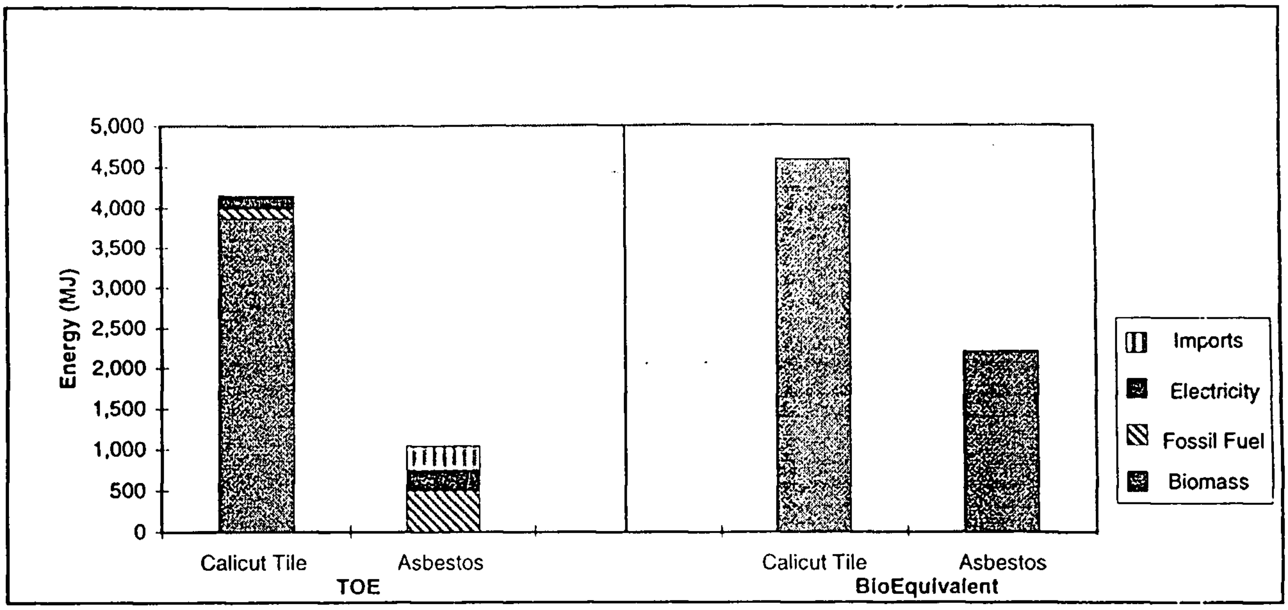


Figure 7.5 - Energy Comparison for Roof Construction

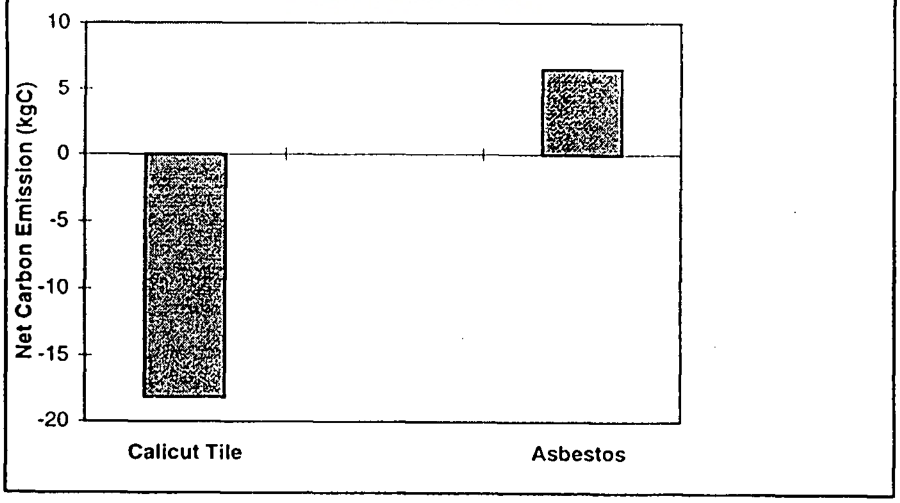


Figure 7.6 - Carbon Emission Comparison for Roof Construction

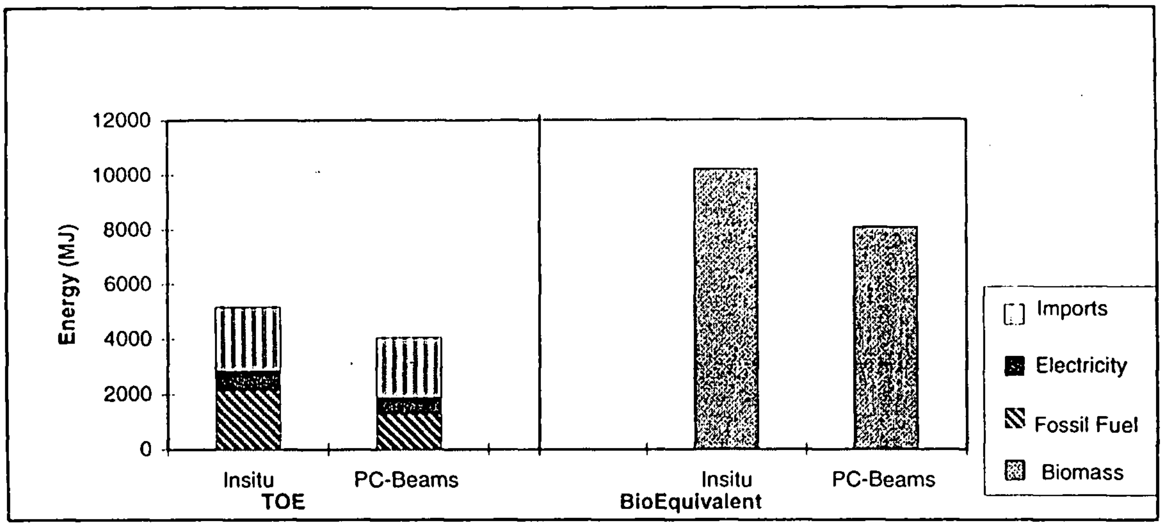


Figure 7.7 - Energy Comparison for Slab Construction

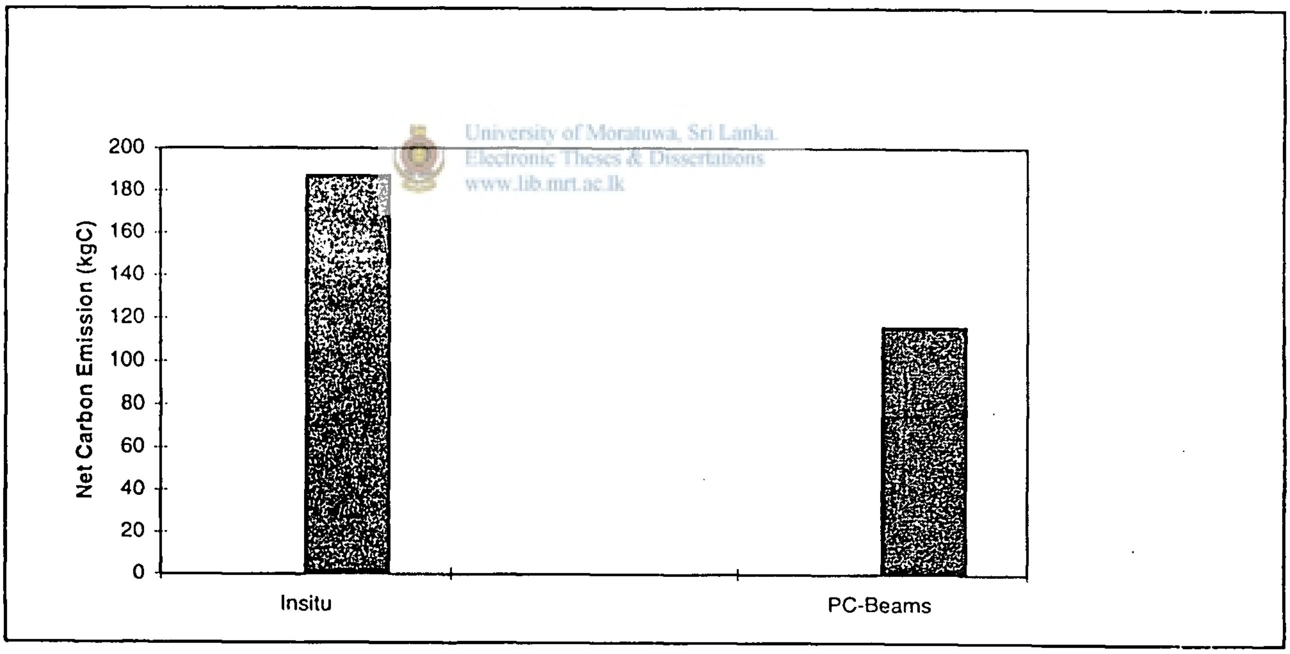


Figure 7.8 - Carbon Emission Comparison for Slab Construction

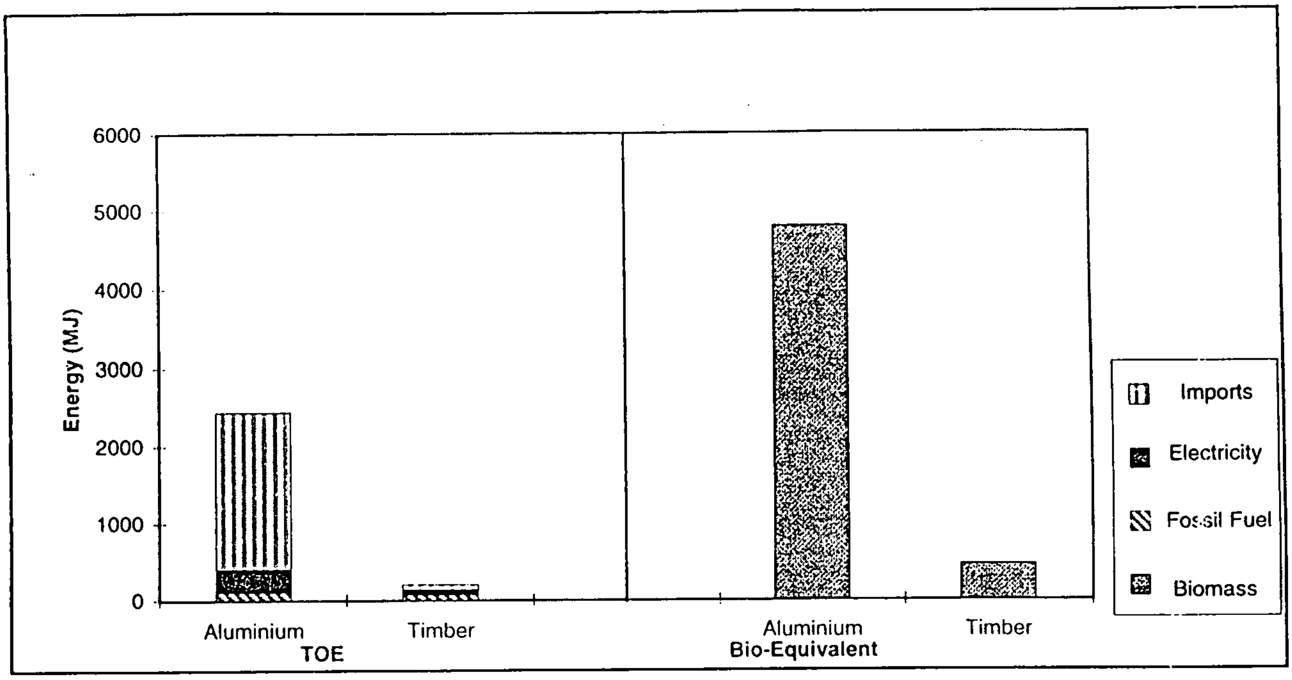


Figure 7.9 - Energy Comparison for Windows

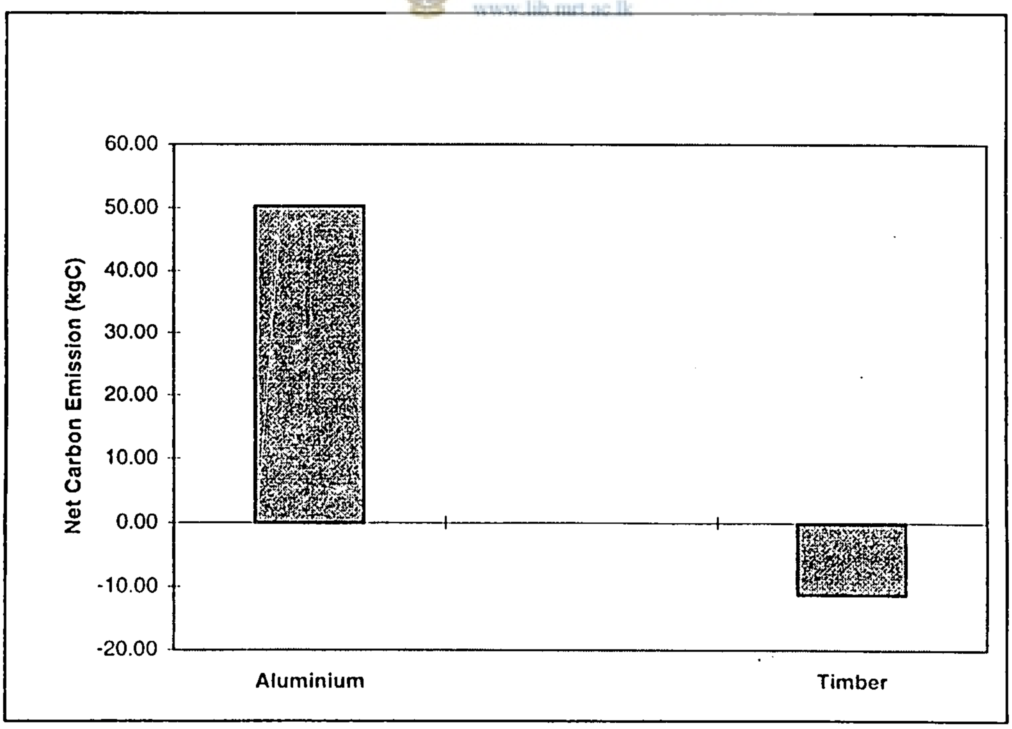


Figure 7.10 - Carbon Emission Comparison for Windows

8. EMBEDDED AND OPERATIONAL ENERGY IN BUILDINGS

8.1. Introduction

As described in Chapter 1, one of the objectives of this research is to arrive at basic data regarding the energies embedded in building materials, elements and finally in a building.

In cold countries such as the U.K. and U.S.A. the ratio between construction and annual operational energy for houses is around 3 to 6; in a temperate country that is a little warmer, this ratio goes up to around 9 (Baird and Chan 1983). However, in a tropical country such as Sri Lanka, the operational energy is likely to be very small as very little heating is required. Such energy, even over a nominal service life of 40 years, may be lower than the energy embedded in the building, except in the case of air conditioned buildings.

8.2. Selection of Buildings for the Energy Analysis

8.2.1. Selection of Building Type

Building construction accounts for approximately 69% of the total activities carried out in construction work (Statistical 1995). According to the gross fixed capital formation by type and purchaser at constant (1990) prices, out of the total building construction carried out approximately 64% is residential buildings (National 1995).

Out of the total housing units in Sri Lanka (excluding Northern and Eastern Provinces) Western Province has got the highest number of housing units of 30% whereas Central Province, Southern Province and North Western Province each has 15% of the total housing units. Out of the total housing units in the Western Province, Colombo District has got the highest number of housing units of 41%, while 38% is in the Gampaha

District (Statistical 1996). Therefore it is justifiable to select a typical house located in Colombo District for comparing embedded and operational energies.

In Sri Lanka according to the gross fixed capital formation by type and purchaser at constant (1990) prices out of the total building construction activity, only 36% were non residential buildings in 1994. This includes office buildings, hotels, industries, commercial, educational, hospitals, industrial, agricultural and other buildings (National 1995). In general, since Sri Lankan residential buildings are not air conditioned, the total number of air conditioned buildings would be well under 36%. However, an office building of eight storeys was analysed to find the effect of air conditioning loading on the operational energy.

8.2.2. Descriptions of Selected Buildings

Materials used in the construction of walls, roofs and floors are important from the point of view of permanency of construction and durability of housing units and also in terms of energy (as described in Chapter 7). Around 87% of the housing units consist of single houses with 58% having floor area between 25-100 m^2, and 16% having more than 100 m^2 (Statistical 1996). Therefore two houses were selected to represent the above ranges (See Table 8.1). One house was selected to lie in between 25-100 m^2 (i.e. 49 m^2) and other to be greater than 100 m^2 (i.e. 120 m^2).

From the point of view of durability, the material used in the construction of walls may be regarded as the most important item. It is observed that around 50% of all housing units are constructed out of bricks and 16% out of cement blocks (Statistical 1996). The most predominant types of roofing material used in construction are calicut tiles and asbestos, i.e. around 66% (Statistical 1996). Therefore the two houses selected had these materials for the walls and roofs (see Table 8.1). Sketches of the two houses selected are shown in Figures 8.1 and 8.2. These are in fact type plans of houses designed by the National Housing Development Authority (NHDA).

As discussed in Section 8.2.1 an office building of eight storeys with a total floor area of 3940 m^2 was used to find the effect of air conditioning loading on the operational energy. Since all the floors have the same dimensions and plan layout only a sketch of the first floor is shown in Figure 8.3. The building was a reinforced concrete framed building with brick infill walls and supported on a reinforced concrete raft foundation.

8.3. Estimation of Embedded Energies

In this study, estimates are made to find the total embedded energy of the buildings described above by "pricing" a bill of quantities in terms of energy. A spread sheet approach was used for these calculations. Data stored in the database were imported to the spread sheet by making use of a coding system as described in Chapter 5. The summaries of these total embedded energies for the typical houses are presented in Table 8.2 and Table 8.3. A similar analysis was carried out for the air conditioned office building and the summary of the total embedded energy is shown in Table 8.4. These calculations were done using average values of the embedded energies of Building materials and elements based on TOE values (see Chapter 5).

There was insufficient data to find the Sri Lankan energy requirement for finishing work such as tiling, sanitary fittings, electrical installations etc. Thus gross energies for the embedded energies of the buildings are calculated by neglecting these items. Therefore the actual construction gross (or embedded) energy requirement will be higher than the calculated value; however other researchers have shown that the contribution from the above items are not that large (Baird and Chan 1983).

Variations to these typical houses were also studied, using different building materials to represent maximum and minimum energy intensive houses. These were compared in order to get a range for the embedded energy of a house. These high and low energy intensive construction material types are based on the comparisons made in Chapter 7 (see Table 8.5). The energies per unit area of these maximum and minimum energy intensive houses are shown in Table 8.6. For the single storey house the gross energy value lies between 2.4 and 4.9 GJ/m^2, and for the 2 storey house it is between 3.5 and 5.7 GJ/m^2. For the air conditioned office building the actual gross energy is 5.5 GJ/m^2.

A review of the literature revealed a very wide range in the gross embedded energy per unit floor area of a building, calculated by different authors, even for the same building type. For residential construction, for example, the range was from about 1.2 to about 8 GJ per square metre (Baird and Chan 1983). The total embedded energies (or gross energy requirements) for houses calculated by various researchers from different countries for house construction are listed in Table 2.4. It is seen that the embedded energies estimated in this study (i.e. between 2.4 and 5.7 GJ/m^2) lie in that range calculated by other researchers, giving confidence regarding the accuracy of the estimated values.

8.4. Influence of Building Components on Embedded Energy

The range of influence on the total embedded energy of the houses by different components made of minimum and maximum energy intensive materials are shown in Table 8.7. These percentages are those of minimum and maximum energy intensive materials, calculated on the basis of minimum and maximum energy intensive houses respectively.

The influence from walls for the two storey house is from 10 - 44%. For the single storey house it is from 29 - 49%. The walls can contribute a significant proportion of the gross energy and they have a wide range as well. This is because there is a large difference in energy contents between brick walls and block walls (see Section 7.3). It also shows that choosing block walls instead of brick walls will make the greatest contribution to the reduction of gross energy in residential buildings of 1-2 storeys. The influence from roofs for the two storey house is from 4 - 7%, where this is 8 - 16% for the single storey house. It should be noted that this energy contribution from the roof is somewhat smaller than the corresponding cost contribution. The influence from windows is 0.6 - 3% for the single storey house and 0.2 - 4.5% for the two storey house. The contribution from the floor slab for the two storey house is 6-7%.

8.5. Operational Energy

As discussed in Section 2.6, in tropical countries such as Sri Lanka, embedded energy in a house (i.e. the construction gross energy requirement) could be as significant or greater than the operational energy over its service life. Therefore it is of interest to examine the ratio of the construction gross energy requirement to the annual operating energy requirements.

An indication of the annual operating energy requirement of the typical houses that have been used in this research was collected by a 1998/1999 survey of house hold electricity consumption (see Tables 8.8 and 8.9). This energy requirement can be of two types namely, (i) electrical energy required for the lightning and other electrical equipment and (ii) fuel used for cooking. Most of the houses surveyed make use of L.P. Gas for cooking, and the contribution from this is around half the contribution from electricity consumption.

For the air-conditioned office building the annual operational energy is 3706 GJ or 964 GJ/m^2 (see Table 8.10), based on an electricity consumption of 213,730 kWh over 4 months.

8.6. Comparison of Embedded and Operational Energy

The ratios between total embedded energy and annual operational energy for the above discussed buildings are given in Table 8.10. For house types A and B, the embedded energies for minimum and maximum energy material options are also given, in addition to the actual values. It is seen that the above ratio lies between 14 to 35 for the houses while for a building with air-conditioning loading it is 5.

This shows the large influence that air-condition loading has on the operational energy. The operational energy of the air conditioned building (964 MJ/m^2) is around 6 times higher than those for the houses (see Table 8.10).

As described in Section 8.2.1 however, though air conditioning has a large contribution towards the annual operational energy of a building, the total number of air conditioned buildings are small for a developing country such as Sri Lanka. Nevertheless, the above results show that the focus of energy efficient design for buildings with air-conditioning has to be on the operational energy. On the other hand, for houses, which are largely not air conditioned, the way to promote energy efficiency is by reducing the embedded energy through the appropriate choice of building materials. This is borne out not only by the high ratios of construction to operational energy ratio obtained, but also by the fact that the ratios for the houses with low energy materials is almost half those for the houses with high energy materials.

The total embedded energy to annual operating energy ratios obtained by other authors are listed in Table 2.9. It is seen that in the case of an air conditioned office building in Sri Lanka, this ratio becomes similar to the ratios obtained for houses in countries where space and water heating is required (Table 2.9 does not give ratios for office buildings in temperate countries - these may well be lower than those for houses). However, for houses without air conditioning in Sri Lanka the above ratio is very much higher than those obtained in temperate zone countries, and varies between 14 and 35 as seen in Figure 8.4.

Table 8.1 - Selection of a House

Type of Specification	Typical House Details Based on (Statistical 1996)	House Type A	House Type B
Floor Area (m^2)	25-100 - 58% > 100 - 16%	120	49
Roof	Calicut tiles or Asbestos -66%	Asbestos	Calicut Tiles
Wall	Bricks - 50% Cabook or Cement Blocks - 16%	Cement Blocks	Bricks
Type of structure	Single House - 87%	Single House (2 storey)	Single House (1 storey)

Table 8.2 - Summary of Total Embedded Energy of House Type A

Description	Biomass (MJ)	Fossil fuel (MJ)	Electricity (MJ)	Imports (MJ)	Total (MJ)
Concrete Work	0	19,482	3,357	10,005	32,843
Masonry Work in Foundations	0	10,527	866	0	11,393
Superstructure Concrete Work	0	24,069	7,224	36,366	67,659
Brickwork & Blockwork	14,529	25,266	4,778	0	44,572
Roof Work	1,426	3,726	1,106	2,380	8,638
Carpentry & Joinery	3,695	1,526	3,162	2,392	10,775
Plumbing	0	2	370	9,330	9,702
Plasterwork & Ceiling	87,999	29,361	4,051	1,013	122,424
Painting	0	13	132	16,400	16,546
TOTAL	107,648	113,973	25,045	77,886	324,552

Table 8.3 - Summary of Total Embedded Energy of House Type B

Description	Biomass (MJ)	Fossil fuel (MJ)	electricity (MJ)	Imports (MJ)	Total (MJ)
Concrete Work	0	275	33	0	308
Masonry Work in Foundations	5,002	8,950	751	0	14,704
Superstructure Concrete work	0	1,123	383	2,030	3,536
Brickwork & Blockwork	108,524	8,649	1,046	0	118,220
Roof Work	33,253	806	461	0	34,520
Carpentry & Joinery	1,848	1,200	3,564	1,007	7,619
Plumbing	0	1	123	3,099	3,223
Plasterwork	24,381	8,617	1,123	0	34,121
Painting	0	3	34	4,200	4,237
TOTAL	173,008	29,625	7,519	10,336	220,488

Table 8.4 - Summary of Total Embedded Energy of the Airconditioned Office Building

Description	Biomass (MJ)	Fossil Fuel (MJ)	Electricity (MJ)	Imports (MJ)	Total (MJ)
Concrete work	0	3,712,197	1,423,422	6,086,230	11,221,849
Brick Work	3,773,065	299,229	36,508	12,180	4,120,981
Joinery	805,242	13,505	39,998	32,969	891,714
Roof Plumbing	0	3	548	13,671	14,223
Water Distribution System	0	5	784	20,416	21,205
Drainage Work	0	16	2,703	67,918	70,637
Wall Finishes	701,931	162,912	20,032	0	884,875
Painting Work	0	160	1,590	197,060	198,809
TOTAL	5,280,238	4,188,027	1,525,585	6,430,444	17,424,293

Table 8.5 - High and Low Energy Intensive Construction Materials

Type of Construction	High Energy	Low Energy
Wall	Bricks	Cement Blocks
Roof	Calicut Tiles	Asbestos
Windows	Aluminium	Timber
Slab	Insitu Concrete	Prestressed Concrete Beam Slab

Table 8.6 - The Embedded Energies of Maximum and Minimum Energy Intensive Houses

		Storeys	
		1	2
Energy (GJ/m^2)	High	4.7	4.8
	Low	2.2	2.6

Table 8.7 - Range of Influence on the Total Embedded Energy of a House by Different Components made of High and Low Energy Intensive Materials

Type of Component	Influence Range for Different Types of Houses	
	Type A (2 Storey)	Type B (1 Storey)
Wall	0 10 44 100	0 29 49 100
Roof	0 4 7 100	0 8 16 100
Windows	0.6 3 100	0.2 4.5 100
Slab	0 6 7 100	

Table 8.8 - Survey Results of Annual Operational Energy for House Type A

House No.	kWh per each Month													Avg. Monthly Units (kWh)	Avg. Annual			Total Energy (GJ)
	1	2	3	4	5	6	7	8	9	10	11	12	13		Units (kWh)	TOE (MJ)	Cooking (GJ)	
1	212	155	134	212	139	139	135	184	206	204	201	200	200	179	2142	12383	3500	15.88
2	305	279	281	311	294	295	285	302						294	3528	20392	6900	27.29
3	137	112	129	126	122	130								126	1512	8739	4600	13.34
4	77	149	119	144										122	1467	8479	6900	15.38
5	74	68	85	77										76	912	5271	4600	9.87
6	112	115	112	120	115									115	1378	7963	4600	12.56
7	110	122	102	105										110	1317	7612	4600	12.21
8	250	243	308											267	3204	18519	6900	25.42

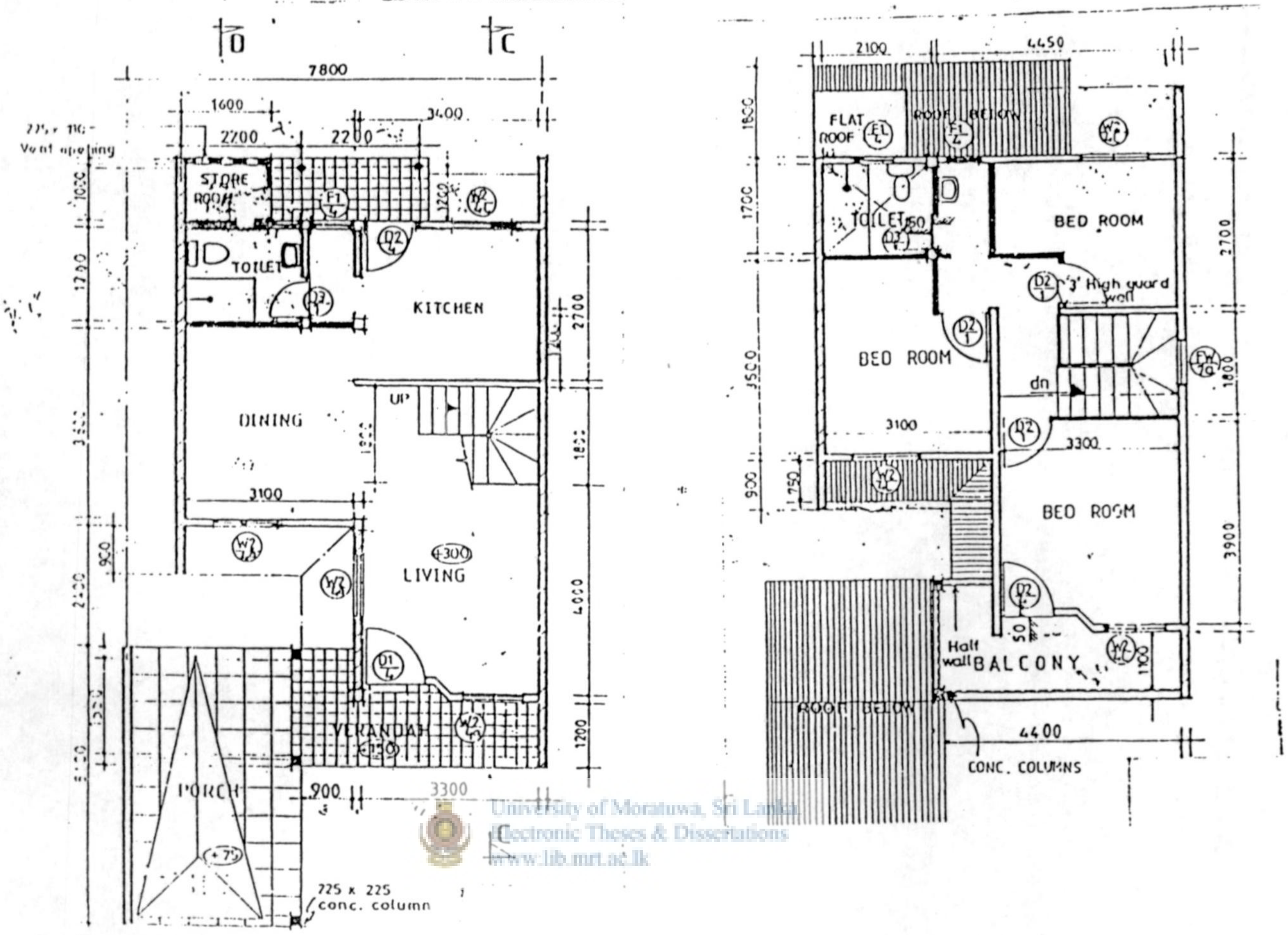
Table 8.9 - Survey Results of Annual Operational Energy for House Type B

House No.	kWh per each Month													Avg. Monthly Units (kWh)	Avg. Annual Units (kWh)	TOE (MJ)	Cooking (GJ)	Total Energy (GJ)
	1	2	3	4	5	6	7	8	9	10	11	12						
1	64	59	49	58	66	65	59	58	57	62	66	67		61	732	4,231	4,600	8.83
2	62	64	54	56	55	56	48	66	50	50	58	56		56	675	3,902	4,600	8.50
3	63	67	57	28										54	648	3,745	1,725	5.47
4	75	30	30	92	83	80	49	50	75	85	50			54	649	3,751	1,725	5.48
5	92	90	88	89	90	92	96							92	1108	6,404	3,450	9.85
6	62	68	65	64	66									62	744	4,300	4,600	8.90
7	57	70												65	780	4,508	3,450	7.96
8														70	840	4,855	3,450	8.31
9														69	828	4,786	2,123	6.91
10	76	92												84	1008	5,826	2,760	8.59
11	98	95												97	1158	6,693	3,450	10.14
12														75	900	5,202	1,971	7.17

Table 8.10 - Comparison of Embedded and Operational Energy

Type of house	Construction Energy(Embedded) (GJ)			Annual Operational Energy (GJ)	Construction/ Annual Operational		
	High	Low	Actual		High	Low	Actual
A (2 Storey)	581	313	325 (3.6 GJ /m^2)	16.5 (138 MJ/m^2)	35	19	20
B (1 Storey)	231	107	220 (4.5 GJ/m^2)	8 (163 MJ/m^2)	29	14	28
Air Conditioned Office Building			17,424 (4.4 GJ/m^2)	3,706 (964 MJ/m^2)			5

Total Floor Area : 120 m^2



Ground Floor Plan

Upper Floor Plan

Figure 8.1 – Ground Floor and Upper Floor Plans of House Type A

Floor Area : 49 m^2

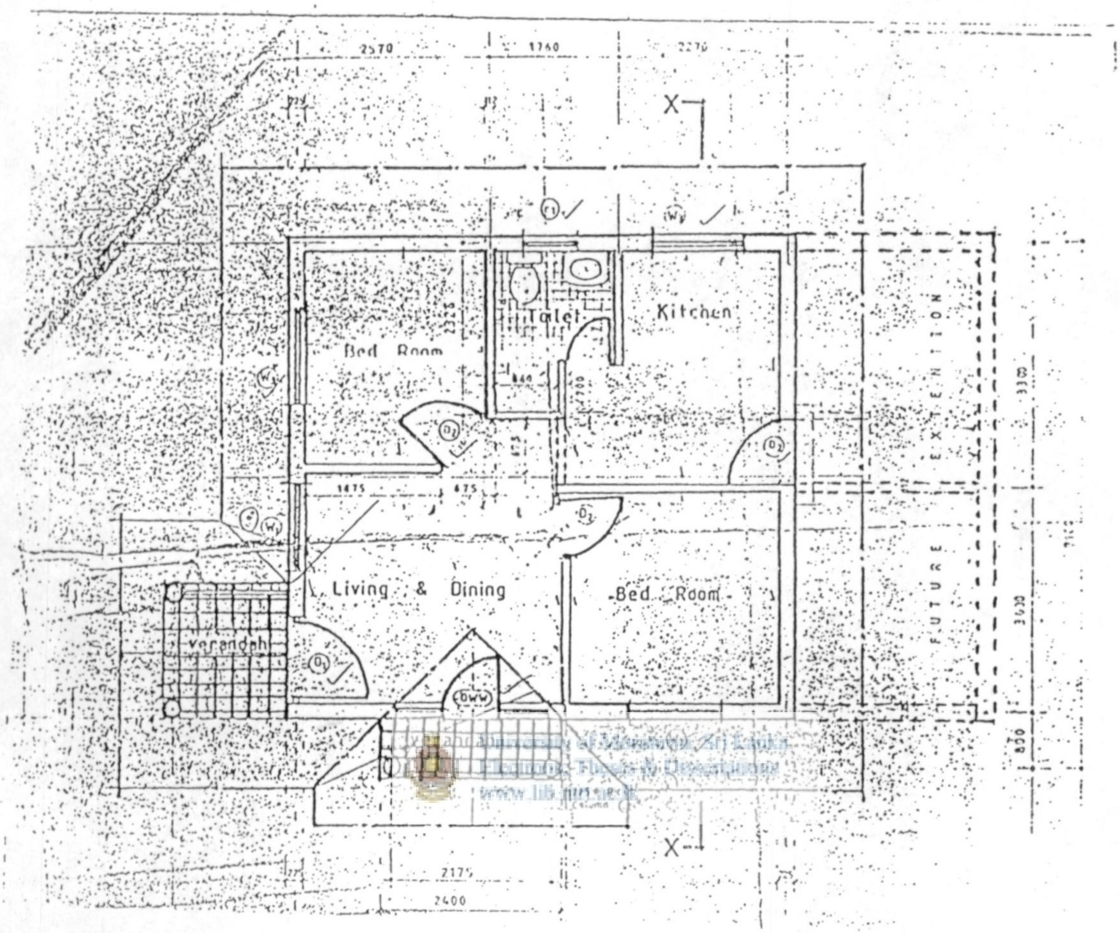


Figure 8.2 – Floor plan of House Type B

Total Floor Area of the Building : 3940 m^2

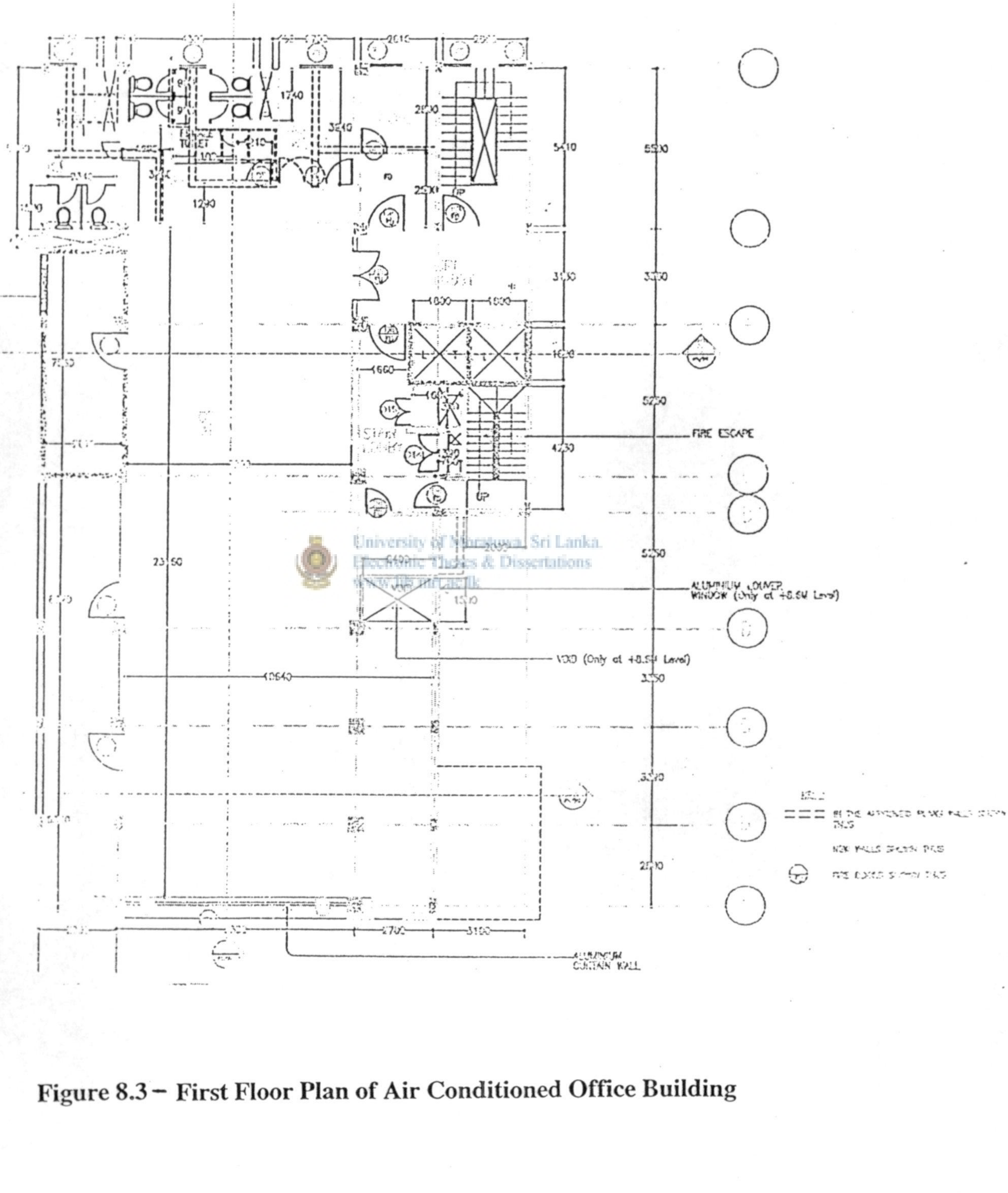


Figure 8.3 – First Floor Plan of Air Conditioned Office Building

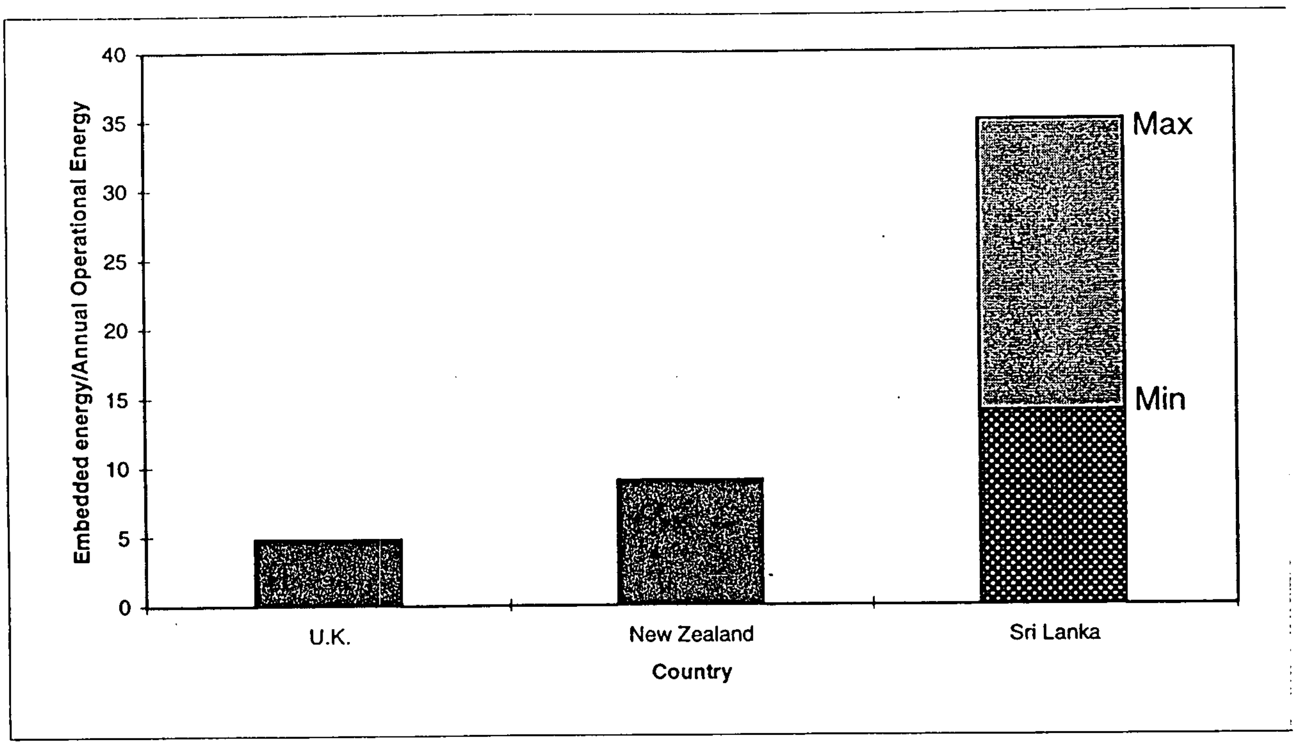


Figure 8.4 - Comparison of Embedded and Operational Energy for Houses

9. CONCLUSIONS AND RECOMMENDATIONS

Since many recommendations (both for implementation and further research) flow from the conclusions, both conclusions and recommendations are grouped under various topics. The conclusion and recommendation components are however identified within each topic.

9.1. Hierarchical Arrangement of Building Elements and their Sub Components

(Conclusion)

All building elements (e.g. brickwall), materials (e.g. bricks) and "primitive" raw materials (e.g. clay) can be placed in an aggregation-decomposition hierarchy. Each stage of a building material can be considered to have energy inputs that are defined as "proximate" (i.e. production energy and transport of raw materials) and "remote" (i.e. embedded energy of raw materials). This product oriented hierarchy complements the IFIAS (1974) process oriented hierarchy. The process analysis carried out here basically captures most of the energy inputs associated with levels 1 and 2 in the IFIAS (1974) scheme, where these two levels accounts for around 90% of the embedded energy in a product.

9.2. Database Design and Usage

(Conclusion)

The relational database that was designed and the recursive algorithm that was developed can be used to represent and calculate the embedded energies and carbon coefficients of building materials and elements that are hierarchically arranged, such that some materials are raw materials of others. It can also handle multiple sources of data and perform the calculations to give the energies corresponding to average, maximum and minimum values. The energy data is also classified in two ways in the database - i.e. (i) by process (production, transport of raw materials and embedded energy of raw materials) and (ii) by fuel type (biomass, fossil fuel, electricity and imports). The database outputs can be exported to a spreadsheet to perform other analyses.

9.3. Transport Energy

(Conclusion)

In the analysis carried out here it was assumed that the final building is located in Colombo City for the purpose of determining transport and hence total energies. The contribution from the transport component was found to be small except in the cases where quarry products, timber products, cement blocks and concrete where contribution is around 10-20%. Therefore it is seen that these database values can be used, with some caution, for buildings even outside the Colombo City or District.

9.4. Energy Quality Analysis

(Conclusion)

According to energy quality calculations carried out (based on efficiency considerations) 1 GJ of electricity is equivalent to 5 GJ of biomass energy and 1 GJ of fossil fuel is equivalent to 1.34 GJ of biomass energy. In addition to that, 1 GJ of electricity is equal to 2.78 GJ of fossil fuel energy.

For the conversion system to be mutually consistent, the fossil fuel to electricity factor is maintained at 2.78 (based on a 36% efficiency of thermal electricity), as it is fairly well established. The biomass to fossil fuel factor is increased from 1.31 to 1.8 in order to increase this "quality gap" rather than reducing the "quality gap" between biomass and electricity. The energy contents of building materials could thus be compared on the basis of an equivalent amount of the lowest quality energy (i.e. biomass energy), and the energy contents were obtained in "bio - equivalent" units of energy.

(Recommendation)

The study adopted an efficiency based approach for comparing energy quality, since it has a clear basis and since it will not distort the original energy values too much. However, a more fundamental approach can be considered in future studies, using the concept of exergy, by which the degradation of thermodynamic potential can be estimated.

9.5. Relationship between Selling Prices of Building Materials and Fuel Types

(Conclusion)

Although the price per unit of biomass energy based on the actual prices of the products is not a very reliable one, it is around one third of the actual price per unit of biomass energy. Manufacturing done using wood fuel is mostly in remote areas where raw materials and human energy sources are widely available and where capital investment and overheads are low (e.g. in brick manufacturing). Therefore in general it is possible for the price of products to be close to the actual price of energy. For fossil fuel and electricity on the other hand, the actual prices of products are much higher than the actual prices of the energy sources. This may be due to the high initial cost of the machinery required and their maintenance costs and other overheads, together with the cost of raw materials. It is also probably reflecting the fact that there is greater value addition in processes that use fossil fuel and electricity as energy sources.

9.6. Comparison of Alternative Forms of Construction

(Conclusion)

The analysis carried out indicates that among the more common construction materials considered, the lowest energy option appears to be the timber. Wood products have a negative carbon coefficient, i.e. they store more carbon than is emitted in their use for house buildings and thus give a beneficial effect towards halting global warming as well. Therefore to minimise adverse energy effects and to give a beneficial effect to halting global warming, policy measures to promote timber products are desirable.

However, because of the scarcity of timber, the use of timber as a raw material for building elements will result in further undesirable deforestation. Although a greater area is currently being reforested by the Forest Department than is being officially deforested, the question still remains as to whether the local timber available can meet the increase in demand for timber. Biotechnology may well play an important role in this regard in the future.

9.7. Comparison of Alternative Sources of Fuel

(Conclusion)

It is also seen that materials which use timber fuels (e.g. bricks and tiles) consume more energy. However, the use of timber fuels is more competitive when compared on a bio-equivalent unit basis. Furthermore, with respect to carbon emissions, wood fuels are considered to be self-sustaining, as the carbon released during burning is that which has been absorbed from the atmosphere and stored.

As Sri Lanka does not posses any fossil fuel reserves, we need to import all our fossil fuel. The need for Sri Lanka to develop its own sources of energy and raw material to meet the projected increase in demand is evident. Therefore policy measures may have to be put in place in order to reduce dependence on imported energy and raw materials.

(Recommendation)

Though the use of wood as a fuel once again raises the spectre of deforestation, fuel wood farming, a new form of agriculture of quick- growing trees grown by farmers specifically for fuel, has been shown to be one of the fastest developing and most environmentally friendly sources of energy. Fuel-wood farming is particularly well suited to the humid-tropical region in which we live, as the growing of trees is well proven as the agriculture we do best.

9.8. Overall Environmental Costs

(Recommendation)

The variety of energy sources and the consequences of raw material extraction would also result in differing environmental costs. For example although the mining and transporting of river sand, which is a major raw material for cement blocks, may have a rather low energy cost, thus resulting in a low embedded energy for cement blocks, the environmental cost of sand mining may be high, giving rise as it does to river bed degradation and coastal erosion (National 1992). Hence, further studies must account for a comprehensive environmental costing of building materials, using the techniques of environmental economics.

9.9. Imported Energy

(Conclusion)

The question also arises as to whether the embedded energies of imported raw materials should be given importance when making decisions regarding the choice of building materials. For example, though aluminium windows are around 12 times more energy intensive than timber windows, 88% of the total embedded energy in the former is of imports (i.e. aluminium billets). Hence, on the one hand, the use of aluminium windows may be considered acceptable or even desirable, because the energy expenditure is incurred overseas, and not nationally. On the other hand a continuing shortage of world energy sources and an increasing world demand for energy will increase the market price of energy, which in turn will be reflected in the increased price of imports. Thus eventually the embedded energy of imports will play an important role in the choice of building materials.

9.10. Influence of Building Components on Embedded Energy

(Conclusion)

The energy contribution from walls for the typical two storey house is from 10- 44%. For the single storey house it is from 29 - 49%. The walls can contribute a significant proportion of the gross energy and have a wide range as well. This is because there is a large difference in energy contents between brick walls and block walls. It also shows that choosing block walls instead of brick walls will make the greatest contribution to the reduction of gross energy in residential buildings of 1-2 storeys. The contribution from roofs for the two storey house is from 4 - 7%, where this is 8 - 16% for the single storey house. The contribution from windows is 0.6 - 3% for the single storey house and 0.2 - 4.5% for the two storey house. The contribution from the floor slab for the two storey house is 6 - 7%.

9.11. Significance of Construction Energy Compared to Operational Energy in Sri Lanka

(Conclusion)

The ratio between total embedded energy and annual operational energy for the buildings selected lies between 14 to 35 for the houses while for an office building with air-conditioning loading it is 5. This shows the large influence that air-condition loading has on the operational energy. It is seen that in the case of an air conditioned building the above ratio becomes similar to the ratios obtained for houses in countries where space and water heating is required. However, for houses without air conditioning in Sri Lanka the above ratio is very much higher than those obtained in temperate zone countries.

However, though air conditioning has a large contribution towards the annual operational energy of a building the total number of air conditioned buildings are small for a developing country such as Sri Lanka,. Nevertheless, the above results show that the focus of energy efficient design for buildings with air conditioning has to be on the operational energy. On the other hand, for houses, which are largely not air conditioned, the way to promote energy efficiency is by reducing the embedded energy through the appropriate choice of building materials. This is borne out not only by the high ratios of construction to operational energy ratio obtained, but also by the fact that the ratios for the houses with low energy materials is almost half those for the houses with high energy materials.

9.12. Life Cycle Energy Costing

(Recommendation)

Although not dealt with in this research, life cycle energy costing is a direction in which this work can be extended. A notional life span would need to be assumed, and this may well depend on socio-economic change rather than on the durability of buildings. A discount rate would also have to be assumed for energy inputs, and the energy inputs for repair and maintenance also assessed. Projections for changes in operational energy consumption may need to be made, and these may well reduce with time, due to approaches such as demand side management. The net effect of life cycle costing is likely to increase the significance of construction energy over that of operational energy, as the former will be annuitised with a positive discount rate.

9.13. Combination of Energy and Environmental Indicators

(Recommendation)

When alternative forms of construction are considered, in selecting the optimum solution based on energy and carbon emission calculations, in some cases the selection criteria gives contradictory results, as in the case of roof construction. In terms of energy the preferred option is the asbestos roof whereas on the basis of carbon emission the preferred option is the calicut tiled roof. Therefore there is a clear need to find a way to combine these energy and environmental indicators, after considering other environmental indicators as well (i.e. SO_x, NO_x, particulates etc.).

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