THE ENVIRONMENTAL IMPACT OF FRAME MATERIALS

AN ASSESSMENT OF THE EMBODIED IMPACTS FOR BUILDING FRAMES IN THE UK CONSTRUCTION INDUSTRY.

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Mike Jaggs for reminding me that there are people worse off than me. Him.

CONVERSION FACTORS

Conversion Factors	
1 tonne of UK crude Oil	7.55 Barrels
1 Gallon	4.54609 Litres
1 Kilowatt (kW)	1000 Watts
1 Megawatt (MW)	1000 Kilowatts
1 Gigawatt (GW)	1000 Megawatts
1 Terawatts (TW)	1000 Gigawatts
1 Petawatt (PW)	1000 Terawatts
1 Gigawatt Hour (GWH)	0.08598 Thousand Tonnes Oil Equivalent
1 Kilowatt Hour (kWh)	3.6 Megajoules (MJ)
1 MegaJoule/Kilogram (MJ/kg)	1Gigajoule/Tonne (GJ/t)

DECLARATION

Except where specific reference has been made to the work of others, this thesis is the result of my own work.

No part of this thesis has been submitted to any University or other educational establishment for a degree, diploma or other qualification.

Martin Brocklesby Date

SUMMARY

There are many important environmental issues involved in the construction and use of buildings which are either undergoing or require further research. The lack of detailed embodied energy assessments models has been identified and limits possible environmental analysis. This study examines the current state of research into the environmental impact of frame materials, assesses the quality and range of data available, sets up a new framework for evaluation of materials and uses several example structures to assess the environmental impact. This has been achieved by, firstly, studying the environment related literature available concerning the frame of the building, separate from other considerations, to provide a clear understanding of the processes involved. Second, data is extracted from the literature and processed to provide a homogenous approach and level field from which frame analysis can take place. Gaps in the available data are identified.

Third, the identified gaps are filled using data derived from sources ranging from manufacturers' literature to direct analysis of on site activities. Fourth, a model has been created to assess the environmental impact of the building frame. The factors assessed within the remit of environmental impact are: embodied energy, embodied CO_2 and transportation hours. The embodied energy includes the primary energy for all raw materials, transportation, office overheads and contractor operations. These are calculated from the winning of raw materials, through manufacture, to demolition and recycling. Embodied CO_2 encompasses the same range of data, but with respect to the CO_2 , transportation hours estimate the time spend on the road by vehicles involved in the embodied energy and CO_2 calculations. Finally data from several buildings has been used, to evaluated the environmental merits of each with respect to each other and to other buildings for which calculations have been performed. Conclusions have been draw and further work suggested.

1. INTRODUCTION

Modern environmentalism came to the fore in the sixties due to a combination of factors including an increased ability to analyse the complex interactions and interrelationships involved, physical realities of pollution and environmental damage and increased media coverage and public involvement. This provided both the incentive and the ability to examine the long term consequences of human action on the environment. However, as with most spheres of scientific activity, there is no single answer to the environmental problems reviewed and no unified agreement on what actions should be taken or even if the 'symptoms' have been correctly identified.

There are many points of major interest to environmentalists, but possibly the factors of most concern in construction are the depletion of resources, both renewable and exhaustible, damage to the environment and the production of 'greenhouse' gases. The search for improved environmental friendliness in the construction industry has a number of causes - cost effectiveness, need for a new selling point, fear of legislation and increased costs, and the fear of adverse public opinion. An important point to remember is that, given this is a relatively new area, there are areas where fixed definitions are lacking and which are therefore open to differing interpretation. Solutions to today's perceived questions may turn out to be the cause of more problems than they solve. One such policy change which has a small impact on construction involves the trend to use diesel as a fuel in cars and the subsequent realisation that rather than being less polluting, these may be more harmful waste in diesel than new petrol alternatives. This is not the first area where perceptions have changed and will probably not be the last.

These grey areas not withstanding, there is general agreement that action needs to be taken to reduce the environmental impact of human activities.

1.1 Sustainability

The ideas of reducing environmental impact and examination of ecological issues fall broadly under the heading of 'sustainability' and 'sustainable development'. Sustainable development is not a clearly defined idea and could mean different things to different people. More radical environmentalists might argue that the term 'sustainable development' is an oxymoron, and that no development is sustainable in so far as all development incurs environmental penalties of one sort or other.

For the purposes of this project the terms sustainability and sustainable development have been taken to mean a move towards balancing economic and environmental costs and adjusting decisions accordingly. Construction is currently, along with most other industries, a long way from being sustainable in the long term.

The environmental implications of sustainable development in construction have been split into two broad branches - Engineering and Geographical. The engineering approach looks at the more tangible aspects of construction, those which can be measured directly. The geographical approach looks more at the human impact of these processes. Although the areas of concern overlap, the ways of looking at the situation differ. For example, production of concrete requires a large amount of aggregate and the provision of this aggregate, either through sea dredging or quarries, has a calculable energy cost per tonne which includes energy used by plant, transportation and so on. These can be thought of as the Engineering Environmental Implications. It also has an impact on people living near the site through pollution, damage to the landscape, etc. These can be thought of as the Geographical Environmental Implications. It can be easily seen that in some cases these factors will directly overlap but in others they will not. For example noise pollution can be directly measured, but it is not possible to compare this figure with the energy requirement of a piece of plant. With this in mind, factors have been sorted under these two headings by means of how directly calculable they are. This is a simplification however, given the complexity and sheer range of factors involved, it is thought to be the best available course.

These issues affect the environment in a number of ways and at different levels - for example on the macro scale the depletion of the ozone layer and related global warming as described by Edwards et al (**1**) or on a micro level construction noise and dust. There are also a range of issues in between.

Other considerations, which could be considered more important than the environmental implications, are the economic and legal aspects. Knowing how much improvements will cost, who will pay and what future changes are possible is vital to successful implementation of any environmental policy.

1.1.1 Environmental Impacts

Table 1-1 shows data from work carried out in Scandinavia by Björklund, Jönsson, and Tillman (**2**). Based on a study of construction materials, this details the wide range of parameters involved in the production of a 1 kg steel slab - the raw materials which must be extracted, the energy used in processing, and the emissions both air and water. Even in this detailed examination some factors, of which the quantities were very small, have been excluded. The relative importance allocated to any of these factors will depend on who is doing the analysis and the perspective used. If this type of analysis was carried out for all construction materials and processes, it would be possible to build up a picture of all inputs and emissions for the frame. However this presents two main problems - firstly the data was calculated in Scandinavia and as such can not be directly applied to the situation in the UK (although the methodology could be applied). Secondly, unless all the materials and processes are analysed, any calculations based on only some data will be biased. For any assessment to produce fair results, there must initially be a 'level field'. These factors are all directly measurable and will fall into the 'Engineering' category.

Table 1-1: Measurable Environmental Impacts (2)

PRODUCT:	Steel Slab 1 kg	
Parameter	Load	Unit
Raw Materials		
Raw Liquid Iron	985	g/kg
Recycled Steel	49.2	g/kg
Lime (Burnt)	120	g/kg
Alloy Materials	7.94	g/kg
Additives	4.75	g/kg
Chemicals	1.94	g/kg
Energy Use		
Electricity	0.928	MJ/kg
Oil (Eo1)	0.001	MJ/kg
Oil (Eo5)	0.053	MJ/kg
Diesel	0.035	MJ/kg
Petrol	0.002	MJ/kg
Gas (LP Gas)	0.027	MJ/kg
Gas (Coke Gas)	0.337	MJ/kg
Emissions To Air		
Carbon Dioxide	55.7	g/kg
Sulphur Oxides	41.6	mg/kg
Nitrogen Oxides	69.2	mg/kg
Particulate (inc. Metals)	0.923	g/kg
Lead	0.432	g/kg
Cadmium	9.73	µm/kg
Copper	0.146	mg/kg
Chromium	91.9	µm/kg
Mercury	32.4	µm/kg
Nickel	0.281	mg/kg
Zinc	3.46	mg/kg
Emissions To Water		
Total Nitrogen Content	7.36	mg/kg
Total Phosphorus Content	97.3	µm/kg
Manganese (aq)	2.43	mg/kg
Zinc (aq)	0.865	mg/kg
Lead (aq)	0.376	mg/kg
Copper (aq)	76.2	µm/kg
Chromium (aq)	23.8	µm/kg
Nickel (aq)	14.1	µm/kg
Waste		
Industrial Waste	83.7	g/kg
Hazardous Waste	0.137	g/kg

These factors are by no means the only parameters and for any given project may not be the most significant. Chevalier (3) suggested a range of others which are shown in Table 1-2.

Table 1-2: Items Difficult To Quantify (3)

ITEM	Unit
Biotic resource depletion	-
Global warming power	kg
Ozone depletion potential	kg
Human toxicity	kg
Ecotoxicity	m^3/kg
Photochemical oxide formation	kg
Acidification	kg
Nitrification	kg
Residual heat in water	MJ
Odour	m^3
Noise	Pa^2s
Damage to ecosystem and landscapes	m^2s

Although Chevalier suggests units to measure these factors, it would be difficult to actually measure these items on a material by material basis, although it might be possible to do this on a country wide basis, depending on the level of accuracy required. These are examples of 'Geographical' factors.

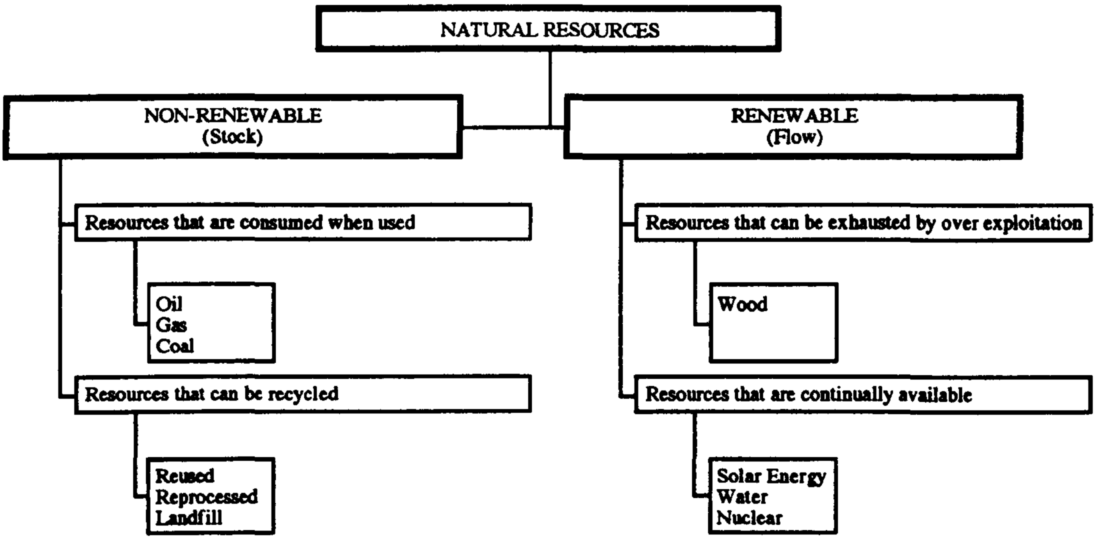
In addition to quantifying these factors, the relative weight given to each of these factors is difficult to assess - is nitrification more important than acidification? The answer to this question would depend on a range of factors. It is not possible to directly compare the various factors without applying some element of human judgement which will always be open to different interpretation. The same problem occurs when trying to make comparisons between items in Table 1-1 and Table 1-2.

Some of the problems associated with classification have been outlined by Owens & Owens (4) and these are -

- The intangible nature of many environmental 'goods' (the problem of 'quantifying the unquantifiable').
- The enormous uncertainty surrounding complex environmental issues.
- The uneven distribution of costs and benefits in time, geographical location and society (the problem of social and inter generation equity).
- The problem of distinguishing between need and demand.

These concepts apply to the resources used in any process. Resources can be further split into different categories (Figure 1-1) which affect the view taken of use - if the resources are renewable or non renewable. Currently virtually no distinction is made between the different types in construction work, but the indications are that this is changing.

Figure 1-1: Classification Of Natural Resources (4)



Most of the resources used in the construction of the frame are non-renewable or stock items - there are finite quantities of these items. As noted in the diagram, some of these resources can be recycled, for example steel and aggregates (although because recycling could occur does not mean that it will or is justifiable in simple energy terms). Also most of the energy used in construction is from non renewable sources, although low impact buildings provide a good example of the use of renewable resources for heating, cooling and lighting. Timber can be used in large quantities in construction, for example for shuttering, and this item is a renewable or flow item, but can be exhausted by over use and will require planning and management to be sustainable. Generally construction should move towards using managed renewable resources if it wishes to become sustainable.

1.2 Reasons For Assessing Environmental Impact

As noted, there are many possible reasons to carry out an environmental audit, some of an immediate and practical nature and some which are more indirect. The reasons that will have most impact in construction will probably be the immediate and practical rather than the more nebulous and impractical ones.

1.2.1 General Ideas

There is currently debate about exactly what effect increasing use of technology is having on the environment especially in areas such as releasing greenhouse gases or depletion of resources. There are however some facts which have been established and these can be stated with some certainty. For example burning fossil fuels, such as oil and wood, releases CO_2 and this gas increases the greenhouse effect by trapping energy being radiated from the Earth. The construction industry and its output, as a major user of fossil fuel, is contributing significantly towards this effect. In addition construction is a major polluter through the procurement, use and disposal of its materials. These factors, because they can not usually be pinned down to cause and effect, have a variable impact.

One of the main reasons that designers, contractors and clients could need this information in the future is that legislation may demand it. Since current legislation lags behind the perceived threats to the environment there is little doubt that more will be enacted.

1.2.2 Environmental Cost

The environmental cost of a process is the negative effects on all of the factors discussed in the previous section. However the exact parameters are not set and what is viewed as significant will depend on what is thought to be sustainable and what is unsustainable. The environmental costs (or impacts) must be reconciled with the monetary costs if they are to be truly represented in everyday activities.

There is a general perception in the UK construction industry that producing a low impact building carries a cost premium - requiring better grades of materials (for example triple glazing rather than double) and increase vigilance in specification (for example use of woods from renewable stocks), however the evidence for this is mixed. The environmental and monetary costs have been considered under two major headings: embodied and operational. To avoid confusion between environmental and financial factors the term ‘environmental impact’ has been used in preference to ‘environmental cost’. Where the term ‘cost’ is used without qualification, it should be taken to include all factors, both financial and environmental.

1.2.2.1 Embodied

The embodied environmental impacts are those ‘built in’ to a structure over the complete life cycle, for example in materials. The environmental impacts and financial costs are generally thought to increase when producing a ‘low impact’ building instead of a ‘standard’ building. While this may seem to be a contradiction, the low impact element is generally related to the operational rather than embodied element. However there can be benefits in reducing environmental impact which occur from simple examination of the building specification, for example the frame materials selection. As examined in the rest of the thesis, this choice is complex and various answers have been provided for the embodied impacts of each frame type. Steel and concrete frames can be generally viewed as being equally valid solutions in construction terms and the financial cost will be approximately the same (although for any specific building the sums may differ), therefore any reduction in environmental impact which can be made by selecting frame materials should be neutral in other terms.

Thorp (5) carried out an analysis of the energy and cost implications of frame selection, shown in Table 1-3. Although these figures were produced in 1990 and might now be regarded as suspect in the light of new work, they do illustrate that it is possible to get different energy costs for similar frames and thus similar monetary costs. The timber frame has by far the lowest embodied energy, but as suggested in the text, timber can only be used in low rise (3 floors or less) buildings and is thus not a direct competitor in many cases.

Table 1-3: Embodied Energy Cost (5)

	Reinforced Concrete (GJ)	Structural Steel (GJ)	Timber (GJ)
Concrete	4550	1600	
Reinforcement	7600	500	
Structural Steel		15000	
Steel Decking		2200	
Steel Fittings			550
Formwork	330		
Structural Timber			3600
TOTAL	12480	19300	4150

There are also possible monetary and embodied impact savings through the reduction in mechanical and electrical services which occurs in low impact buildings, however this will mainly be reflected in the operational costs. Any overheads for low energy products will tend to be reduced as environmental solutions become more readily available. It is also possible that monetary cost will be added during planning and construction due to the unfamiliarity with the techniques involved.

1.2.2.2 Operational

The operational environmental impacts are those incurred in operating a structure over the complete life cycle, for example in fuel use for heating.

Operational energy is determined by the quantity and use of heat, cooling and ventilation equipment installed as well as lighting, equipment and other small loads. A low impact building should always reduce the energy requirement, although as noted the embodied impacts may increase. Clement-Croomes (6) quoted figures which show how having passive cooling rather than air conditioning can reduce the operation costs (Table 1-4). The low energy cost figures still leave room for large improvements, but it is clear that reductions of around 50% are possible even at this stage.

Table 1-4: Typical Office Running Cost (6)

Office Type	Annual Energy Consumption kWh/m^2		Running Cost Cost £/m^2	
	Typical	Good	Typical	Good
Air Conditioned				
(i) Prestige	620	390	22	15
(ii) Standard	420	220	14	8
Naturally Ventilated				
(i) Prestige	290	150	7	5
(ii) Standard	240	120	6	4

1.2.3 Environmental Economics

There are many different ideas about how economics can be used to control environmental impacts including energy use and pollution. Most environmentalists would argue that the current situation requires more regulation, tighter laws and higher fines.

1.2.3.1 Environmental Economics Theory

The modern industrial economy can be likened to a throughput machine that profits by transforming raw materials and energy into products. In a competitive marketplace, individual businesses carry out this function in ways which tend to maximise their individual productive efficiencies. That is, they strive to continually reduce the costs of acquiring and using raw materials, energy, labour, and other resources. In theory, a competitive economy should root out pollution over time, as individual businesses strive to increase profits:-

> *All pollution and all waste is lost profit. . A central purpose of any business that seeks profits should be to maximise efficiency, and thereby reduce and ultimately eliminate pollution and waste*
>
> William K. Coors.

As a general statement this holds true although when looking at the construction processes, which tend to produce large amounts of waste (see section 4.2.7), it would probably prove more costly to eliminate all waste than to accept it, albeit reluctantly.

So generally pollution is a sign of imperfect efficiency; raw materials and energy that have been incompletely transformed into products or services. When the costs of acquiring and using resources are not fully accounted for (internalised) by the businesses or individuals directly responsible for them, waste is not eliminated.

Failure to externalise cost causes resource depletion and there are two ways to avoid this: restrict freedom to use or restrict the resources. In the context of the environmental resources (air, water, land and raw materials) command and control regulations do the former - they tell people how to carry out economic activities. More market based laws do the latter by using these laws to define external costs out of existence. They achieve this by isolating externalised cost categories and assigning specific legal responsibility for them. Costs that are externalised by businesses are typically borne by the environment, individuals (the taxpayer or consumer) and future generations. For example, extracting fossil fuels imposes costs on the land and water, and burning them emits pollutants into the air. These impose costs not only on the environment, but on taxpayers and consumers. In addition, consuming non-renewable resources today prevents their later use, and thereby imposes costs on the future.

If the planet earth is conceived of as a bank, then the assets are its natural resources. When a process takes fossil fuels from the earth the only financial costs involved are in extracting them from the ground. It does not pay the true costs of creating them because fossil fuels and resources have already been manufactured over time and stored in the earth. Costs imposed on the earth's environment are not included in the profit and loss statements of the businesses or individuals responsible for them so they tend to be maximised. As long as the damages are within government-established standards then contractor or building user is free to inflict them, even if eliminating them would be less burdensome for society overall. Environmental policies plug these leaks in the industrial economy by imposing a cost and extending ownership for each unit of pollution and waste externalised to 'common' resources like air and water.

1.2.3.2 Environmental Economics In Practise

For the economy overall, a comprehensive set of environmental laws can serve as a powerful agent for industrial renewal, not only by applying the 'polluter pays' principle, but also by cultivating the full application of ideas and technologies that can increase the value-added manufacturing, and thereby decrease society's collective appetite for physical resources. Some of the practical steps which can be taken include -

- Taxes on Consumption and Pollution

Green taxes are imposed on things of which we require less - consumption, pollution, and waste. By increasing the costs of utilising raw materials and energy, and of producing pollution and waste, green taxes are intended to drive the development of technologies that increase energy and materials efficiency. At a time when the public's acceptance of higher taxes is low, green taxes may best be considered an alternative to existing taxes, rather than an augmentation of them. The landfill tax falls into this category and can be judged to have been a success, helping to increase the awareness of the need to recycle.

- Pollution Fees

This makes pollution free up to arbitrary limits set by the government, then sudden creates a cost which depends on the current view held by the enforcing body.

The development and application of comprehensive policies, in concert with the ongoi application of knowledge driven technologies, have the potential to expand the resour productivity of the industrial economy by reducing the physical resource requirement a increasing the knowledge content of products and services; although this is somewh limited in the construction of frames, using high strength concrete would be an exampl Over time, this can reduce demand for raw materials and energy, thereby tending reduce their price. Efficiencies could eventually lower the value of many raw materia increasing the likelihood that they will be left in the ground, decreasing environmen impact and cultivating the emergence of an economy characterised by declining was production.

1.2.4 UK Economic Practice

The points discussed previously in this section suggest a number of possible alternativ in handling environmental issues using economics. In UK some of these methods ha been applied, with limited success. Three ideas which have an impact on the constructi process are discussed.

1.2.4.1 Carbon Tax

A carbon tax is levied in the UK, both on motor spirit (petrol) and on fuels used to he structures. The level of taxes levied on these types is significantly different, as noted section 1.2.4.3. The levelling of VAT on fuels at 8%, later lowered to 5% illustrates t potential difficulty and unpopularity of this type of tax.

Revenues raised in this way might be used to improve the energy efficiency of user There is wide scope for improvements using relatively low level measures, such improved insulation.

The impact of this type of tax will depend on the level of implementation, but while the are raised to produce government revenue rather than as environmental taxes which a used for environmental benefit, the effect will be limited.

1.2.4.2 Landfill Tax

The landfill tax has introduced levies on waste taken to landfill - £2 per tonne on ine waste (soil, concrete and brick rubble), more on the varieties of active waste. T majority of the waste produced from frames (both in terms of construction a demolition) is inert, although there will be some elements of active waste. This tax meant to act in two ways - reduction of waste and encouraging recycling. It was observe that, where recycling was performed, it may not result in a benefit to the compan supplying the waste. This tax may have resulted in a higher incidence of illegal tippin but since it is relatively new, there is currently little evidence to support this. For ine

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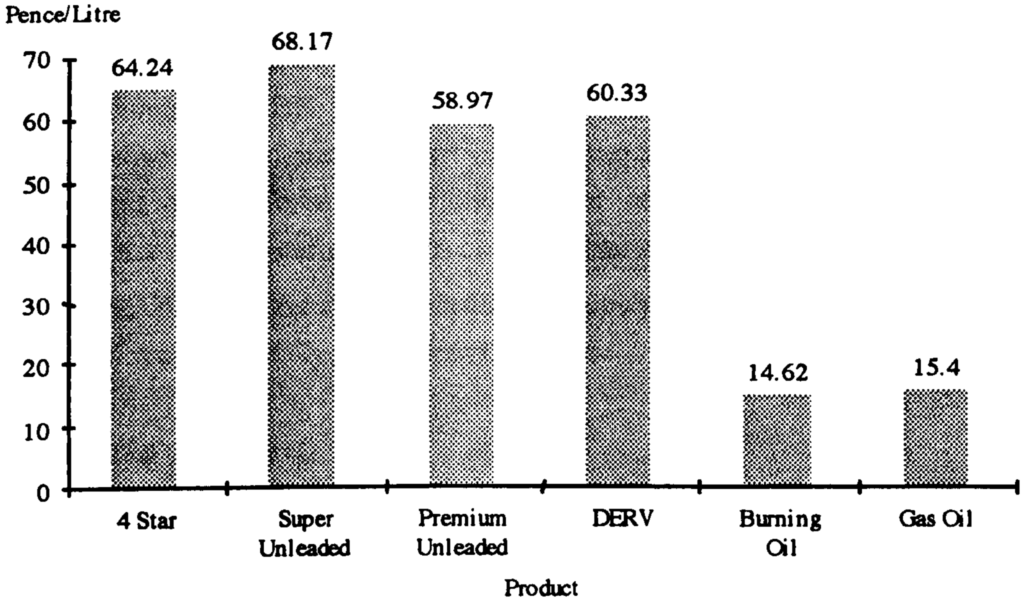
1.2.4.3 Cost Of Diesel Fuel

A distinction is drawn between two kinds of diesel - DERV (diesel engine road vehicles) should be used for vehicles for which road tax is payable and Gas oil which is used for site based items of plant such as excavators.

The only physical difference between DERV and gas oil is that the later is coloured pink, however there is a substantial difference in cost. The cost for DERV is around fours times the cost for gas oil. Figure 1-2 shows figures supplied by the DTI (7) for typical fuel prices in March 1997 and, although the actual cost changes over time, this basic relationship holds true.

Figure 1-2: Typical Retail Prices of Petroleum Products (7)



Although most construction related transportation will use DERV, some anomalies arise. For example mobile cranes use gas oil since they work on site work, but will use the same fuel for movement by road. In environmental impact terms DERV and gas oil have been taken as identical because the differences in terms of transport and distribution are insignificant (see chapter 3). The price differential has nurtured a situation in construction where the fuel consumption of items of plant is considered as virtually irrelevant - the technical editor of Plant Managers Journal suggested that fuel consumption was too esoteric to be covered in his publication (8). This situation is perhaps understandable given that large items of plant can cost in excess of £250, 000.

An increase in the price of gas oil to similar levels as DERV would have a major effect of the cost of operating plant and would almost certainly raise the profile of energy use of plant, but might also have a detrimental effect on the volume of work carried out via increased monetary costs. In environmental terms this would have two outcomes - a lower volume of work would reduce the energy and emissions produced however it might also mean that repairs and new buildings would be put off, causing companies to continue using older, more energy expensive offices.

1.2.5 Environmental Law

There is a growing quantity of statute concerned with construction and the environment. In most cases this will apply equally to all frame types. There are however a number which will be of consequence to the frame selection process, both directly and indirectly.

In addition this is an area of the law that can be expected to expand rapidly as there is an increase in knowledge of the interaction between the environment and buildings. A good guide to this area can be found in the CIRIA environmental handbook series (12).

The statutes applying to the environment come from both the UK government and the European community. UK legislation tends to be different for England and Wales and Scotland, although the general thrust of such legislation tends to be similar. The two major acts currently in force are the Control of Pollution Act and the newer Environmental Protection Act which is currently replacing the older act.

The ideas behind environmental protection acts are described both explicitly in the section on economics and generally throughout the thesis.

1.3 Kyoto Summit

The summit in Kyoto in December 1997, provides a good indication of how energy and emissions may be dealt with on a world and national scale.

The summit dealt mainly with production of CO_2 and other greenhouse gases, with some nations signing agreements to limit emissions. The targets which have been agreed (subject to ratification) are shown in Table 1-5.

Table 1-5: Emission Reduction Targets (9)

Country	Emission Targets (% of 1990 levels by 2012)
Iceland	110
Australia	108
Norway	101
New Zealand	100
Russia	100
Ukraine	100
Croatia	95
Canada	94
Japan	94
United States	93
EU Countries (inc. UK)	92

These targets are based on a percentage of the emissions made in 1990 and have to be ratified by the individual nations to become statute. Ratification is not a certainty in some countries, particularly the United States. These targets mean that countries which started with high emissions in 1990 would still be a large polluter, unless the targets were bettered by a significant margin. Other factors covered in Kyoto include the naturally occurring gases carbon dioxide, nitrous oxide and methane, as well as some man made ozone damaging substances.

The targets should be seen against the background of emissions which are already falling slightly in most of the EU countries including the UK. The level of emissions is also falling dramatically in the former iron curtain countries, due to the collapse in heavy industry post communism, rather than any environmental initiatives.

Another factor which must be considered is 'emission trading' (**10**) where countries which achieve and exceed the set targets can 'sell' the surplus to countries which have not reached the required levels. This means that the ex communist block countries with much reduced heavy industry, have ready made surpluses to sell.

The outcome is that the net reductions may be much lower than might at first appear, as countries which exceed targets sell surpluses allowing other countries to take less action. There might also be a positive effect if countries where improvements were difficult to make effectively paid inefficient plants in other countries not to produce. Emissions trading was included at the insistence of the US, which is one of the greatest polluters.

The actual effect of emissions trading is not known because this is the first time it has been tried on such a large scale, although trials within the US have proved encouraging (**10**). It is possible that this type of scheme could be introduced within the UK and if this was the case, accurate assessment of emissions might become a priority.

One other financial possibility which emerged came from representatives of the insurance industry as a counter to the fossil fuels lobby. The insurers, who control around 1/3 of the total global equities market, stand to lose huge amounts of money due to the climate changes caused by emissions. For example the drought in the UK in 1990 cost insurers £500 million per year and payments are expected to rise by 50% to £750 million a year by 2020 (at 1990 prices) (**11**). This means that insurers have an interest in investing in environmentally sound companies. Given this, companies with bad emission problems might find it difficult to raise new finance or find the share price falling as insurers sell, producing a new imperative to become green. A representative of General Accident commented...

> *What we are saying to individual companies in which we have large shareholdings is that we are analysing their strategies on the environment......If they have not got a strategy for dealing with climate change they will not be a good investment.*
>
> Andrew Dlugolecki, Kyoto Summit 1997 (**11**)

1.4 Construction And The Environment

This thesis seeks to examine the literature and models currently available concerning the frame of the building, separate from other considerations, to provide a clear understanding of the processes involved. Issues are only examined if they are directly related to the frame. For example, the frame design impacts strongly on the thermal mass and so this is examined, but it has little effect on the fitting out and so this aspect is not covered.

CIRIA special publication 94 (**12**) lists 14 major issues relating to the construction industry's use of energy and the associated environmental impacts. Five of these issues are considered directly relevant to this work and these are paraphrased below.

- New buildings have long lives but are replaced slowly and so represent a long term commitment to future energy use. Therefore, it is important to ensure that energy efficiency standards are raised for new buildings as they accumulate in the stock.

- The construction industry should set its own voluntary standards for energy efficiency which exceed the minima specified in the building regulations.

- The construction industry's expenditure on fuel and materials is considerable and it is in its own interests to seek savings.

- Air conditioning is unnecessary in most buildings, and in those where it is required, it can be zoned to crucial parts of the building only. This results in reduced capital and running costs and also enables a justifiable claim of environmental friendliness to be made.

- Continued work on energy models is important both to support the development of eco labelling schemes and to promote energy efficient design. In particular there is a need to develop simple models of energy use in non-domestic buildings and also to address the usability of detailed simulation models.

Each of these factors has been considered through out the thesis and applied to the methodology and calculations. One other point has also been held in mind, with the aim of starting to address the situation:

> ***Much of the information needed to undertake a comprehensive environmental or energy assessment is not yet adequately developed.***

1.5 Conclusions

The environment is a very wide subject to cover. There can be very few factors which do not have an environmental impact of some kind. All of the factors can be view from different perspectives.

The construction industry has a major impact on the environment, both directly via site operations and materials procurement, use and disposal, and indirectly as the structures are used. The industry as a whole should take action to assess and control environmental impacts. There are several tools which can be used to increase the probability of this happening the most important being financial and legal. While these tools do not always have the desired effect, they are more likely to be applied if the construction industry is seen to be slow in responding to the issues.

The aims of the study described in this thesis therefore are:

1. To investigate the relative importance of embodied and operational energy.
2. To investigate the degree of interaction between embodied and operational energy
3. To determine the relative environmental performance of concrete and steel in terms of defined impacts and using a range of parameters
4. To identify the best methods of reducing environmental impacts measured
5. To develop a model which will allow a consistent analysis to be performed on a range of buildings and which is capable of change to take advantages of changes in prevailing conditions in the environmental impact assessment field.
6. All of these comparisons should be carried out in such a way as to be repeatable (within the limits imposed by the inherent variability of the subject) and transparent to outside observers.

1.6 References

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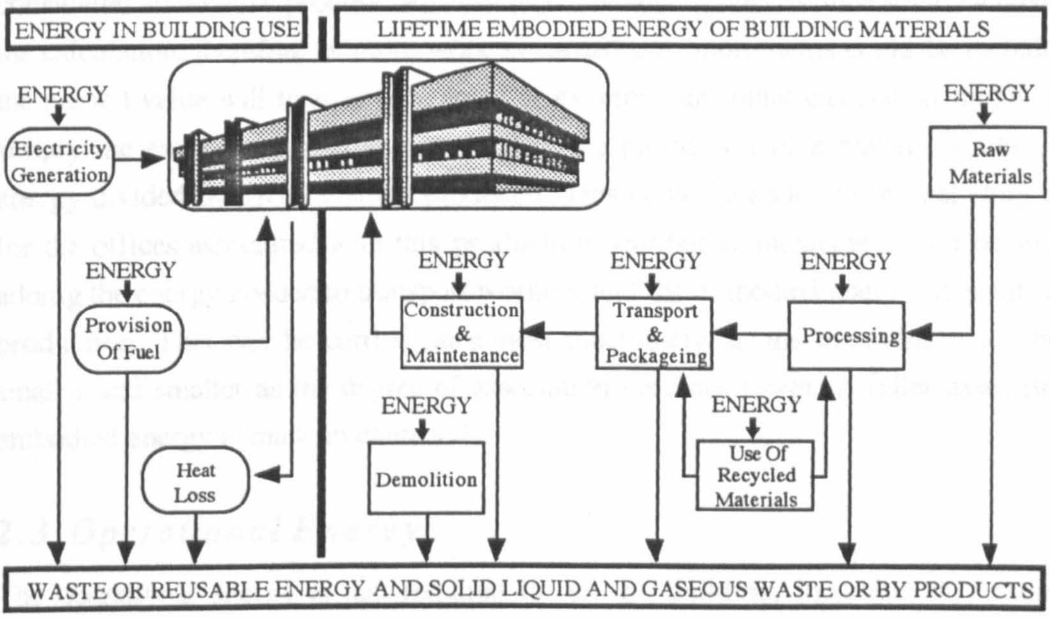
2. ENERGY PROVISION AND USE

As has been suggested in the introduction, there are many possible items which come under the broad heading of environmental impact. The majority of these are caused, either directly or indirectly, by the provision and use of energy. The extent of the impact will depend on a range of factors which are discussed in the following sections.

2.1 Energy Calculations

The first thing that must be examined when trying to assess energy use in construction are the parameters used for study. Their are several models presenting the factors involved in measuring the energy over a complete building life cycle. Possibly the clearest, suggested by the Building Research Establishment (BRE), is shown in Figure 2-1. It can be seen even in this macro set up that there are a large number of interactions to be considered and that on a micro scale the complexity increases massively. The model is split into two broad headings - Energy in use (occupational energy) and lifetime embodied energy of building materials.

Figure 2-1: Life Cycle Energy Consumption (1)



2.2 Embodied Energy

The definition of life cycle is very important in the context of calculating the complete energy requirements of a building. There are two types of life cycle to be considered in this context - the life cycle of the materials used in the building (including the components of the structural elements) and that of the building itself. The building life cycle encompasses the life cycles of all the materials used from extraction through use to final disposal. Ideally this should include any emissions from the materials in landfill sites -

including energy generated from methane or other useful waste products. This is outside the scope of all currently available models.

The term embodied energy refers to the energy required in order to produce a material or structure. This value is usually quoted in gigajoules (GJ) per unit of quantity, for example cement might be quoted as 8 GJ/tonne[1].

The embodied energy is thus a subset of the total life cycle energy and the ratio of these two factors to each other will vary and is discussed in greater detail in Chapters 5, 9 and 10.

The inclusion or exclusion of specific items can have a very large effect on the 'energy balance' between different materials. This is most clearly stated by Cole and Rousseau (2)

> *There is no absolute or correct energy intensity of a material. A stated value is a direct function of what was included and what was excluded from its derivation.*

Sections 4.2.2 - 4.2.7 define the factors involved in a complete building life cycle. For any given building or component the 'mix' of factors, and hence the relative importance of each, will vary.

An important point to note is that the calculation of an embodied energy figure can be considered an additive process. All currently available figures exclude some element from the calculation, therefore as more work is carried out, more items could be included and the quoted value will tend to increase. For example, an initial calculation might include simply the energy immediately involved in the production of a material - total factory energy divided by gross volume produced. This could be added to by including energy for the offices associated with this production. Further refinements would be made by adding the energy needed to transport workers and the embodied energy of plant used in production. This can be carried on almost indefinitely as the additions made become smaller and smaller as the degree of association becomes lower. A fuller assessment of embodied energy is made in chapter 4.

2.3 Operational Energy

The operational energy is that required to run the building, including all heating and cooling, ventilation, lighting, office equipment and any other items required to make the structure operable. Initially the level of energy required will be determined by the equipment the building is fitted out with especially the heating and cooling systems, although in the longer term the building may well be refitted with different equipment.

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[1] The unit GJ/tonne is the same as MJ/kg which is also quoted - figures quoted with either of these units are interchangeable without a multiplication factor. In this report the unit GJ/tonne has been used, except where the figure is imported from another report which has used MJ/kg

Calculation of the embodied energy will come before (construction phase), during (repair and maintenance) and after (demolition and recycling) the period when the building is in use. A fuller assessment of operational energy is made in chapter 4.

2.4 Production Of Energy

The calculation of life cycle or embodied energy figures for construction can not be carried out without knowing the background to energy production and use in the UK. This chapter details the basis on which energy and CO_2 have been made and illustrates these with relevant figures and tables.

Energy figures can be quoted in a number of ways. National figures tend to be measured in tonnes of oil equivalent (TOE), while energy for construction tend to use kilojoules (kJ) or kilowatt hours (kWh). The magnitude of some of these figures means that they are quoted as mega, giga, tera or peta (each of these being 1000 times larger than the preceding figure). Where figures have been changed between different units the following conversion factors have been used -

1 Thousand TOE = 41.87 Terajoules = 11.63 Gigawatt hours

2.5 Primary And Delivered Energy

For all measurements of embodied energy a distinction should be made about whether the figure quoted is primary or delivered energy, because this has a large difference on the calculation.

Delivered energy is that which is required at the point of use, for example a litre of fuel in a petrol tank. Primary energy includes every item of expenditure needed to provide the energy at the point of use. Table 2-3 shows the energy requirement figures for the UK in 1996. This shows that 1.86 petawatt hours of energy were used in the UK during the year, however an additional 0.85 PWh were required in the supply, distribution and use of this energy. Adding these two figures together yields the primary energy requirement. Therefore for the UK as a whole in 1996, losses were 31% of the total primary energy input.

Table 2-1: Conversion Losses All Energy Sources (3)

Conversion Losses: 1996 Figures	TOE# (1000's)	PWh
Total Primary Energy Input	231890	2.70
Conversion Losses*	71936	0.84
Final Energy Consumption	159954	1.86

\# Tonnes Of Oil Equivalent
* Losses in conversion, distribution and Use

This can be expressed in simpler terms: for every 1 unit of primary energy input, only 0.69 was available at the point of use. The actual split between primary and delivered will depend on three major factors - the type and quantity of fuel used, and the efficiency of the machines used in conversion. This presents one of the major problems in interpreting some of the available materials data as in many cases no distinction is made between primary and delivered.

The UK uses fuels provided from a basket of supplies (shown in Figure 2-2). The relative proportions of coal and gas has changed remarkably in recent years, with the deregulation of power supply causing the so called 'dash for gas', where older coal fired stations have been phased out in favour of new gas turbine stations. The reasons for this are mainly financial, but as detailed in the following sections, this has large implications both for overall efficiency and on the generation of CO_2.

2.5.1 Renewable Resources

Figure 2-3 shows the energy which is derived from renewable resources. The scale of this charts, relative to Figure 2-2, should not be forgotten - hydro electric power which provides 16.7% of the total renewable energy counts for 0.15% of the total for all energy. Overall the total energy use was of the order of 230 million tonnes of oil equivalent (TOE) while total renewable sources provided 1.72 TOE, less than 1% of the total and only 10% of the electricity imported from France.

Using renewable resources in place of coal and gas will have a positive effect on emissions production, because they produce insignificant quantities (mainly associated with construction of installations). It should also be noted that a number of the renewable sources perform the useful function of reducing waste either by burning or controlled decomposition.

Figure 2-2: Inland Energy Consumption By Fuel 1996 (4)

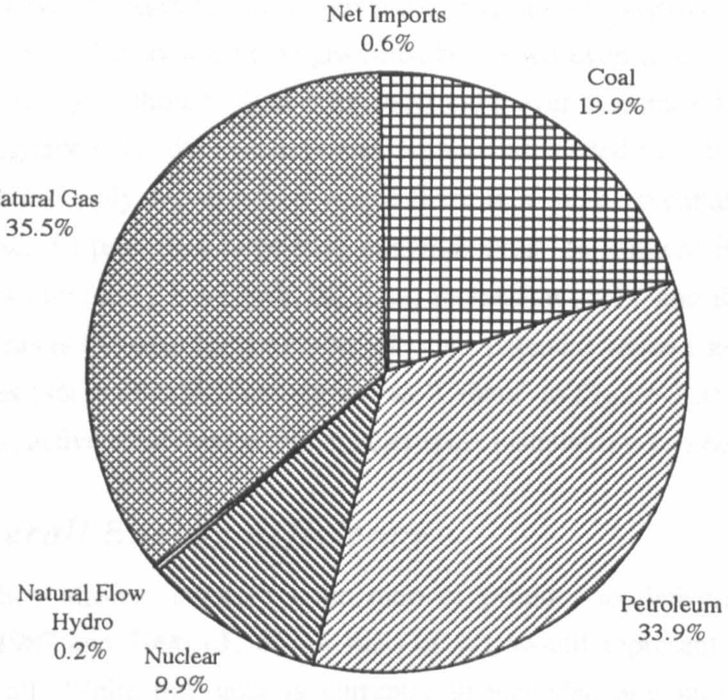
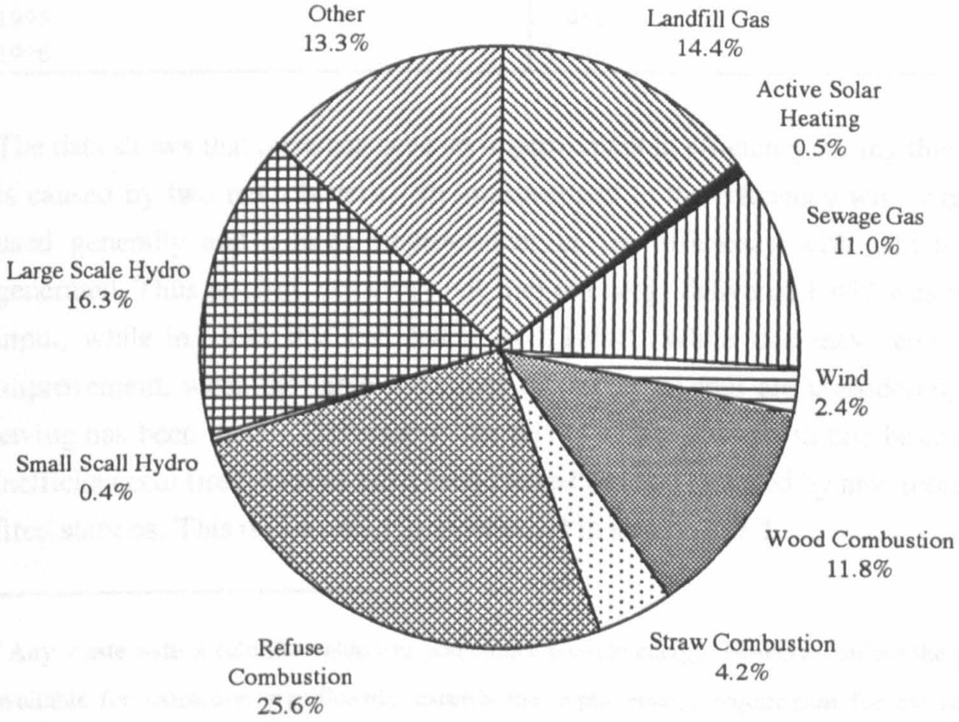


Figure 2-3: Renewable Energy Production (4)



The case of landfill gas is a useful one to examine because of a number of points it raises. The material is sent to landfill and the energy extracted at that point. Burning methane to produce power is desirable for a number of reasons - a possible dangerous build up of gas underground is avoided (the gas must be vented even if it is not used), a potential addition to the greenhouse effect is lowered and power is extracted from a waste material. On the negative side, the installation of equipment needed to extract and use the gas is expensive and only worth while where there is a large potential, for example a large landfill site. To provide a large site, materials must be brought in from further around than might previously have been the case, increasing traffic and thus increased pollutant release. This is the case for a number of other potential waste energy sources[2]. In some other cases (some of which are shown as 'Others' in Figure 2-3) such as chicken litter, used tyres, active solar, and wind, smaller scale installations can be successfully used.

2.6 Overall Energy Efficiency

The numbers shown in express the ratio of primary to delivered energy in the UK between 1987 and 1996 (**3**, **5**). A ratio of 1:1 would represent 100% efficiency - no losses at all. While this goal is currently unattainable any move in that direction is welcome.

Table 2-2: Overall Energy Efficiency

Year	Ratio Of Primary To Delivered Energy
1987	1.472
1995	1.456
1996	1.440

The data shows that there has been an improvement in efficiency during this period which is caused by two main factors - an improvement in the efficiency with which energy is used generally and a large improvement in the efficiency with which electricity is generated. Thus in 1987, for every one unit of energy delivered 1.472 was required as an input, while in 1996 this had fallen to 1:1.440. While this may seem like a minor improvement, when the large quantities of energy overall are considered, a significant saving has been made. The reasons for this can be put down to one basic factor - older inefficient coal fired stations have been phased out and replaced by new more efficient gas fired stations. This is discussed in more detail in section 2.7.1.

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[2] Any waste with a calorific value can potentially provide energy. However, unless the possible energy available for extraction significantly exceeds the input energy requirement for extraction (including transportation), there is no likelihood that this energy will be used. Other situations could be envisaged, for example where landfill space was at a premium and burning for energy, even at a net energy loss, might be considered.

2.7 Specific Energy Efficiency

The energy efficiency figures quoted in the preceding section are based on an overall figure for all fuels, however each type of fuel will have an individual rating. Table 2-3 shows examples of conversion efficiency for all types of fuel used, both from primary to delivered and from delivered to useful energy. The figures for conversion to useful energy are derived from a range of products, but for any given set up will vary around these mean figures. Oil is the most efficient energy form overall (and is also more compact than other sources, hence the use for transportation). Once delivered, electricity is very efficient in terms of useful energy[3], however the generation and transmission entails large losses. In spite of this electrical energy is used extensively in situations where other fuel types would be inconvenient (for example lighting and office equipment). It is also used, however, in areas where other forms of fuel might be more efficient, such as space heating.

Table 2-3: Energy Conversion Efficiency (6)

Type Of Fuel	DE:PE Efficiency	UE:PE Efficiency	Overall Efficiency (DE x UE)
Coal	0.98	0.60	0.59
Gas	0.90	0.70	0.63
Oil	0.93	0.70	0.65
Electricity	0.30	0.98	0.29

PE = Primary Energy
DE = Delivered Energy
UE = Useful Energy

Generally the calculations for construction do not require the figure for conversion from delivered to useful energy to be known. This is because a given quantity of fuel will produce a definite quantity of material, the actual efficiency with which this is achieved is relatively unimportant. The conversion from delivered back into primary energy is however, very important, especially for electricity.

This is the reverse of the situation for companies, for whom the useful energy is very important while, because payments are only made directly for delivered fuel rather than primary energy, this calculation will not enter the equation. Losses from primary to delivered will be incorporated in the price paid but the user will not be aware of the breakdown.

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[3] The useful energy is the ratio of delivered energy to used energy - the amount each machine can usefully use from the energy it is supplied.

CO_2 will be produced whenever a fossil fuel (coal, oil and gas) is burnt. The actual quantity of gas produced will depend on the specific variety of material burnt. There will also be some variation within the fuel type.

2.7.1 Electricity Generation

The changes in electricity generation, caused by the deregulation of the industry by the UK government, has resulted in great changes in the mix of fuels used - coal being largely replaced by natural gas. In 1992, coal provided 61.2% of the total capacity, while gas provided only 2.0%. By 1996 this had changed to 42.9% and 21.4% respectively. The substitution of new combined cycle gas turbine (CCGT) plants for older stream coal fired stations has resulted in a great improvement in the ratio of primary to delivered energy[4]. This is shown in Table 2-4 - the primary energy required in 1996 was the same as the primary energy in 1992, however the delivered energy increased from 25.7 to 28.1.

This shift in efficiency means that any embodied energy calculations involving significant electrical use, made on the basis of, for example 1987 figures, such as Shorrock and Henderson (5) will be flawed (although the basic principles will be correct, the multiplication factors will be incorrect). There are also implications for two construction materials, PFA and Lytag, both of which are made from the waste produced from use of coal in power stations. The quantities of raw material production for these products has fallen and it is possible that they might become totally unavailable at some point in the future.

Table 2-4: Electrical Energy Efficiency

Millions Tonnes Of Oil Equivalent	Primary	Delivered	PE:DE
Fuels Used In Electricity Generation (1996)	76.6	28.1	2.72
Fuels Used In Electricity Generation (1992)	76.6	25.7	2.98
Fuels Used In Electricity Generation (1987)	71.5	21.5	3.33

PE = Primary Energy
DE = Delivered Energy

The figures used to produce Table 2-4 are derived from national data and, as such include energy imported from France, currently running at around 5% of the total delivered energy. The embodied energy and CO_2 for this element is difficult to calculate because of the differing composition of the power stations in France - predominantly nuclear (around 70%). For this calculation therefore, the energy imported has been excluded.

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[4] The ratio primary to delivered energy is simply the reciprocal of delivered to primary energy and visa versa. Thus a PE:DE of 3.33 is equal to a DE:PE of 1/3.33 = 0.30. This can also be expressed in text. For delivered energy of 1 unit there is a primary energy requirement of 3.33 units or for every 1 unit of primary energy used only 0.3 is delivered to users.

Using these figures it is possible to update the data in Table 2-3 as shown in Table 2-5. The increase in overall efficiency from 0.29 to 0.36 represents a significant reduction in both energy and CO_2 for the same energy requirement (although the demand for energy has risen, the primary energy required is the same).

Table 2-5: Efficiency Of Electricity Generation

Type Of Fuel	DE:PE Efficiency	UE:DE Efficiency	Overall Efficiency (DE x UE)
Electricity (1992)	0.30	0.98	0.29
Electricity (1996)	0.368	0.98	0.36

PE = Primary Energy
DE = Delivered Energy
UE = Useful Energy

The basket of fuels used to produce electricity in 1992 and 1996 are shown in Figure 2-4 and Figure 2-5. Both of these charts represent a primary energy input of 76.6 thousand TOE.

2.8 Primary And Delivered Energy In Construction

Table 2-6 details the CIRIA estimate for energy (delivered) used in construction in the UK. It can be seen that actual 'building' activities make up around 14% of the total energy used in construction. One significant point to note is that a proportion of the operational energy requirement should be counted towards embodied energy - construction materials are produced and used by companies, architects, contractors, and manufacturers who all use buildings, which all make use of operational energy. This factor is discussed later in the thesis.

Figure 2-4: Fuels Used To Generate Electricity 1992 (3)

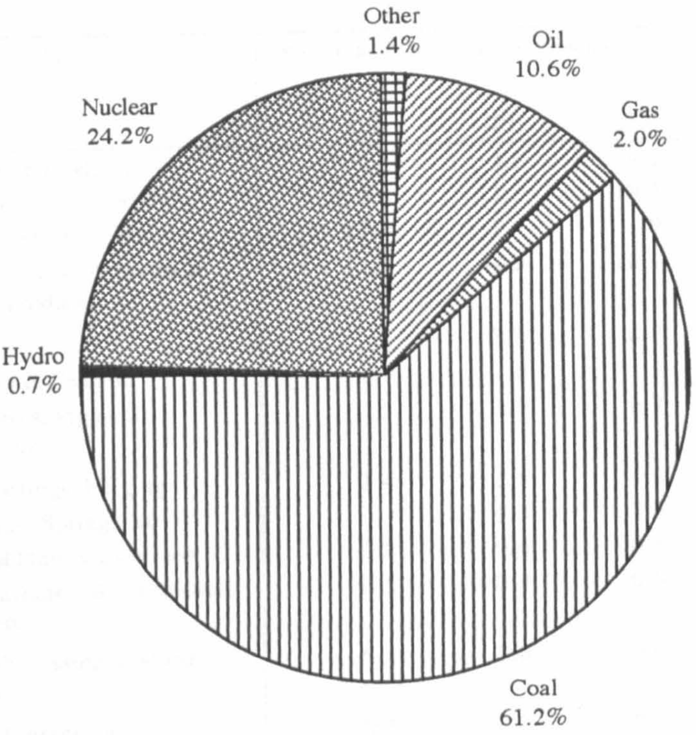

Figure 2-5: Fuels Used To Generate Electricity 1996 (3)

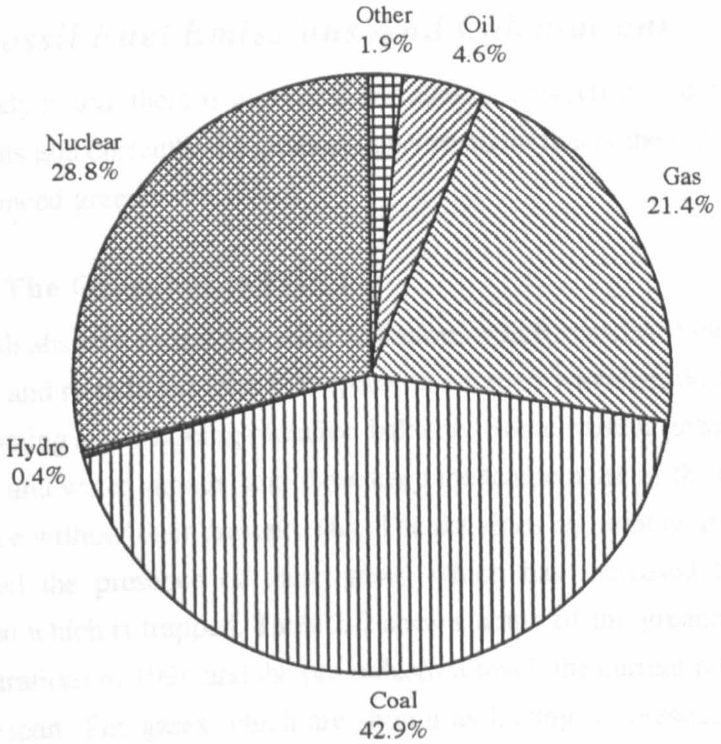

Table 2-6: Construction Energy By Fuel Type (7)

Commodity/Activity	Solid Fuels (PJ)	Oil Products (PJ)	Natural Gas (PJ)	Elect (PJ)	Total (PJ)
Iron, Steel & Products	5.0	3.8	5.1	3.3	17.2
Structural Clay Products	5.4	11.3	18.7	2.7	38.1
Cement, Lime & Plaster	27.8	1.4	1.9	2.6	33.7
Concrete, Stone, Asbestos & Abrasive Products	11.5	44.9	10.9	12.5	79.8
Glass		3.3	6.2	1.7	11.2
Refractory & Ceramic	1.9	2.6	11.1	1.7	17.3
Paints, Dyes, Pigments & Printing Inks		1.9	0.7	0.4	3
Metal Castings, Forging	1.4	1.5	4.5	2.2	9.6
Fastenings, Springs, etc.		1.3	0.6	0.6	2.5
Industrial Plant & Steelwork	0.2	0.6	0.5	0.3	1.6
Other Machinery & Mechanical Equipment	0.1	0.9	0.9	0.7	2.6
Timber Processing & Wood Products	0.1	7.8	0.8	0.6	9.29
Plastics Processing	0.1	0.7	0.9	0.8	2.5
Other	13.4	20.5	15.7	8.7	58.3
Sub Total	66.9	102.5	78.5	38.8	286.69
Construction	0.0	40.5	2.5	3.5	46.5
Total	66.9	143.0	81.0	42.3	338.0

2.9 Fossil Fuel Emissions And Calculations

As already noted, there is a general correlation between increased fuel use and increased emissions and currently the greatest concern about this is the link with global warming by the enhanced greenhouse effect.

2.9.1 The Greenhouse Effect

The earth absorbs shortwave solar radiation, which is redistributed by the atmosphere and oceans, and re-radiated back into space on a longer wavelength. For the earth as a whole, the incoming and outgoing radiation balance. Some natural gases exist (including carbon dioxide and water vapour) and these keep the temperature of the earth 33°C warmer than it would be without their presence (8). The activities of humans in burning fossil fuels has increased the presence of these gases which has increased the amount of outgoing radiation which is trapped. Table 2-7 shows some of the greenhouse gases including the concentrations in 1994 and the pre industrial level, the current rate of growth per year and gas lifespan. The gases which are shown as having no presence pre industry are purely man made and are not directly associated with fossil fuels. There are three main greenhouse gas produced from fossil fuel: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) and of these carbon dioxide is the greatest problem, partly due to the relatively extended lifespan and partly due to the large quantities produced.

Table 2-7: Growth In Greenhouse Gases (8)

	Pre Industrial Level (ppmv)	1994 Average Concentration (ppmv)	Rate Of Change (per annum)	Lifetime (Years)
CO_2	280	358	0.40%	50-200
CH_4	0.7	1.72	0.60%	12
N_2O	0.275	0.312	0.25%	120
CFC-12	0	0.000268	0.00%	50
HCFC-22	0	0.00011	5.00%	12
CF_4	0	0.000072	2.00%	50000

Table 2-8 shows the CIRIA (9) estimate for the relative contribution of greenhouse gases. This illustrates that the quantity of gas present does not necessarily correspond with the effect - methane has a greater effect than nitrous oxide, even though there are smaller concentrations.

The different effectiveness of gases leads to some interesting anomalies, for example, natural gas (mostly methane) leaking from a pipe is potentially a greater problem than natural gas burnt as fuel because it is a more effective greenhouse gas than the combustion products. The DTI estimates that leakage from pipes was responsible for 9% of all methane emissions in the UK in 1995 (10).

Table 2-8: Gases Contributing To The Greenhouse Effect (9)

Element	Greenhouse Contribution
Carbon Dioxide (CO_2)	50%
Methane (CH_4)	19%
CFC 12	10%
Tropospheric Ozone	8%
CFC 11	5%
Nitrous Oxide (N_2O)	4%
Water Vapour	2%
Other CFC	2%

Table 2-9 shows the government statistics for emissions from fuels burnt (10). This table uses figures for carbon dioxide in terms of weight of carbon rather than weight of carbon dioxide. Therefore a conversion is required to change to the weight of carbon dioxide, based on the molecular weights of carbon and carbon dioxide (5). So every 12 g of carbon produced equates to 44 g of carbon dioxide[5].

Table 2-9: Primary Fossil Fuel Emissions (10)

	Natural Gas g/GJ	Oil g/GJ	Coal g/GJ
Carbon Dioxide (weight of carbon)	14000	19000	25000
Methane	4	3	17
Sulphur Dioxide		590	940
Black Smoke		17	51
Nitrogen Oxide	65	140	270
Volatile Organic Compounds	5	2	14
Carbon Monoxide	5	15	220

Clearly the quantity of carbon produced is significantly greater than any of the other emissions. Therefore, even allowing for the greater efficiency as a greenhouse gas of other emissions, the total quantity of CO_2 released means that it is the most important cause of warming and should be highest on the list of targets for reduction. It should also be remembered that a reduction in fossil fuel use will lower all emissions by the factors shown.

Table 2-10 shows the gross emissions by fuel type for 1995. The data reflects the figures in Table 2-9 with coal producing large quantities of carbon and sulphur dioxide. Also of note are the emissions from the petroleum derivatives used in transportation - the large majority of carbon monoxide being produced by motor spirit (petrol). Also worth noting is the large quantity of black smoke emissions from DERV (diesel). Transportation generally has a large impact in most areas and these issues are discussed in chapter 3.

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[5] The formula for calculating CO_2 from a fuel is simply the carbon content of the fuel divided by the calorific value. Thus is the weight of carbon produced. This then needs to be multiplied by 44/12 which is the relative molecular weights. The carbon content of the fuel will vary, as will the calorific value so care is required when making calculations.

Table 2-10: Emissions By Fuel (10)

	Carbon Million t	Sulphur Dioxide Thousand t	Nitrogen Oxides Thousand t	Black Smoke Emissions Thousand t	Volatile Organic Compounds Thousand t	Carbon Monoxide Thousand t
Coal	46	1659	518	76	25	313
Solid Smokeless Fuel	2	32	4	12	2	100
Petroleum						
Motor Spirit	19	16	643	14	609	4631
DERV	12	35	423	163	72	196
Gas Oil	7	48	215	33	28	49
Fuel Oil	9	457	115	11	4	47
Burning Oil	2	1	7			
Other Petroleum	6	26	74	2	6	21
Natural Gas	41		164		13	14
Other Emissions	5	90	134	44	1576	106
Total	149	2364	2297	355	2335	5477

Much of the work carried out studying construction and the environment makes use of calculations by Shorrock and Henderson (5). For example the reports by CIRIA (9), published in 1994 use these figures. As already noted, the energy figures provided in that work are based on 1987 figures and so are the CO_2 calculations. While the changes which have occurred are not as problematic as for energy, some of the values (specifically calorific values) have changed and the CO_2 value for electricity is affected in the same way as the energy value.

None of the publications which have quoted this work as a reference explicitly state whether the formulas or the data are used for base calculations. This means that any derived CO_2 values could be significantly in error. The problem is largely unavoidable in so far as calculations using data from year X will always be suspect viewed from year Y. However, if any report noted what basic values had been taken, problems could be minimised.

The CO_2 production figures for both DTI and Shorrock and Henderson/CIRIA are shown in Table 2-11. The DTI values have been multiplied as suggested, by the molecular weights, to provide parity with the other data. The differences shown are not great in themselves, but would be magnified when used over the whole construction industry or even a specific building.

Table 2-11: Primary Energy Carbon Dioxide Production

Fuel CO_2 Contribution	DTI kg/GJ	Shorrock/CIRIA kg/GJ
Coal	91.7	91
Gas	51.3	50
Oil	69.7	69

CIRIA have used the figures provided to produce a companion to Table 2-6, detailing CO_2 production in construction. This is shown in Table 2-12. The biggest single producer of CO_2 is concrete and stone contributing 36% of the total. This is a simple reflection of the values in the similar energy table - energy multiplied by CO_2 contribution (the figures quoted in Table 2-11 are for primary CO_2 and thus should only be applied to primary energy calculations).

Table 2-12: Construction CO_2 By Fuel Type (9)

Commodity/Activity	Solid Fuels	Oil Products	Natural Gas	Elect	Process	Total
Million Tonnes	(PJ)	(PJ)	(PJ)	(PJ)	(PJ)	(PJ)
Iron, Steel & Products	0.46	0.32	0.28	0.76		1.82
Structural Clay Products	0.5	0.95	1.03	0.62		3.1
Cement, Lime & Plaster	2.56	0.12	0.1	0.6	0.59	3.97
Concrete, Stone, Asbestos & Abrasive Products	1.06	3.77	0.6	2.89	6.12	14.44
Glass		0.28	0.34	0.39		1.01
Refractory & Ceramic	0.17	0.22	0.61	0.39		1.39
Paints, Dyes, Pigments & Printing Inks		0.16	0.04	0.09		0.29
Metal Castings, Forging	0.13	0.13	0.25	0.51		1.02
Fastenings, Springs, etc.		0.11	0.03	0.14		0.28
Industrial Plant & Steelwork	0.02	0.05	0.03	0.07		0.17
Other Machinery & Mechanical Equipment	0.01	0.08	0.05	0.16		0.3
Timber Processing & Wood Products	0.01	0.66	0.04	1.16		1.87
Plastics Processing	0.01	0.06	0.05	0.18		0.3
Other	1.23	1.72	0.86	2.01		5.82
Sub Total	6.16	8.63	4.31	9.97	6.71	35.78
Construction		3.4	0.14	0.81		4.35
Total	6.2	12.0	4.5	10.8	6.7	40.1

2.10 Conclusions

Buildings account for a large proportion of all the energy used in the UK, both in terms of the energy used in operating existing structures and the construction of new buildings. Total energy use (primary energy basis) equalled 232 million tonnes oil equivalent (TOE) (3) in 1996 and of this around 116 is for operational use in buildings and 11.6 for materials embodied energy. This means that around 55% (7) of the total energy required is used, in one way or another, in structures.

A significant amount of work has been carried out into calculation of the building operational energy requirements, but less so into embodied energy due to the relative proportions of each and therefore their perceived influence. It should therefore be noted that the 11.6 million TOE used in the construction process represents half of all the energy produced by nuclear power stations and 6.5 times all the energy produced from renewable resources in the UK in 1996. It should also be remembered that some of the energy used in building operation is used by architects, contractors and materials suppliers, and should thus be counted in the embodied energy of the facilities they create. In addition as future designers decrease the energy use required of buildings, moving towards a target of a 'zero emissions building', embodied energy will become relatively more important.

Due to the rapid rate of change in the efficiency of energy supply, especially with respect to electricity generation, any calculations made on the basis of old figures should be regarded with extreme caution. One possible solution to this is to provide detailed figures for delivered energy use which can then be updated with primary energy data as required. This would require a standard methodology to be used by all parties making calculations. This also applies to calculations made for other countries, especially ones where power generation is carried out using significantly different spread of input fuels. Generally there is a positive linear relationship between energy use and emissions, although this will be different for each fuel and especially for electricity. Given this relationship and the importance of CO_2 as a greenhouse gas, these two factors could be concentrated on to simplify environmental modelling, although other factors should not be forgotten.

Nuclear and renewable energy sources produce very little CO_2, but both forms of generation have other associated problems. Nuclear power in particular presents many problems both in operational safety and disposal of nuclear waste. The real cost of nuclear power, taking disposal into account is very difficult to calculate. Renewable resources are much safer than nuclear power but can require installation in environmentally sensitive areas or be visible for long distances (for example wind farm sites on hill tops). Currently the cost per kWh, due mainly to the high capital costs and the relative newness of the technology, reduces the use of this type of power.

Any calculations made should be 'data stamped' to ensure that the age and source of the base data is clear. The figures used in transportation energy are detailed in chapter 3.

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3. TRANSPORTATION ENERGY AND EMISSIONS

The need for transportation occurs throughout the life cycle of a structure from the initial construction to demolition and disposal. Although the DTI provide, in conjunction with the Department of the Environment, Transport and the Regions (DETR)(1), a table showing gross road use (Table 3-1), it is not possible to assess what proportion of these quantities are construction related. However, significant proportions of the car, light good vehicles (LGV) and heavy goods vehicles (HGV) can be linked to construction.

There has been a clear trend between 1985 and 1995 for increased road use, especially for articulated heavy goods vehicles (although some of this has been simply been a transfer from smaller to larger vehicles). Construction makes use of all types of transportation, but most will either be light or heavy goods vehicles.

Table 3-1: Vehicle Road Use (1)

Billion vehicle kilometres	1985	1995	% Change
Cars And Taxis	250.5	353.2	41%
Motor Cycles	7.4	4.1	-45%
Larger Buses And Coaches	3.7	4.7	27%
Goods Vehicles			
Light Vans	25.2	39.1	55%
Heavy Goods By Type			
2 Axle Rigid	13.3	16.1	21%
3 Axle Rigid	1.3	1.5	15%
4 or more Axle Rigid	1.3	1.5	15%
3 Axle Artic	0.7	0.4	-43%
4 Axle Artic	4.4	2.9	-34%
5 or more Axle Artic	1.9	7.4	289%
All HGV	22.9	29.8	30%
All Motor Vehicles	309.7	430.9	39%
Pedal Cycles	6.1	4.5	-26%

3.1 General Ideas

Transportation will be the main energy component for some materials where extraction is relatively easy but large volumes require movement - aggregates for concrete for example. Measuring this factor is extremely complicated due to the variable nature of transportation methods and routes possible. For example, while it is possible to make an estimate for the environmental costs of a concrete batching plant, working out the implications of transporting the batched concrete to site would require knowledge of each wagon, road conditions and distances involved. One possible way around this is to use a weighted average system looking at gross flows from area to area of materials either on a macro or micro level, although this involves gross generalisations.

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3.1.1 Suggested Figures In Transportation

The majority of transportation that occurs during the frame construction phase - materials movement to and from site - makes use of road haulage, usually on a regional basis. The materials used in frame construction are produced in a relatively large number of locations. In some cases rail or barge would be used, for example for bulk materials, however this will be limited to situations where the materials are situated close to a railhead or canal.

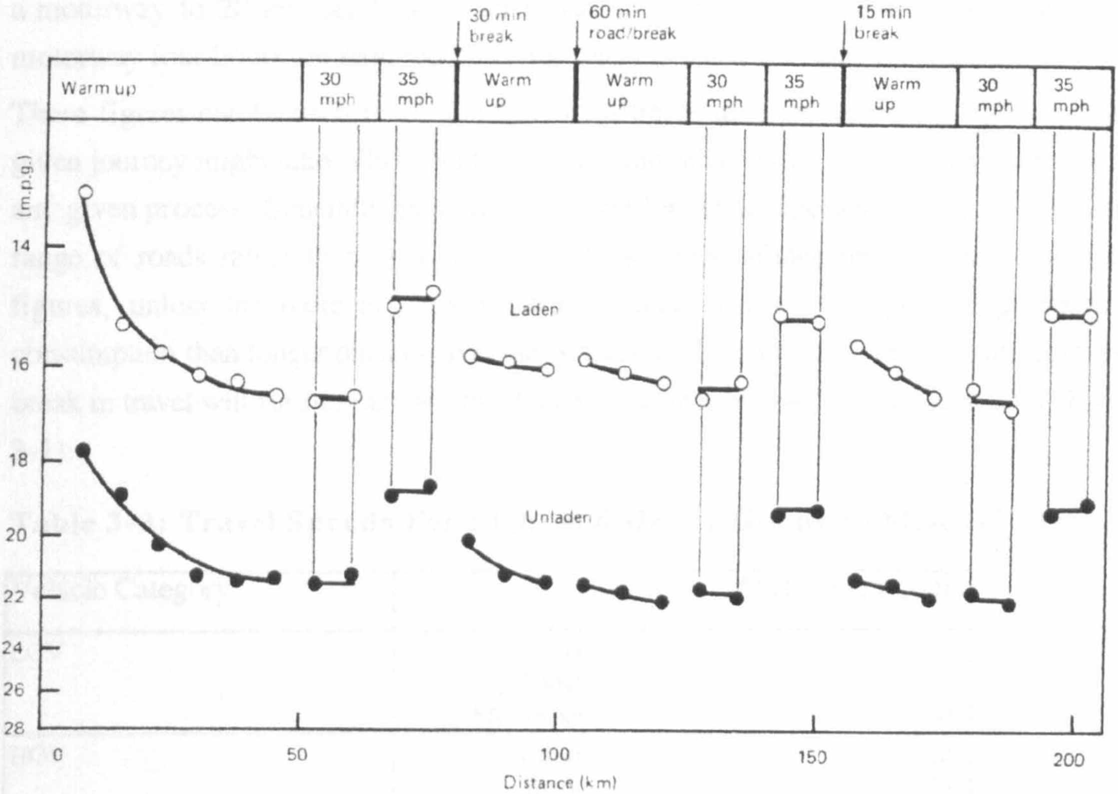
Road transportation is the most energy intensive form of transportation - Table 3-2 shows estimates of transportation energy cost per tonne for road and rail over different distances. Rail transportation has a lower energy per tonne for 200 km than road for 100 km travelled. The average cost for both road and rail falls with increased distance - this reflects the energy to load and unload materials, which is constant whether the distance moved is 1 or 1000 km. Transportation by water will have even lower energy costs. Where possible, transportation should occur using the most efficient form available.

Table 3-2: Buchanan & Honey Transport Energy (2)

Item		Embodied Energy MJ/t
Transport	Road 30 km	114
	Road 50 km	190
	Road 100 km	230
	Rail 200 km	146
	Rail 500 km	365

The actual energy consumed for any given material transport will depend on three major factors - the efficiency of the vehicle, the route travelled and the traffic encountered - and a number of lesser factors - the skill of the driver, whether the engine is warm, the degree of loading and vehicle aerodynamics. These factors are illustrated by Transport Research Laboratory (TRL) data. The TRL provide a system for calculation of average fuel consumption (3) over a working day. Figure 3-1 shows the measurement for an HGV over a sample day, including simulated breaks and different travel patterns. While these figures were calculated under very controlled conditions, rather than the possible extremes of actual road travel, there are significant variations. Fuel consumption in real world conditions could be expected to vary even more in a mixed working day, although when travel occurs with constant speed and conditions, for example a motorway, energy consumption could be much more even.

Figure 3-1: Average Fuel Consumption (3)



It is interesting to note that the vehicle fuel consumption increases by about 34% when going from unloaded to fully loaded. This is supported by work at the Energy Technology Support Group (ETSU)(**4**) which suggests, based on road testing of 17 and 38 tonne vehicles, that fuel consumption increases by 10% with a half load and 30% with a full load.

ETSU are also currently researching the possible use of alternative fuels (**5**, **6**). Sources such as natural gas, liquefied petroleum gas (LPG) and biodiesel[1] could all be used subject to engine conversion and limitations on fuel tank size. The renewable sources will generally generate lower emissions than for petrol or diesel. Some of these fuels have been in use in specialised cases, such as for agricultural vehicles, for long periods but they are not currently widely accepted.

ETSU estimates that production of oilseed rape, which is used to produce biodiesel, could not substitute for more than 7% of 1992 DERV requirement even if all the land currently set aside under the European Common Agricultural Policy were used for this purpose.

Table 3-3 shows average figures for distance travelled in an hour over different road types in both a light and heavy goods vehicle. The results range from 80 km per hour on

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[1] Biodiesel is produced from agricultural crops - for example rapeseed. It is therefore renewable.

a motorway to 20 km per hour in an urban environment - for every hour spent on a motorway four hours are required on urban roads to travel the same distance.

These figures can be used in conjunction with travel distance to predict how long any given journey might take. This could be used in the calculation of total traffic incurred by any given process. Generally most journeys over longer distances will be travelled over a range of roads rather than only one type. This factor dilutes the usefulness of these figures, unless the route is known. Shorter routes will tend to have a greater fuel consumption than longer ones on average because of the effect on 'warming up' and each break in travel will further increase this factor as shown by the TRL research data (Figure 3-1).

Table 3-3: Travel Speeds For Light and Heavy Goods Vehicles (7, 8)

Vehicle Category		Average km/hour
LGV	Urban	36
	Rural	56
	Motorway	80
HGV	Urban	20
	Rural	40
	Motorway	80

3.1.2 Transportation Energy Calculations

The figures for distances travelled in a given time must be supplemented with figures for actual fuel consumption and these are quoted in three basic ways - miles per gallon (MPG), kilometres per litre (km/lt.) and litres per one hundred kilometres (lt./100 km). Since these all measure fuel consumption, a figure given in, say, MPG can be converted into either of the others and so on.

The data shown in Table 3-4 is given as energy per litre of fuel. Diesel can be seen to have the most energy closely followed by petrol, with LPG some way back.

Table 3-4: Energy Per Litre Of Fuel (6)

	GJ/lt.
Petrol	0.0353
Diesel	0.0388
LPG	0.0260

The high energy potentials of petrol and diesel are the main attractions of these as fuels for road transportation - large distances can be travelled using a relatively small and light fuel reserve (the vehicle fuel tank) which leaves more space for the paying cargo. Alternative fuels are at a disadvantage in this respect.

For every gigajoule of fuel in the fuel tank must be added the production cost. This data is shown in Table 3-5 to Table 3-7. These tables show the energy overhead, in megajoules per gigajoule and associated CO_2 emissions.

The energy shown in Table 3-4 is the energy in a delivered litre of fuel - the potential energy of a litre of fuel actually in the vehicle tank (delivered energy). There is however, an energy requirement to win, process and transport the fuel to the place of use (primary energy).

Table 3-5: Production Energy & Emission Figures For Petrol (6)

Petrol	Energy MJ/GJ	CO_2 kg/GJ
Extraction	62.4	3.4
Transport	8.2	0.6
Refining	96.3	6.1
Distribution	2.0	0.2
	168.9	10.3

Table 3-6: Production Energy & Emission Figures For Diesel (6)

Diesel	Energy MJ/GJ	CO_2 kg/GJ
Extraction	58.7	3.2
Transport	7.7	0.6
Refining	53.4	3.0
Distribution	1.9	0.2
	121.7	7.0

Table 3-7: Production Energy & Emission Figures For LPG (6)

LPG	Energy MJ/GJ	CO_2 kg/GJ
Extraction	64.7	3.5
Transport	8.6	0.6
Refining	35.8	2.7
Storage	7.5	0.4
Distribution	5.6	0.4
	122.2	7.6

For clarity these tables have been reiterated in Table 3-8, which has combined the energy and production requirements to produce a total energy figure for a gallon of fuel. It should be remembered that the distance travelled in a vehicle using one unit of fuel will derive from the energy in THAT UNIT of fuel - the energy excluding production cost.

However, to be correct in costing the energy requirement the production energy must be added in.

For example, a diesel HGV with one gallon of fuel in its tank might travel 9 miles (it travels 9 miles per gallon) and this has derived from expending 0.176 gigajoules of energy (the energy from one gallon of diesel). However for that fuel to be in the tank of the HGV required an extra 0.0219 gigajoules in production cost (0.176 x 0.1217) therefore the total energy to travel 9 miles would be 0.1979 gigajoules.

Table 3-8: Energy Per Litre Of Fuel Including Production Cost

	Energy		Waste	Total
	GJ/lt.	GJ/Gallon	GJ/GJ	GJ/Gallon
Petrol	0.0353	0.160	0.1689	0.1876
Diesel	0.0388	0.176	0.1217	0.1979
LPG	0.0260	0.118	0.1222	0.1326

The information contained in Table 3-9 - Table 3-11 shows the life cycle energy and emissions for a range of vehicles. These figures can be used, as a basic average, to calculate actual energy and emissions for each road trip. The figures are limited in range and do not provide sufficient information to be of use for the generally more specialist equipment used in the construction industry, for instance heavy cranes or concrete mixer wagons.

Table 3-9: Vehicle Energy & Emission Figures For Petrol & Diesel (6)

		Fuel l/100 km	Fuel MPG	Fuel MJ/km	CO_2 g/km
LGV§	Petrol	13.6	20.9	4.8	309
LGV	Diesel	10.3	27.6	4.0	267
HGV	Diesel	32.8	8.7	12.7	853
Old Bus	Diesel	44.3	6.4	17.2	1119
New Bus	Diesel	34.1	8.4	13.2	885

§ Petrol light goods vehicle with three way catalyst

Table 3-10: Life Cycle Energy Use And Emissions For Petrol & Diesel (6)

		Energy MJ/km	CO_2 g/km
LGV§	Petrol	5.6	358
LGV	Diesel	4.5	295
HGV	Diesel	14.3	942
Old Bus	Diesel	19.3	1238
New Bus	Diesel	14.8	977

§ Petrol light goods vehicle with three way catalyst

Table 3-11: Vehicle Energy & Emission Figures For LPG (6)

		Fuel MJ/km	CO_2 g/km
LGV§	Catalyst	4.6	274
LGV	Catalyst	12.7	766
HGV	Lean Burn	14.0	834
Old Bus	Catalyst	18.9	1060
New Bus	Catalyst	14.5	864

§ Bi Fuel LGV with three way catalyst

Table 3-12: Life Cycle Energy Use And Emissions For LPG (6)

		Energy MJ/km	CO_2 g/km
LGV§	Catalyst	5.2	309
LGV	Catalyst	14.3	863
HGV	Lean Burn	15.7	941
Old Bus	Catalyst	21.2	1205
New Bus	Catalyst	16.3	975

§ Bi Fuel LGV with three way catalyst

Using these figures calculations can be made for the fuel consumed in transportation and associated energy. The ETSU figures also allow calculation of a range of emission values including for CO_2 and NO_X. An estimate can also be made of the time spent travelling and so a calculation could be made for the trip hours incurred for any given operation or building. The figures shown in Table 3-13 are derived from the preceding tables and represent the energy and CO_2 figures per gallon for petrol, diesel and LPG.

The figures for diesel CO_2 are slightly lower than those quoted by the DTI for oil in section 2.9, (13 kg/gallon = 66 kg/GJ, DTI figure for oil 69 kg/GJ) however these figures have been formulated especially for transportation fuels and have therefore superseded the general data.

Table 3-13: Derived Fuel And CO_2 Figures

	Total GJ/Gallon	CO_2 kg/gallon
Petrol	0.1876	12
Diesel	0.1979	13
LPG	0.1326	29

3.2 Conclusions

Transportation is an important user of energy and contributes large quantities of greenhouse gases. There are factors other than simple energy and emissions associated with transportation - congestion, danger to road users and pedestrians and time lost to traffic for example. Any move towards reducing traffic could therefore have a large benefit in many areas.

The actual calculation of fuel use and time spend on travelling is very difficult due to the possible variations in prevailing conditions. A journey of 10 miles on a specific length of road and in one particular vehicle could take vastly different times and use different quantities of fuel depending on the traffic, the weather or the driver. This possible variability is multiplied many times when considering the permutations possible in any construction project - the distances, plant used, plant efficiency and site access will all vary in addition to the factors already noted. In other cases simple economics can decide the environmental impact, for example selection of a batching plant 10 miles from site rather than one 2 miles from site due to relative costs involved.

In spite of this, it is possible to use average figures for fuel consumption and average speeds to assess transportation impact. Figures taken over time and averaged will include all the elements mentioned, even though a specific journey might not conform to the pattern. In line with other assessments in this thesis, good transportation practise has been assumed and this will to some degree minimise the variable factors. The general guidelines given by the Freight Transport Association (FTA)(9) are assumed to have been followed -

- Help drivers get the best from their vehicles.
- Make the vehicles as energy efficient as is economically worthwhile.
- Select the best vehicle for the job.

There is currently no detailed assessment of the transportation element associated with specific structures and this would be a useful figure to have with a view to reducing transportation impact. There is also little data for general travel patterns for plant and machinery and the associated fuel use. This data would be needed for an accurate assessment.

3.3 References

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4. FACTORS IN BUILDING DESIGN

Building design plays a key role in determining environmental success. It plays a major part in establishing the embodied energy and operational energy requirement and overall user satisfaction. Of these factors, embodied and operational energy can both be calculated in terms of actual quantities, subject to certain limitations discussed in sections 4.2 and 4.3.

Although ultimately user satisfaction is the most important factor in determining success or failure, as discussed in section 4.4.1, it is much harder to quantify. Some studies have provided limited numerical data in this area but most work focuses on the numerical values which can be calculated for energy and emissions.

Due to the relative unfamiliarity of this type of assessment, there are currently a significant number of figures available only for two components - Energy and carbon dioxide (CO_2) emissions. Other factors should not be discounted, but the sophistication to calculate them with any degree of certainty is currently not in place.

Where the term environmental impact is discussed, in broad terms it means all the impacts from all the energy and emissions associated with an action. Realistically however it is confined to the associated energy and CO_2. Minimising environmental impact therefore implies a reduction of all those factors, but generally means a reduction in energy and CO_2.

Although these two factors, along with other unmeasured emissions are closely linked in most cases, there may be instances where a decrease in one results in an increase in the other. This is true, for example, in the production of electricity, where nuclear power results in only small quantities of CO_2 compared with coal, but may result in other harmful effects.

4.1 Minimising Environmental Impact

There are two main methods of minimising the environmental impact of buildings. The first is to minimise the embodied energy. This is done by trading off between materials which can provide a similar level of functionality but with different embodied energy values. The second method is to reduce the operational energy requirement. There are a wide range of possible methods to achieve reduced operational energy use.

The minimisation of embodied and operational energy may also require a compromise within the design, so that a reduction in operational energy may increase embodied energy.

4.2 Embodied Energy

Embodied energy can be defined as being the sum of direct and indirect energy consumed in all processes involved with a building or component during a complete life cycle for that item. CIRIA estimates that about 4.5% of national demand for energy is used as construction materials compared with approximately 50% used as operational energy (the day to day energy requirements to run a building). This generates around 40 million tonnes of carbon dioxide annually (1).

Work carried out by Davis Langdon & Everest (2) in conjunction with the BRE suggests that the major components of total life cycle energy consumption of a building are factors not related at all to the structural material, but rather the operational energy and that used in repair, refurbishment and maintenance. This work makes a number of assumptions, for example that the design life will be fully used and so uses this as the basis for calculations - usually 60 years. This will not always be the case - work done by Golton (3) suggests that the design life is often unimportant when consideration is made of a building's future. In addition as future designers decrease the energy use required of buildings, moving towards a target of a 'zero emissions' building, operational energy will become relatively less important.

4.2.1 Important Factors In Calculation Of Embodied Energy

Apart from the limits on data collection there are a number of other factors which should be considered when calculating embodied energy.

4.2.1.1 Partitioning

Partitioning is the process of dividing costs (both financial and environmental) between products which are produced from the same process. For example, production of steel results in not only the main product but also, with minimum extra processing, ground granulated blast furnace slag (GGBS). This material was regarded as waste but is now considered a useful material, serving as a substitute for cement in concrete. This in turn reduces the embodied energy of the concrete it is used in.

Due to the fact that this is a novel concept, there is no clear agreement on how partitioning should occur. If no partitioning occurs there is clearly an over estimate of the environmental cost of one material and an underestimate of the other. One simple method for splitting is based on the relative commercial values of the two products.

4.2.1.2 Feedstock Energy

In some cases materials which could be used for power generation are used for other purposes. There is therefore a 'penalty' attached from the energy thus forgone. The most obvious example of this is the use of oil products as a carrier medium for chemicals, for example additives to concrete often use gas oil.

One other example which occurs in frame construction, is the use of wooden formwork. Wood has a calorific value of approximately 10 GJ/t. If the material is used as shuttering then this energy is not used. It is possible that, after use, the used timber would be either burnt or used for landfill methane extraction and in this case the energy is realised. Where this occurs, it is possible that the embodied energy of formwork could be lowered because the wood has two uses. The major problem in evaluating the feedstock energy is the uncertainty over the end use - in the case of shuttering, after use on site the wood could be either burnt on site (although this is less common than it might previously have been), taken to landfill or used as energy.

4.2.1.3 Non Economic Carbon Use

In some cases a manufacturing process takes advantage of a fuel source within materials that could otherwise be used for energy production. There is therefore a question of whether to include this energy in the overall calculation.

An example of this which occurs in this study, is the processing of pulverised fuel ash (PFA), a waste product from coal fired power stations. PFA has two major uses in frame construction (as well as several other non building uses) - as a cementitious material in concrete and as a lightweight aggregate[1] (trade name Lytag). As the name suggests, PFA is the remains of burnt fuel and, because a coal fired station is not particularly efficient (see section 2.5), this contains an unused carbon content. This is then burnt in the process of turning the ash into a useable (saleable) product.

There is therefore a question about whether to include this energy in the calculation of PFA embodied energy. Clearly the material has already been used as fuel and as much energy as possible has been extracted at the power station (there is no reason to think that useful fuel would be disposed of). The wasted energy is accounted for in the primary to delivered conversion factor (see Chapter 2) and there is thus a partitioning issue, both because the PFA is a waste product which is imported with a zero embodied energy and because of the energy still available in the product.

4.2.1.4 Sequestered CO_2

For materials which fix CO_2, there is a suggestion that a deduction be made from the emissions to reflect this value. This applies in particular to timber products. This means that as a tree is grown it fixes a certain quantity of CO_2 (the negative amount) but processing produces some emissions (the positive amount). This gives a net value for the timber as long as it is in the structure. When the structure is demolished, the fixed

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[1] The production of LYTAG requires an extra stage after the production of PFA for cement replacement. The processing of PFA involves grading the materials for different uses - larger elements are used for LYTAG, while finer particles are used as cementitious material.

(sequestered) CO_2 again comes into play. Some of the values detailed from other works include this negative value for CO_2 (see Table 4-3). For timber, the net effect of this element will depend on the balance of planting to cutting in the country in question. It should be remembered that the CO_2 is only fixed for as long as the timber is held in the structure.

4.2.1.5 Recycled Materials

Recycled materials are generally held to have an initial embodied energy of zero - although concrete may have an embodied energy of 8 GJ/t in terms of calculating a structural energy figure, demolition rubble is said to have an embodied energy of 0 GJ/t. This could also be thought of a special form of partitioning. It is possible to say that, once a building has come to the end of the design life, the lowest energy solution would be to simply leave it standing. The energy for demolition and disposal is in addition to that absolutely necessary. In practical terms, leaving a structure would not happen for a number of reasons - the value of land being the most important of these. However, in the same way that GGBS has a value and can be said to share some of the pig iron embodied energy, if waste has a value, it could be said to share some of the structure embodied energy. This value is not necessarily calculated only by a resale value, but could be set against the cost of disposal.

However, a common sense approach would be that end of use buildings need to be demolished and that the waste produced should be reused to limit environmental impact. Any assignment of a carried over embodied energy to waste would reduce the desirability of recycling, and this is to be discouraged.

4.2.2 Raw Materials Extraction

The extraction of raw materials will be more important for products which require a large input, especially when these are bulky. Both steel and concrete frames will require significant amounts of raw materials. However these materials tend to be provided on a local basis for concrete, but imported from abroad for steel. Materials importation presents some problems in energy calculation because of, for example, making sure of data parity.

Aggregates incur major environmental costs, although for transportation rather than extraction. Figures from Amato (4), shown in Table 5-6, suggest that the transportation cost can be as much as one half of the total embodied energy for bulk materials. Raw material extraction is an area where there is a large amount of controversy about damage to the environment - especially where quarries are situated in areas of natural beauty. Concrete is clearly the major user of quarried materials both in terms of raw materials for cement and aggregates for mix production.

The production and use of timber is a slightly different case from the other materials for a number of reasons -

- The range of timber varieties
- The renewable nature of the resource if correctly managed
- The impact on CO_2

It is possible to view timber as an environmentally neutral material although this will only be the case in certain situations. Since trees lock up CO_2 as they grow and only release it on destruction, if all timber used is replenished with an appropriate quantity of saplings no change in the net quantity of this pollutant will occur (excluding the relatively small costs associated with felling and treating). The truth of this argument depends on stocks of wood being correctly managed (for example replacing tropical hardwood with softwood would not result in a balance and may also have a negative impact on the variety of woodlands). Given these facts it may be possible to neglect the CO_2 cost for any given use of the material, although this should be justified by the circumstances. This is clearly an area where some of the economic ideas discussed in Chapter 2 may come into play with heavy surcharges to internalise[2] the total cost.

The overall level of raw materials extraction is closely linked to the quantity and level of recycling. Generally increases in materials recycling will reduce the demand for new materials while at the same time reducing waste. This should generally be encouraged in the interests of lowering construction impact.

4.2.2.1 Embodied Energy Value For Aggregates

Most sources quote figures for a range of construction materials (these are included in section 4.2.3), however MacSporran et al (5) examined the quarrying and recycling processes in detail. This assessment includes estimates for the plant involved in each of the processes as well as the quarry and transportation process. These values were calculated using delivered rather than primary energy. Overall the total energy required for new aggregates is only 63% of that required for recycled, but most of this comes from the higher transportation energy - recycled aggregates were more bulky than new and required movements around urban areas. The energy required for plant, both for production and transportation is significantly lower than the direct requirements for production and movement (fuel and operation costs) (see Table 4-1). The embodied energy for plant was calculated by simply taking the mass of steel in, for example, the

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[2] ie make each company pay ALL the costs incurred, for example from the damaged caused by exhaust gases, rather than only buying fuel.

crusher and multiplying by the embodied energy for steel, which was taken as 38.4 GJ/t. This value is significantly higher than that used in this thesis. There is also no assessment of the production energy for items of plant.

Table 4-1: Processing Energy For Aggregate (5)

	New (GJ/t)	Recycled (GJ/t)	New:Recycled (%)
Direct Production Energy	0.0370	0.0380	97.4
Production Plant Energy	0.0068	0.0039	174.4
Transport Fuel Energy	0.0170	0.0540	31.5
Transportation Plant Energy	0.0021	0.0046	45.7
Total	0.0629	0.1005	62.6

Calculations for transportation models other than that used would result in different energy results. This work represents the most complex calculations which had been carried out up to that point (1994). The majority of other reports produced more simple data for a wider range of values.

4.2.3 Raw Materials Processing & Manufacture

Whereas concrete uses most raw materials, steel requires the most intensive processing for any frame material, because virtually all the work takes place at this stage. Up to this point there has been limited published work on the functioning of steel works, although the doctoral thesis by Alex Amato (see section 5.2) provides some information. There is currently some work being carried out which should produce detailed analysis of the European steel production, however this study was not available in time for inclusion in this research.

Most of the information available for concrete and related processes gives results for aggregates and finished concrete, with little detail.

4.2.3.1 General Embodied Energy Values

Some of the earliest figures were proposed by Wright and Gardiner (7) and these have been used as a basis for a number of other studies. Figures calculated by Cole & Rousseau (6) compare selected values for different countries. Other figures from Buchanan and Honey (20), are based on New Zealand industry and the energy balance of that country. Some of the best currently available public domain values in the UK are from the BRE (8), but even these are not very exhaustive. A summary of these figures for structural materials is shown in Table 4-4.

Table 4-2: Wright & Gardiner Embodied Energy (7)

		Embodied Energy		Embodied CO_2	
		MJ/kg		MJ/m^3	
	Range	Low	High	Low	High
Aggregate		0.03	0.30	50	450
Cement		7.25	8.25	10800	12400
Bricks	Commons	1.00	1.50	1250	1875
	Flettons	3.00	5.00	3750	6250
Timber		1.50	6.00	1500	2500
Steel		30.00	50.00	210000	390000

Table 4-3: Buchanan & Honey Embodied Energy (20)

Item		Embodied Energy MJ/unit	Unit
Timber	Rough	848	m^3
	Air Dry Treated	1200	m^3
	Glulam	4500	m^3
	Kiln Dry Treated	4690	m^3
	Formwork	283	m^3
	Softwood	15470	m^3
	Plywood	9440	m^3
Cement		8980	t
Concrete	Precast	4780	m^3
	Insitu	3840	m^3
Mortar	Lime (1:2)	2500	m^3
	Cement (1:2)	5980	m^3
Steel	General	34.9	kg
	Rods	34.9	kg
	Sections	59	kg
	Pipes	56.9	kg
Aggregate		290	t
Masonry	Stone	290	t

Table 4-4: BRE Embodied Energy & Carbon Dioxide (8)

		Embodied Energy			CO_2
		Low	High	Indicative	
		GJ/t	GJ/t	GJ/t	kg/t
Aggregates	Natural Crushed Rock	0.02	1	0.5	45
	Fixed Site Recycled	0.02	1	0.4	37
	On Site Recycled	0.02	0.1	0.1	8
	Sand & Gravel	0.02	1	0.4	31
Cement	Average	3	7.5	5.3	1090
	With PFA/GGBS	-	-	4.8	920
Bricks	Flettons*	0.5	5	5	630
	Common Stock*	1.8	4.4	3.8	540
	Facing & Engineering*	-	-	6.5	920
	Facing & Engineering†	-	-	10	1400
Softwood	Imported	0.5	9	7-9	600-1000
	Indigenous	-	-	5.7	710
Hardwood	Imported	0.5	10	7-10	600-1100
	Indigenous	-	-	5.7	710
Glass	Flat	10	30	13	110
	Glass Fibre	30	60	30	2500
	Mineral Fibre	-	60	24	2200
Steel	New Strip	23	50	35	3400
	New Section	25	45	32	3200
	Recycled Strip	-	-	10	1800
	Recycled Section	-	-	9	1600
Plaster	Plaster	1.5	8.3	1.8	160
	Plasterboard	10	80	2.7	240

* Continuous Kiln
† Intermittent Kiln

These tables clearly show the wide range of figures currently available. For example the BRE give a range of 3 to 7.5 GJ/t for cement, Cole & Rousseau 9.4 GJ/t and Wright & Gardiner a range of 7.25 to 8.25 GJ/t all for the same material! A similar spread occurs for steel embodied energy values with a range from 9 GJ/t (BRE recycled steel) to 59 GJ/t (Buchanan & Honey). The range of figures available are summarised in Table 4-5.

Table 4-5: Range Of Figure For Embodied Energy

Energy	Minimum GJ/t	Maximum GJ/t
Steel	9.0	59.0
Cement	3.0	9.4
Concrete	0.9	3.8
Aggregate	0.02	1.0

Table 4-6: Buchanan & Honey CO_2 Emission Figures (20)

Carbon	Released kg/m³	Stored kg/m³	Net kg/m³
Treated Timber	22	250	-228
Glue Laminated Timber	82	250	-168
Structural Steel	8132	15	8117
Reinforced Concrete	182	0	182
Aluminium	6325	0	6325

Table 4-7: Cole & Rousseau Embodied Energy By Country (6)

Energy		Canada MJ/kg	US MJ/kg	NZ MJ/kg	Switzerland MJ/kg	Finland MJ/kg
Cement	Cement	5.9	9.4	7.4	4.9	4.9
	Concrete	1.2	1.3	2.0	0.9	-
	Mortar	2.2	-	-	1.4	-
Brick		4.9	5.8	-	3.0	3.0
Metal	Aluminium	236.3	192.0	145.0	261.7	189.0
	Steel	25.7	39.0	32.0	28.0	-

4.2.4 Construction

Construction operations are very important when determining the embodied energy for materials. The methods used in construction will determine the type and duration of plant use, the amount of waste generated and the total duration of the contract. Which material has an advantage in this area will depend on the design of the building and the timing of the work. In general, the energy used on site will be electricity (office equipment, tower crane, lights, etc.) and diesel (items of plant). Due to the use of electricity, it is important for calculations to be correct, as discussed in chapter 2.

One specific area where significant savings in energy and emissions could be made is the reuse of materials on site, both in the context of demolition waste and excavated materials. Significant use of either of these resources would reduce the demand on both raw materials and transportation.

There has been little work carried out in this area to date and one of the major problems encountered in this study was the limited data on energy used by construction plant. The 1990 Construction Weekly Plant Directory annual (9), a register of construction equipment, asked contributing manufacturers for information on fuel consumption, but notes that

> *While some manufacturers have been quick to respond, many have been reluctant or simply refused.*

It is interesting to note that the 1991 edition, the last year the annual was published, contained no data for fuel consumption. Even when fuel consumption data is available, it must be coupled to a value for the work carried out to be of use.

The actual methods employed on site will depend on a number of factors - the equipment available, the preferred contractor methodology, time constraints as well as the frame material selected. In most cases there will be at least two methods and possibly more of achieving any given goal.

Some general site restrictions can be suggested that might have a major impact on the methods selected -

- Waiting and access restrictions on the public highway, could mean that few deliveries would be required. On a specific level, concrete pumping would be preferred to crane and skip because this is generally quicker.
- Access through the site and storage availability would have an impact on materials handling and delivery to site. If space is limited, materials would be expected on a just in time (JIT) basis
- Overswing rights for a tower crane could be limited and where this is the case other placement methods might be preferred.

The possible permutations for site construction methods are almost limitless and each contract will be different, even for similar designs.

Buchanan and Honey suggested some energy rates for construction processes, shown in Table 4-8, although clearly these have been reduced to a simple level. Basing the preliminary and administration work on the contract value might be a good method of evaluation - a more expensive contract will generally entail more work - but a system based on actual measurement of work would be preferable.

Table 4-8: Buchanan and Honey Construction Energy (20)

Item	Embodied Energy	Unit
Preliminaries	39.5	MJ/$
Administration	22.5	MJ/$
Earthwork	100	MJ/m^3
Site Work	1	MJ/MJ

4.2.5 Repair, Refurbishment and Maintenance

This is an area where durability is an important issue. Refurbishment should not be particularly important for a building frame. Repair and maintenance can however be very important. Although there are cases of steel frames requiring large amounts of work, there are many more cases of concrete requiring restoration. This is not a problem with concrete as a material, but rather with the specification and workmanship involved during construction.

Generally, where a frame has been constructed to a high standard there should be no major maintenance problems within the design life. Extension of the frame life beyond this may entail an increased repair scheme.

4.2.6 Demolition

There are a large number of environmental impacts involved with demolition - dust and noise pollution, waste materials produced and energy used in demolition. The methods employed will differ greatly depending on the building location and site restrictions, but also on the recycling strategy employed. Where there is no recycling scheme in place the plant and time requirement will be much lower than where a high level of reuse is required. Recycling requires the methodical stripping out of materials and may extend the contract time slightly. Two examples of demolition for recycling are the BRE Phoenix building (**13**) and IBM laboratory (**10**) buildings.

4.2.7 Waste

The quantity of waste produced during a building life cycle will have a marked impact on the total energy requirement. There are many areas where waste can be produced - in any area where material or energy use is more than the minimum needed to satisfactorily complete a given object or operation. For example, it is possible to say that any building design which fails to take advantage of the surrounding environment to lower the operational energy requirement is producing waste.

There are a number of places where waste can enter the disposal system. To fully assess embodied energy all these need to be considered. The assessment shown in Figure 4-1 is based on work by Lauritzen (**11**).

Materials with simple processing requirements will tend to have an environmental advantage in this area since there will be less opportunity for waste to occur. Also in this respect materials which require more work to be carried out on site, rather than off site in a factory environment, will tend to produce more waste than those which do not. On both these counts, in situ cast concrete seems to be at a disadvantage because of the large number of stages and the 'on site' nature of work. No detailed comparison is available looking at the relative waste produced for all frame materials.

Table 4-9 shows the waste on 86 sites surveyed by Enshassi (**12**) in the Gaza Strip, Israel. Although these figures are unlikely to exactly represent UK figures, they clearly show the scope for underestimating waste and energy savings in this area. Direct waste occurs from working practises such as cutting and mishandling, while indirect waste arises through, for example, substitution where materials are incorrectly used.

Figure 4-1: Production Of Building Waste (11)

1. Extraction & Processing Of Raw Materials	A certain amount of low quality and waste material arises, but these are often disposed of in the quarry and have no influence on outside waste streams so they are not usually considered as waste.
2. Production Of Building Materials	Industrial production of building materials, cement, construction steel, timber, prefab building elements, etc. leads to some waste and excess materials. This can be as much as 5% of production.
3. Construction Waste	Much waste arises from packaging, concrete forming, excess, etc. Approximately 20-40 kg of waste is produced per square metre of constructed flooring.
4. Waste From Maintenance And Repair	This generates mixed building waste, the amount depending on the type of work, specifically whether it is structural or not.
5. Demolition Waste	Waste from both partial demolition (refurbishment work) and total demolition. Estimated at one to two tonnes per square metre of flooring.

Table 4-9: Materials Loss Resulting From Direct And Indirect Waste (12)

	Waste			
Material	Direct (%)	Indirect (%)	Total (%)	Normal Allowance (%)
Common Bricks	3.2	2.0	5.2	2.0
Facing Bricks	4.9	2.2	7.1	3.0
Steel Bars	2.1	1.5	3.6	2.0
Shuttering	6.9	4.1	11.0	4.5

Demolition waste is an area in which there is an increasing quantity of information. Demolition work carried out in conjunction with the BRE low energy building (**13**) has shown the possibilities for increasing the useful life of construction materials. Although a number of problems arose, specifically the restrictions imposed by the construction program, the transport distances involved in moving reclaimed materials around the country and the availability of storage sites while materials await the next use, generally the program was considered a success.

In good environmental design the idea of waste is closely associated with recycling. The BRE recommends five stages in the disposal of waste. In descending order of desirability, these are reduce, reuse, recycle, recover energy and dispose.

To reduce waste simply means the elimination of unnecessary waste through, for example, tight ordering procedures and good stock control. Reuse means taking whole elements and, after cleaning as required, using in a new setting. Generally reused items are high value such as architectural features, potentially however any item which can be removed without damage can be handled in this way. Recycling involves using the material in another form. Frame materials tend to fall into this category. Concrete and masonry can be sorted, crushed and used as sub base or as aggregate, as in the BRE building. Steel can be incorporated into new elements. The recovery of energy can take place in a number of ways. Some waste material, as shown in Table 4-10, has a calorific value which can be exploited for power generation. Recently waste materials have been used in the production of cement (**14**).

Table 4-10: Calorific Values For Waste Materials (15)

Materials	Calorific Value (MJ/kg)
Dry Hardwood	18-19
Sawdust & Chips (Dry)	17.4
Cardboard	20.0
Asphalt	39.8
Tyres	34.9
Average Household Waste	12-14

Structural materials such as concrete and steel have no calorific value to be extracted in this way. It is possible however that the embodied energy of these materials might go down if waste materials were used in their creation. Disposal will usually involve simple use of landfill sites. Although frame materials lack a recoverable waste value, this gives a possible advantage in land fill. These materials are inert so they do not give off methane gas, eliminating the need for special techniques to be employed in making safe after dumping.

All of these options incur extra energy expense mainly through transportation and repurposing (for example crushing) operations. These will generally increase the lower the grade of recycling. Increases in financial cost can, as noted in the BRE study, be offset by the resale values of the waste materials and the reduction in landfill charges.

4.2.8 Recycling

Speare (**16**) identifies two main reasons to recycle - the need to conserve resources and the need to manage waste - both of which are part of the drive to provide sustainable development.

CIRIA (**1**) figures suggest that recycled aggregate can only fulfil an estimated 11% of current demand and further that 11 million tonnes of building waste material in total is recycled but with capacity for a further 70%. This figure also includes some refuse from the construction process rather than simply demolition. In terms of structural elements there is very little scope for reusing sections because of the obvious difficulty in disassembling without damage to individual members. The majority would either be expected to be recycled or disposed of as landfill.

There are a number of propositions to define the types and stages of recycling. Speare suggests use of the terms reduction, reuse, recovery and disposal. Since in this context reduction is looking at the broader issues of reducing quantity of material used, it is simpler to say that this is covered in other areas.

A study of demolition in Melbourne, Australia carried out by Salomonsson and MacSporran (**17**) suggests that there are three possible ways of handling materials produced by demolition - direct Reuse, Reprocessing and Landfill disposal and these agree broadly with the reuse, recovery and disposal suggested by Speare. The study produced waste recycling figures for a specific site and these are shown in Table 4-11. This work should be viewed in conjunction with the data for recycled aggregates, also by Salomonsson and MacSporran with Tucker and detailed in section 4.2.2.1.

Table 4-11: Material Recycling (17)

Material	Reuse		Reprocessed		Landfill	
	t	%	t	%	t	%
Concrete	0	0	63200	70	27100	30
Brickwork	11600	60	2900	15	4840	25
Structural Steel	1630	15	8710	80	540	5
Reinforcement	0	0	1640	50	1640	50
Timber	1330	50	0	0	1330	50

There is a marked difference in the recyclability of the different materials - 60% of the brick is reused but none of the concrete. This is because the concrete members are easy to demolish but very difficult to dismantle without damage. In addition structural members will have been subjected to unknown loading history and reuse would raise issues of fitness for use in a new structure. These figures suggest that there may be a large market for recycled materials if the conditions are correct in this country. Much of the crushed concrete waste has initially been used as hardcore, however there are now mix designs which allow perfectly acceptable concrete to be made using this material (**18**).

The definitions used by Speare and Salomonsson are less complex than the five recycling headings proposed by the BRE (detailed in section 4.2.7) because they exclude both elimination of waste and recovery of energy. The BRE definitions should be considered better since they increase the scope of the life cycle energy calculations. The table below shows the relative quantities of materials recycled for the BRE building -estimated at 96% or higher.

Table 4-12: Summary Of Demolition Waste Management (13)

Material	Disposal Option	Estimated Quantity	Unit
Bricks	Low level recycling	500	m^3
Corrugated Roofing Sheets	Reused	300	m^2
Roofing Timber	High Level Recycling	300	m^2
Slate Cladding	Reused	40	m^2
Iron & Steel	High Level Recycling	90	t
Lead & Copper	High Level Recycling	1.3	t
Concrete	Low Level Recycling	600	m^3
Fixture, Fittings & Furniture	Reused	6	m^3
Cast Iron Drainpipes	Reused	10	no.
Remainder Of Building	Landfill	50	m^3

Speare outlined a number of factors which will influence the quantity of a material which is reused and reprocessed which are -

- Value of waste
- Level of contamination
- Reprocessing cost in comparison with production cost
- Variety of use
- Possibilities for reuse in small quantities

Allwinkle & Stembridge (19) identified a number of barriers to increased reuse of building materials and these included

- A lack of standards for the recycled materials
- A lack of facilities
- Transportation and processing cost.

To these factors Speare added several other constraints including

- Geography
- A lack of technical knowledge and equipment
- Perception barriers that waste is only, by definition, waste

These will all tend to become less of a problem as work progresses in this area - this was one of the stated reasons for the BRE building materials being so extensively recycled. CIRIA (1) reported that there are a number of constraints to a greater use of recycled materials -

- Transportation costs and lack of infrastructure.
- Existence of established primary resources market.

- Specifications which are based on primary resources.

The lack of recycling infrastructure might be considered a greater impediment than actual transportation cost, because, as noted by MacSporran (5), waste materials will generally have to be transported to a waste site anyway. However CIRIA noted that

> *A major constraint to greater recycling of bulk materials appears to relate to transportation costs compared with the value of the materials.*

4.2.9 Perspectives

For reasons already outlined, most factors are considered from the energy perspective only because this is the data for which information can be gathered in a systematic and quantitative way. This does not mean that there are no other possible methods of looking at the environmental impact of buildings and some of these have been noted previously. These can either be considered in conjunction with energy or as separate indices and some of those more likely to be used are examined in the following sections.

4.2.9.1 Environmental Footprint

This factor looks at the geographical distances between the areas materials originate from and the location of use. A larger environmental footprint can generally be considered to be less environmentally friendly since it implies greater transportation cost. This only holds true if all transportation costs are the same, which is clearly not the case between, for example sea and land transportation (examined in Chapter 3). It also takes no account of the differing efficiencies of industries in different countries.

It is possible that some system can be derived looking at gross areas and assigning values for production and transportation cost, which would identify areas which would most advantageously be used as a source for materials

4.2.9.2 Emissions and Energy Use

There are a large number of emissions which result both from construction and use of a building. Some of these are direct (CO_2 from transportation) and some are indirect (pollution from power stations). These include -

- Production of CO_2 from use of fossil fuels. Primarily of concern as a green house gas.

- Particulates, particularly carbon, are a source of increasing concern because of possible links to respiratory diseases.

CO_2 is mainly produced in power generation (either through power stations or from building mechanical and electric equipment) and will vary with the type of fuel used, but can also occur from the use during construction and demolition of site equipment such as gas heaters. As can be seen from the table gas produces the least CO_2 and coal the most, however these figures will vary with power station. The CO_2 associated with electricity will depend on how it is generated. A Fuller explanation of energy production is included in chapter 2.

Particulates will be generated throughout the building life time but mainly during the phases up to and including construction and during and after demolition. These factors will all be influenced by the selection of frame material and techniques employed on site.

4.2.9.3 Ecological

The factors identified in Chapter 2 are the most problematic to quantify. The factors which occur most often are at either end of the life cycle - material extraction (for example mining) and disposal (for example landfill or dumping). Given that steel requires much smaller quantities of raw materials and is highly reused it has an advantage over concrete and brick in this area. Timber may actually provide a positive impact - a well managed forest may be used for recreation, but tends to be simply burnt rather than reused at the end of its life. Increasingly demolition waste of this nature may be used to generate power which, as previously discussed, is not an option open in the case of the other structural materials. Buchanan and Honey (20) estimate that timber actually has a negative net carbon emission figure (see Table 4-6), which greatly increases this material's competitiveness with respect to concrete and steel.

4.2.10 Assessment of Values for Embodied Energy and CO_2

There have been a number of attempts to provide accurate figures for embodied energy for construction materials and these vary to a large degree depending on how the variables described above have been accounted for. These figures are derived from a number of sources, mainly Government statistics, industry figures and step by step process analysis. None of these sources can produce totally accurate figures, rather they can be viewed as a snap shot of one process at one point in time using a given set of criteria.

It is clear that for any structure the actual value picked will have a marked impact on any calculations made and on any comparison between materials. The differences in embodied energy figures occur for a range of reasons, mainly the difficulty of getting correct base data for calculations, the differences in industry dynamics between countries and the boundaries for data inclusion. Some of these figures include an element for transportation and some do not.

4.2.11 Using Embodied Energy and CO_2 Data

To use these numbers in a meaningful way requires calculation of the work done by a quantity of the material, specifically the total quantity of material in a structural member or complete building.

This provides a better test of the energy requirements for different materials than a straight comparison of embodied energy as megajoules per tonne will. Comparison without this calculation is misleading because one tonne of steel, say, can be used to produce more of the frame than one tonne of concrete. To increase the accuracy of the comparison, assessment must be made of each building under consideration. This is also true of the initial embodied energy figures.

In addition there are few figures for embodied energy for actual buildings. Some work was carried out by Buchanan and Honey (20) for three buildings types in New Zealand (Table 4-13). As noted earlier, because of the net negative CO_2 emission figure, the timber structures have a clear advantage over steel and concrete. It is unlikely that these figures would be the same in the UK given the differing set up with regard to timber production. For the generic 3-6 floor office building, the only option for which all three material types were used, timber has a lower embodied energy requirement and produces less CO_2 emissions by a large margin followed by concrete and then steel.

One building for which embodied energy and CO_2 calculations have been made, for each of the main construction items, is Linacre College. This information was calculated using figures calculated by Nigel Howard at Davis Langdon And Everest (DLE) for the BRE (21). The calculated values for embodied energy and CO_2 are shown in Table 4-14.

Table 4-13: Honey and Buchanan, Embodied Energy and CO_2 (20)

		Portal Frame	3-6 Floor Office	Hostel
Energy		GJ/m^2	GJ/m^2	GJ/m^2
Concrete	Structural		3.4	2.2
	Non Structural		2.2	1.5
	Total		5.6	3.7
Steel	Structural	1.6	4.4	
	Non Structural	1.6	2.2	
	Total	3.2	6.6	
Timber	Structural	0.2	1.5	1.1
	Non Structural	1.6	2.2	1.5
	Total	1.8	3.7	2.6
CO_2		kg/m^2	kg/m^2	kg/m^2
Concrete	Structural		80.1	43.6
	Non Structural		34.9	26.5
	Total		115.0	70.1
Steel	Structural	29.1	91.4	
	Non Structural	35.2	34.9	
	Total	64.3	126.3	
Timber	Structural	-4.2	1.0	-5.6
	Non Structural	35	34.9	26.7
	Total	30.8	35.9	21.1

Table 4-14: Linacre College, Embodied Energy & CO_2 (21)

Gross Floor Area 986m2	Embodied Energy		Embodied CO_2	
	(GJ)		(Tonnes)	(%)
Site Preparation, Soil Disposition	350	4.4%	29	3.5%
Substructure & Basement	2141	27.0%	226	27.1%
Frame	8	0.1%	1	0.1%
Upper Floors	2212	27.9%	228	27.3%
Roof	254	3.2%	24	2.9%
Stairs	89	1.1%	10	1.2%
External Walls	1194	15.1%	141	16.9%
Windows & External Doors	97	1.2%	9	1.1%
Internal Walls	782	9.9%	86	10.3%
Internal Doors	28	0.4%	3	0.4%
Wall Finished	136	1.7%	13	1.6%
Floor Finishes	349	4.4%	39	4.7%
Ceiling Finishes	237	3.0%	20	2.4%
Sanitary & Disposal Appliances	39	0.5%	4	0.5%
TOTAL	7918		834	
Total/m2	8.0		0.8	

The Linacre college accommodation block, built for Oxford University and completed in September 1994 provides 986m^2 of space. The construction uses structural masonry rather than a steel or concrete frame. The decision to use this form of construction was based on analysis of the competing material energy figures. The proportions of energy and CO_2 coming from each building element is approximately equal, with the greatest difference for external walls (1.8%) and site preparation (0.9%). Based on these figures the 'frame' (composed of frame, upper floors, stairs and external walls) is 44.2% of the total.

4.3 Building Design and Operational Energy

It is important to control the internal environment of the building for one overriding reason - to ensure the performance of equipment functioning within, especially the human resources. The requirements for thermal comfort have been shown to be less stringent when the occupants have more control over their immediate surroundings (**22**). The second requirement, largely based on the needs of computers has decreased in importance as these machines become able to tolerate much wider environmental perimeters. This means that there is no reason why the current trend towards passive systems should not be extended.

4.3.1 Air Conditioning

Air conditioning can be both passive and active. Active conditioning uses mechanical means to provide the required internal environment for both people and equipment. Passive ventilation uses the building design and the external environment to do the same.

Totally passive systems are unlikely to occur due to the large variations in the local conditions possible in this climate. Most commercial buildings will require at least some plant, for example a fan to increase air movement as required. This is supported by the case studies assessed, all of which retain some mechanical equipment. It should also be noted that it is unlikely that natural ventilation can replace full air conditioning as this contains an element of humidity control. While a natural ventilation scheme can have some effect on humidity, for example making use of water features such as lakes, this will never be as close a control as can be exercised by HVAC equipment.

The current consensus is that mechanical air conditioning has traditionally been over specified for a number of reasons (**23**)(**24**)(**25**) which include -

- The requirement for full air conditioning as a prestige element of a building.
- The rapid change in requirements of advancing and new technology, specifically computers. In addition there is often a discrepancy between the energy use rating of equipment and the actual average use. The BRE estimate that this factor can be as much as 80% (**26**)
- The method of payment to mechanical and electrical contractors is generally a percentage of the contract cost which offers no incentive to explore areas which provide a less expensive alternative.
- Inherent conservatism in design to ensure against post completion claims for failure to achieve adequate cooling standards.

Despite this there is little doubt that some elements of mechanical ventilation are required in some specific areas, notably laboratories and lecture halls, but the need is more limited than the current levels of use might suggest.

4.3.1.1 The Cost Of Air Conditioning

Table 4-15 shows typical energy and monetary costs for a range of air conditioning systems. These systems can be made partially redundant when natural ventilation is used resulting in a saving in both running costs and capital expenditure. There may also be a saving on replacement cost during the life of the building. There will also be a clear reduction in CO_2 emissions over the life of the building.

Table 4-15: Typical Characteristics Of MVAC Systems (27)

Air Conditioning	Cost	Capital (1992) £/m^2	Fuel (1993) £/m^2/y	CO_2 kgC/m^2/y
Centralised	Mechanical Ventilation With Heating	100	1.9	8.18
	Constant Volume (Single Zone)	160	3.0	13.64
	Variable Air Volume (VAV)	180	2.4	10.91
	Dual Duct	210	3.4	15.00
Partially Centralised	Centralised Air System With Local	200	3.1	13.64
	Induction System	160	3.2	13.64
	Fan Coil System	170	3.2	13.64
	Unitary Heat Pump Systems	130	3.2	13.64
Packaged	Heating And Ventilation Only	90	1.1	4.64
	Self Contained Units	70	3.5	20.45
	Split Systems	85	3.5	20.45
	Individual Reversible Heat Pumps	110	3.0	15.00
	Variable Refrigerant Flow Systems	130	2.8	13.64

4.3.2 Design Features

There are a number of other factor which will help determine the internal environment of a green building. These factors include shaping strategies involving exposed concrete soffits and matters such as daylight, shading, ventilation and control systems and are having a major effect on the design and layout of concrete buildings.

4.3.2.1 Thermal Storage

One of the methods for eliminating air conditioning involves the use of structural mass as a heat sink to smooth the peaks and troughs of external temperature. This is a complex concept and involves a number of design concepts - heat flow, ventilation, control systems and aesthetic value. In the case of the PowerGen (**28**) building the shaping of the concrete soffit was found to have a beneficial effect on the sound characteristics.

There has been a significant swing towards buildings which take advantage of concrete's high thermal mass to reduce or eliminate air conditioning and there are a number of buildings worthy of study. Nearly all the low impact buildings surveyed made some mention of the use of thermal storage (see Table 4-16: Features Found In 'Green' Buildings), however there are very few figures detailing how its use has affected building performance.

There are a range of heat sink types that can be used to store heat or coolth against a need - the most obvious example being a cool night followed by a hot day. The type most used in buildings is a thermal store, using either latent (including phase change solid to liquid), or sensible (none phase change) energy. Using concrete to store heat in this way has a number of advantages (**29**) - large thermal capacity in a small mass because of relatively high density, reversibility over cycles and durability. The greatest advantage is that the concrete's primary task is structural so inherent thermal mass can be realised with little extra design or cost. Generally the mass utilised will be that used in the floor elements of the structure, which tends to be made from concrete whether the rest of the frame is steel or concrete. The chief point of interest then comes in the quantity of mass that can be accessed - steel framed buildings tend to use composite concrete-metal deck slabs of less thickness than found in insitu cast frame buildings and this will provide less mass to use.

There is little doubt that thermal mass represents an opportunity in construction. A BRE paper (**30**) suggests that....

> *.....building thermal mass can represent an important and viable technique for reduction of peak summertime internal temperatures.*

However several sources have questioned the effectiveness of thermal mass above a certain quantity (**31**)(**32**)with an SCI report stating that

> *....there is very little difference between the effective thermal mass in equivalent steel framed and concrete framed buildings*

and that

> *....the choice of servicing system is far more important than the choice of frame material*

The critical point in the argument is the question of access to the thermal mass. There are several methods that can be used to increase the amount of thermal mass accessible and these are outlined in section 4.3.2.1.1. Although some early examples of these methods have been built, it should be noted that they are largely untested over the long term.

4.3.2.1.1 Thermal Mass Availability

Thermal storage mass is the quantity of heat that can be collected in a quantity of material over a temperature range. Calculated using specific heat capacity and density, thermal storage mass, when coupled with heat transfer to or from the environment, can beneficially affect the thermal comfort of a building. For any given storage mass, an increasing temperature change will result in an increased energy storage. This might lead to the conclusion that increasing slab thickness would linearly increase performance since it increases the potential energy storage capacity through a linear mass increase. However, two factors moderate this; the 'availability' or 'remoteness' of the mass and the ability to transfer and absorb supplied heat which in turn depends on other factors; exposed surface area per unit mass (e.g. flat slabs have a lower surface area than waffle decks), the resistivity of the boundary layer and the thermal diffusivity. Heat transfer occurs in three ways - primary (direct contact with radiation), secondary (contact with a radiative area) and remote (mainly convection). Concrete soffits are heated mainly by 'secondary' radiation and convection. Obstruction of the mass, for example by a suspended ceiling, will reduce its usefulness significantly. Convection transfers can be increased by directing air flow over the heat exchange area either using natural buoyancy or forced ventilation. The surface resistance to heat transfer of the concrete and boundary layer is important since a lower value effectively makes more mass available by speeding up transfer. Evaluation of resistance involves several factors including surface resistance, emmisivity of heat exchanging surfaces and heat transfer coefficients.

One promising method for increasing the potential transfer uses hollow core concrete slabs (**33**)(**34**) primarily under the name of Termodeck (**35**) but these may have a number of drawbacks, for example maintenance and cleaning. In addition the buildings that take this approach seem to use it instead of other design features rather than in conjunction with them. This is discussed in section 0.

Once the boundary layer is crossed, the speed with which the heat distributes through the mass is governed by the thermal diffusivity, which is based on the conductivity and density of the concrete.

4.3.2.1.2 Phase Change Materials

The use of phase change materials could be very useful in controlling the internal environment, but it is not thought that these materials will affect the environmental impact of the frame material.

4.3.2.2 Solar Panels

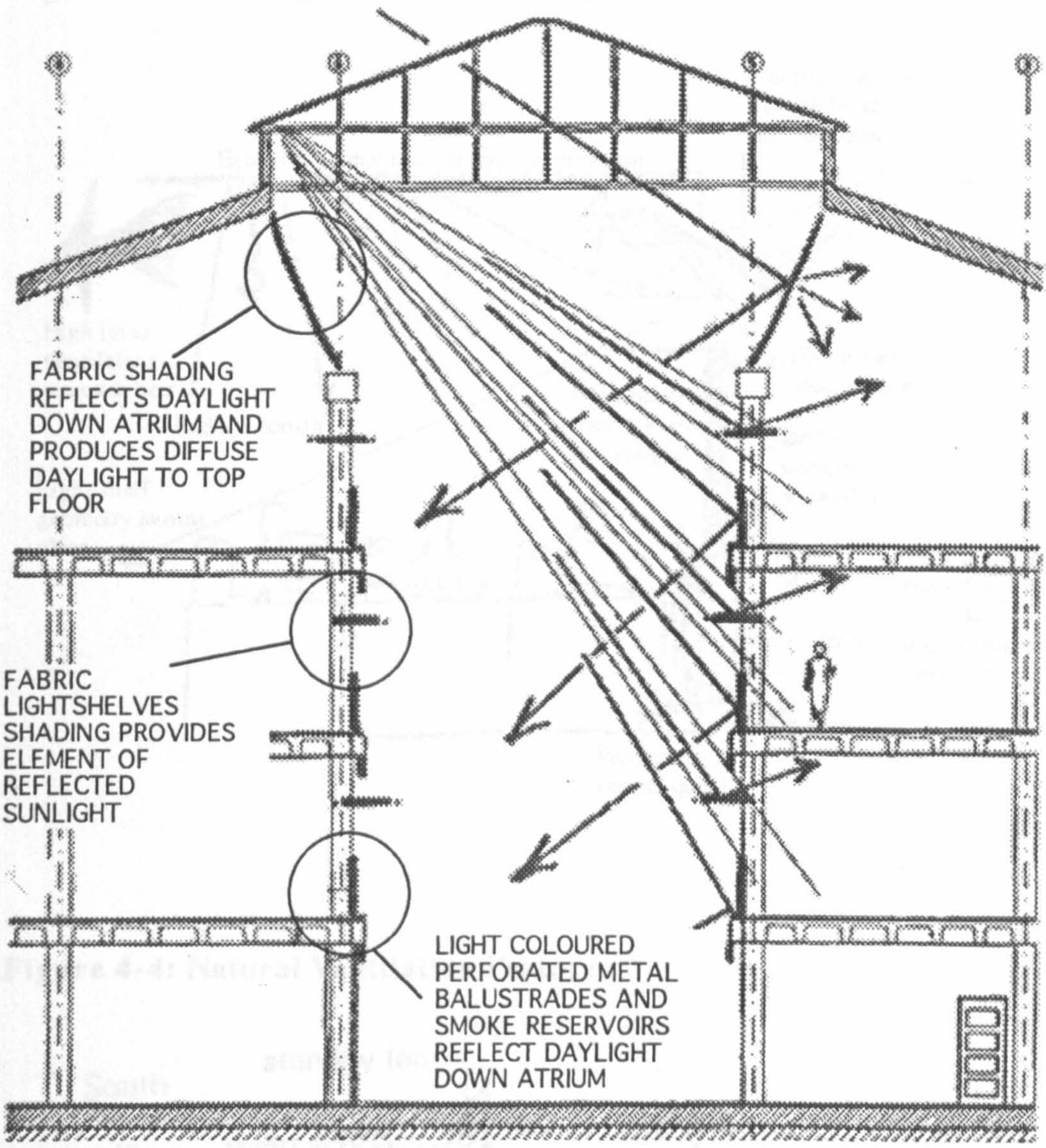
There are two major ways of using solar panels, either as a heat exchange mechanism or via photovoltaics to generate electricity. Photovoltaic panels do not reduce energy consumption as such but do switch the power source to a renewable one with no CO_2 or other emissions (except those involved in construction and repair of the unit). Currently there are few examples of the use of these (only one building of the case studies examined (**36**) featured this type of panel) probably because of the high initial cost.

Heat exchange solar panels are simpler and cheaper than photovoltaic panels. In the only case found of these being used on a non domestic dwelling (**37**), the panels were used to preheat water. The results of this in terms of reduced energy consumption are not known.

4.3.2.3 Use Of Daylight and Natural Ventilation

All green building designs make use of daylight to reduce the lighting requirement. This can occur in a number of ways, for example through the use of shading/light shelves on windows or other areas such as atriums. These features are illustrated in Figure 4-2 which shows a section though the Learning Resources Centre, Anglia Polytechnic University (**38,39,40,41**).

Figure 4-2: Daylighting Features (39)



This design also makes use of an atrium which is a feature found on a number of these buildings. An atrium can serve a number of purposes. As illustrated above, it serves to bring light down into the heart of the structure. It can also serve as a thermal chimney, acting to increase ventilation by creating a pressure difference.

All the buildings surveyed used at least double glazing and most window units included blinds, light shelves or external shading. All these windows were operable by the occupant to increase ventilation and increase user satisfaction. Figure 4-3 shows a number of features designed into the Learning Resources Centre at Anglia Polytechnic University but especially the internal light shelves and the blinds sandwiched between the two panes of glass.

Figure 4-4 shows how the prevailing wind can be used to increase ventilation when coupled with the building design.

Figure 4-3: Heating, Ventilation & Light Flows (39)

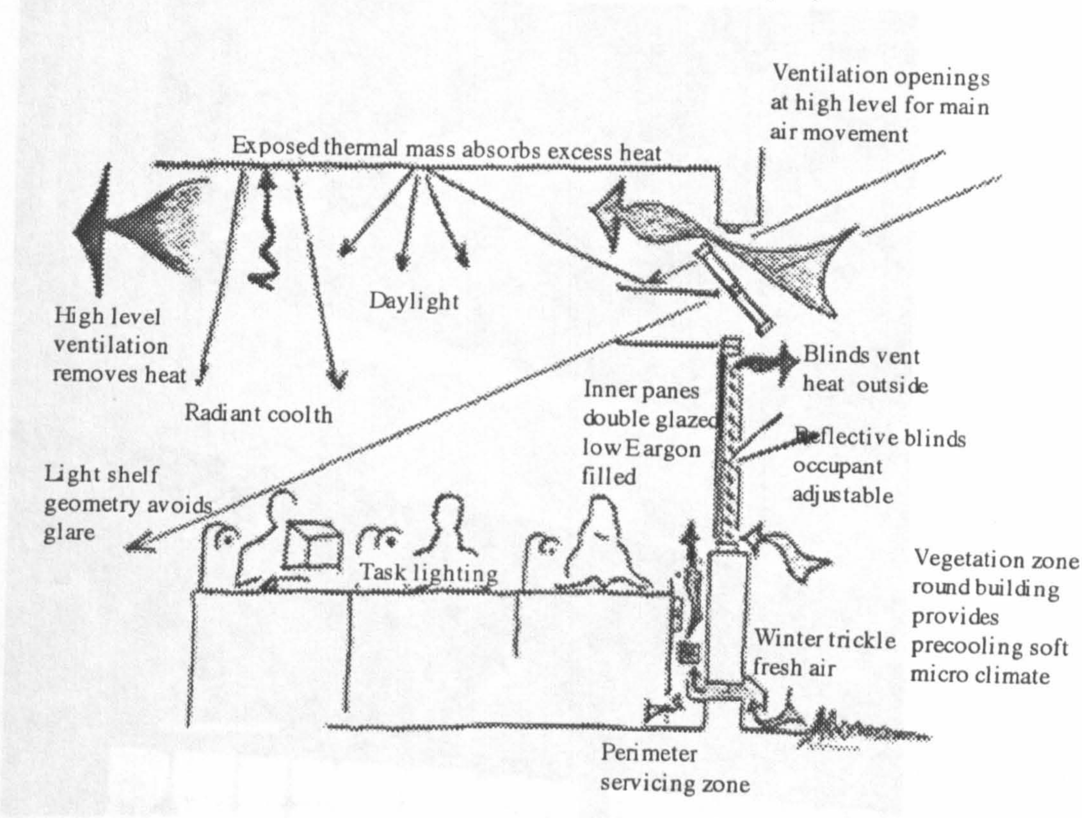


Figure 4-4: Natural Ventilation Feature

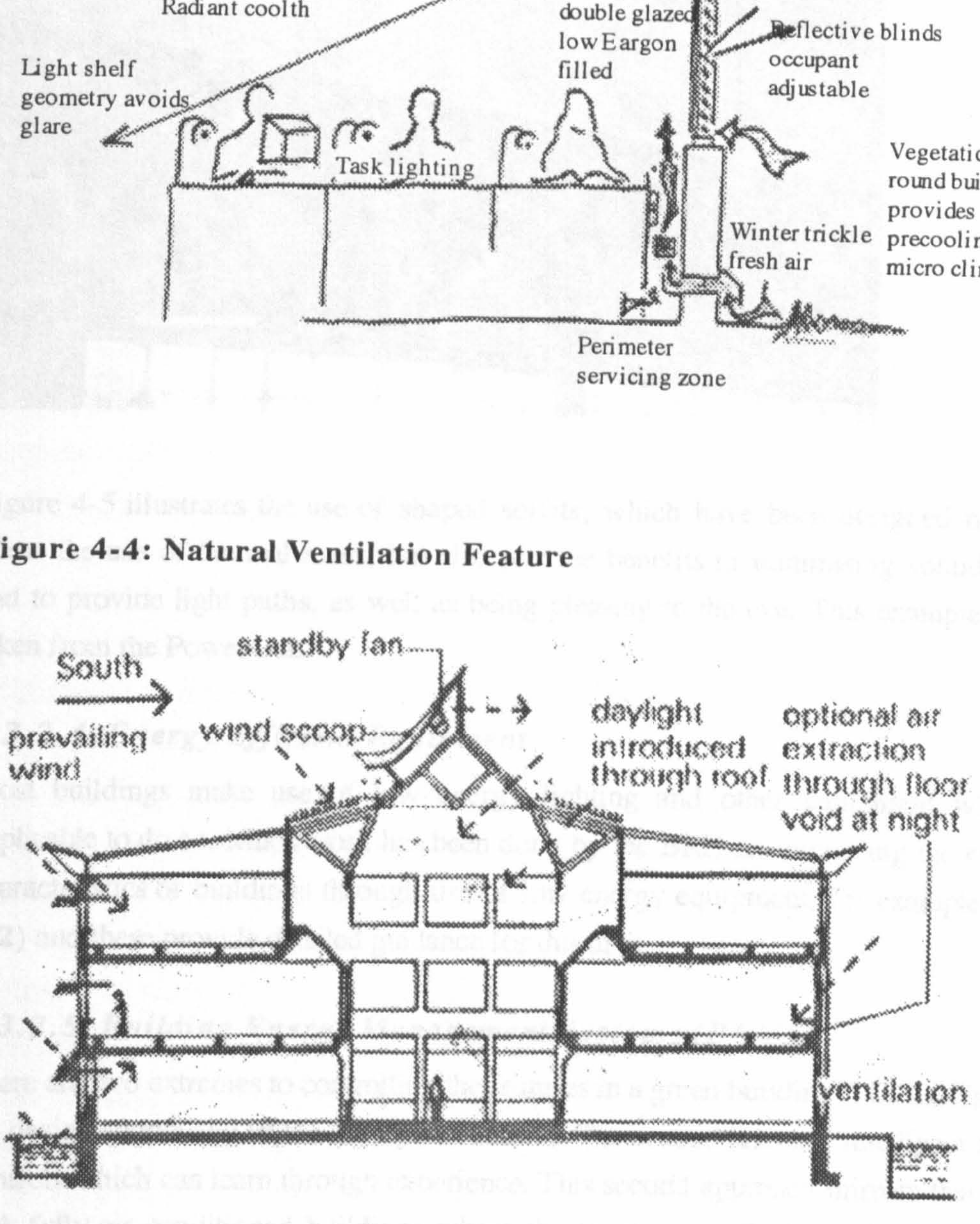


Figure 4-5: Shaped Soffits in the PowerGen Building

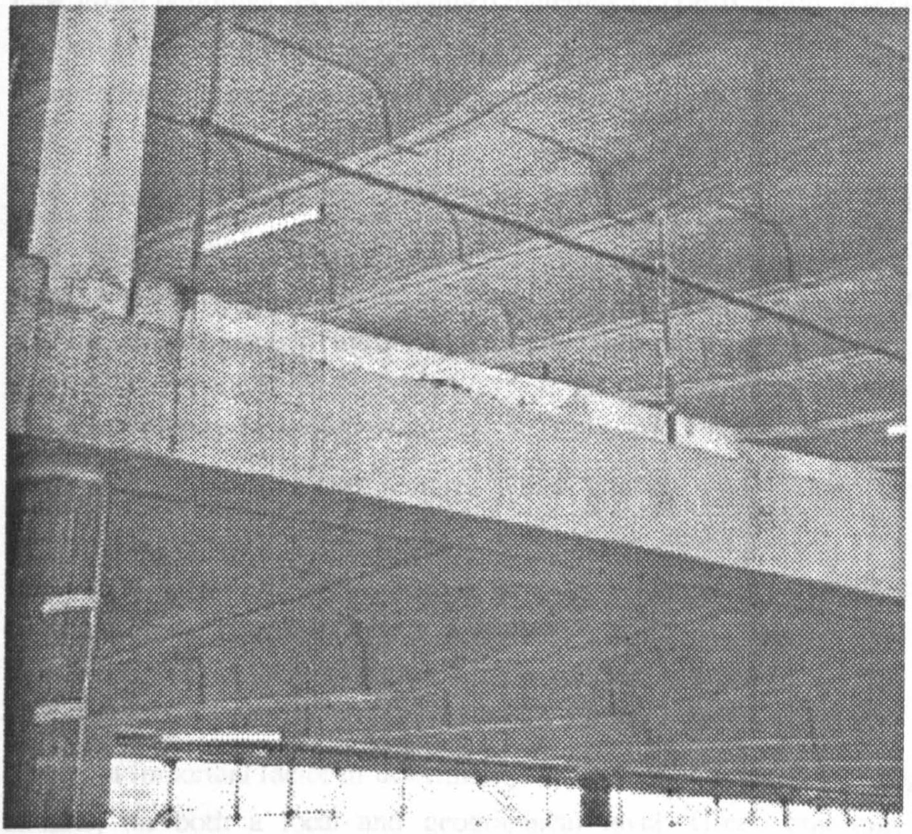


Figure 4-5 illustrates the use of shaped soffits, which have been designed not only to allow the use of thermal mass, but also provide benefits in minimising sound pollution and to provide light paths, as well as being pleasing to the eye. This example has been taken from the PowerGen.

4.3.2.4 Energy Efficient Equipment

Most buildings make use of low energy lighting and other equipment where it is applicable to do so. Much work has been done by the BRE on improving the energy use characteristics of buildings through use of low energy equipment, for example by Moss (**42**) and these provide detailed guidance for this area.

4.3.2.5 Building Energy Management Systems (BEMS)

There are two extremes to controlling the features in a green building. The first is to make the design simple and let the users have control. The second is to use intelligent automatic controls which can learn through experience. This second approach mirrors that involved with fully air conditioned buildings where the users generally have little direct control over their surroundings.

4.3.2.6 Use Of Recycled Materials

Few green buildings yet use reclaimed materials in construction. Recycled materials have a number of benefits in green design notably helping to blend the structure in to the surroundings (often required by the local authorities) and lowering embodied energy and CO_2 requirement.

It is interesting to note that unless more new buildings make use of recycled materials, there will be little incentive to recycle, since there will be no demand for the materials saved and prices will therefore be low. If recycling is restricted to specific areas it will also increase the energy requirement in reuse, through increased transportation cost.

4.3.2.7 Other Features

There are a range of other features which can be used to help reduce the need for mechanical equipment, for example construction underground, rock cooling or earth roofing. However since these tend to be solutions for smaller buildings and are bespoke solutions and as such are difficult to assess.

4.3.3 Factors Limiting Green Building Design

The most important factor in determining the design of a green building is the prevailing climate, on both a local and geographical level. Green buildings are unlike more traditional sealed and air conditioned buildings in that they must interact with the outside to achieve good internal conditions. A given site will provide limitations in the form of size and shape and factors such as nearby buildings, noise pollution and air quality. These factors are linked with broader features such as the possibility for natural daylighting, limiting solar gain and natural ventilation. In addition to assessing how the building will be affected by its surroundings, the designer must address how it will affect the local environment.

Wind is an important factor in green design because it provides the potential for cross ventilation and can increase the efficiency of thermal chimneys. One of the most important contradictions in providing both heating and cooling in the UK climate is caused by the relative length of the heating and cooling seasons. The requirement for cooling naturally is a high ventilation rate, this increases potential heat loss during winter.

In office buildings it is generally thought that cooling is more important than heating due to the high internal gains in these environments and the building design will reflect this. However, all the design features outlined have the effect of reducing the energy requirement for the building, which will reduce the excess internal heat gains. This may lead to a situation where the heat gain is of more concern, especially in the mornings during winter.

4.4 Current Building Design

The adopted building design for a given brief will depend on a large number of factors. Every building is unique and, to some extent, not repeatable. Examination of a number of buildings designed to be green reveals that designers have, in most cases, settled on a range of features which improve environmental performance. Initially 22 projects have been studied to gather real world data about how 'green' buildings are designed and the features found in each tabulated. This does not represent a comprehensive survey of all green structures over the last few years, but rather those that have received most exposure.

Table 4-16 shows the range of features found in these buildings. Some of these buildings have been studied in more detail in the following section. The quantity and quality of data available for each building was variable and this is reflected in the text. More information has been given where it is available. For each of the quoted cases, enough information was available to make a reasonable analysis possible. In all cases, except the Co-op building, the designers have made at least partial use of 'natural ventilation'.

Headings have been used in the tables to save space. Each of the heading and notes explaining the meaning is explained in the key. Full details for the buildings examined, including a brief outline and full list of references, can be found in appendix A.

A number of conclusions can be drawn from a study of these buildings about the methods popular in producing a low impact building. The most important point made is that designing this type of building calls for close integration of the different elements, light, shade, heating and cooling, to be really successful. Designs where one of these elements has been compromised tend not to work as well.

Significant amounts of design work goes towards the use of light and shade and where this works, building occupants benefit. The heating and cooling elements, linked often to the BEMS, have tended not to work as might have been hoped, but improvements will be made as more empirical evidence becomes available.

The use of recycled materials and solar panels are different from the other features considered. Recycled materials can be used on any building to lower the waste element, but not necessarily the embodied energy or CO_2. As noted on the BRE building, recycled materials often have to be brought in from significant distances at a considerable transportation cost. This is an importation point to note because while the infrastructure for recycling does not exist on a local level, this form of waste reduction may not actually reduce the building impact. It will however reduce raw materials exploitation which could make the effort worthwhile in itself.

Solar panels for energy could also be added to any building but the cost is currently a prohibitive factor. As cost decreases, more use will be made of this feature.

Several points were noted which tended to be found in designs that worked well -

- Large quantities of thermal mass were not required, but the design must be geared to use the mass available

- Natural ventilation does not equate to low tech in all cases. The energy management systems employed are often very sophisticated. To get the most out of these systems, they must be 'fine tuned' after occupation and an operator user with good system knowledge should be in control.

- Natural ventilation does not exclude use of mechanical services. Services should be provided as a supplement to the natural process which have been harnessed.

- In buildings where there are zones of different internal requirements, they should be serviced in different ways - natural ventilation for most areas and services for kitchen or computer suites for example.

- Well thought out light paths making use of many surfaces to provide low glare light. If other than a slab with a flat soffit is used, coffers should be used and oriented at 90° to the light source.

4.4.1 Success Of Specific Designs

The success or failure of any building is measured by how well it performs the tasks for which it was designed. In most cases, and in all the buildings surveyed, this means allowing the occupants to work comfortably and efficiently. Some data looking at post occupancy performance of naturally ventilated buildings is available. This information is concentrated in the Probe reports carried out by the Building Services Journal and HGA ltd. Four green and four air conditioned buildings were studied during design and after occupancy and the results **(43,44)** consider how each building performed relative to a number of criteria, based on user perceptions.

Table 4-16: Features Found In 'Green' Buildings

BUILDING	Use Of Thermal Mass	Use Of Shading	Use Of Daylight	Type Of Glazing	Shallow Plan Building	Low Energy Use Equipment	Provision Of An Atrium	Building Energy Management System	Solar Panels	Use Of Reclaimed Materials	Natural Ventilation
Anglia Polytechnic University Queens Building	•	•	•	x3	•*	•	•	•			•*
Association For Consumer Research	•	•	•	x1	•	•	•	•			•*
BRE Low Energy Building	•	•	•	x2	•	•		•	•	•	•*
Britannic Assurance Building	•	•	•	x2	•		•				•*
British Gas Properties	•			x2			•				•*
Cable & Wireless		•		x2							•*
Co-op Headquarters	•*	•*		x3	•		•				
DeMontfort University Queens Building	•	•	•	x2	•	•	•	•*			•*
East Anglia University Elizabeth Fry Building	•			x3				•			•*
Hampshire County Court	•		•	x2							•*
Housing 21 Headquarters	•	•	•	x2	•	•		•*			•*
Inland Revenue Building	•	•	•	x2	•			•			•*
Ionica	•	•	•	x2	•		•				•*
Linacre College Oxford	•		•	x3	•	•				•	•*
Pfizer Offices & Restaurant		•	•	x3			•				•*
Portsmouth University, Portland Building		•*	•	x2		•	•	•*	•		•*
PowerGen	•	•	•	x2	•	•	•	•			•*
RSPB Headquarters	•		•	x2	•	•					•*
University Of Lincolnshire	•		•	x2				•			•*
Victoria Quay	•		•	x2	•		•				•*
Weidmuller	•			x3							•*
Woodhouse Medical Centre			•	x2	•	•					•*

Key To Table 4-16

Use Of Thermal Mass	Indicates where use has been made of thermal mass to assist in temperature control. This is usually used in conjunction with intelligent controls.
Use Of Shading	Indicates that shading has been employed to minimise glare and control heat gain. These can be internal, external or integral in the window units.
Use Of Daylight	Indicates that natural daylighting has been maximised either through building orientation, window design or light channelling.
Type Of Glazing	Single (x1) double (x2) or triple (x3) glazing. Window units can also incorporate shading and ventilation features.
Shallow Plan Building	This indicates an office depth of less than 12m side to side. The use of an atrium to improve light through the middle of the building is also acknowledged.
Low Energy Use Equipment	This indicates that low energy fixtures have been used where possible, for instance in lighting fixtures.
Provision Of Atrium	Shows the number of atria the building contains. These are used in two main ways - to provide stack ventilation or bring in light
Energy Management System	Building energy management system (BEMS). This indicates the use of automatic controls or a computer control system. Advanced examples of BEMS have a learning aspect improving performance over time.
Solar Panels	This indicates the use of Photovoltaic (for power generation in the BRE building) or water heating solar panels (as a preheating system in the Portland building).
Use Of Reclaimed Materials	This denotes if reclaimed materials have been used in any major way in the construction.
Natural Ventilation	Indicates the use of natural processes to heat and cool the building. Nearly all the structures do this, however they all use some mechanical systems and so are all qualified in some way.
*	Denotes that use of a feature is qualified or not implemented to the extent that it has been in other designs.

None of the naturally ventilated buildings worked perfectly and one significantly under performed. In several cases the occupant did not understand the operation of the more advanced features or how the whole system fitted together, resulting in problems.

The report came to a number of conclusions including -

- Internal gain assumptions from office equipment were too high
- Designers must make systems simple, efficient and robust
- Building energy management systems (BEMS) are difficult to use and designers should ensure that software generates clear outputs.
- The best buildings overall are of a mixture of ventilation types
- Advanced naturally ventilated buildings tend not to perform as well as air conditioned buildings.

4.5 Conclusions

The building designs discussed in this section show which ideas are currently considered useful in green buildings and thus should be primarily addressed in any model or assessment.

This report aims to assess the environmental impact of the frame material rather than the whole building and so it is only necessary to address these issues to the extent to which they require modifications of the frame to allow for incorporation in the design. So, for example, the use of solar panels need not be assessed because these are essentially frame independent. This is also true for BEMS (although these may control systems which are frame dependant), the use of atria, the design of windows and the use of low energy equipment.

This leaves a number of areas which are directly linked to the frame design - thermal mass, the use of daylight, plan depth, use of recycled materials and the use of natural ventilation. One of the criticisms that it is possible to level at existing environmental audit models is that they currently take no account of the modifications that need to be made to a structure to accommodate the green design features, concentrating instead on simpler designs.

Any new environmental audit model should be able to compare both standard and green structures to assess the impact such design will have and should be able to use the full range of figures made available.

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41 Cohen R & Leaman, A & Robinson, D & Standeven, M: 'Probe 8: Anglia Polytechnic University Learning Resources Centre', Building Services, December 1996, pp 27-31

42 Moss, SA: 'Energy Consumption in Public And Commercial Buildings', BRE information Paper, IP16/94 1994

43 Bordass, B & Cohen, R & Standeven M: 'Probe 9: Energy And Engineering', Building Services, April 1997, pp 37-41

44 Leaman, A: 'Probe 10: Occupancy Survey Analysis', Building Services, May 1997, pp 37-41

5. ENVIRONMENTAL AUDIT MODELS

The process of tracking energy and environmental impacts of a building, a so called 'environmental audit', can be carried out in a number of ways. Each method assesses the factors (outlined in Chapter 2, 3 and 4) involved in different ways, according to how they are interpreted and the relative importance attached. This can lead to different results for similar structures.

One possible definition of an Environmental Audit, suggested by Cole and Rousseau (1), states that

> *An environmental audit for building construction is an accounting of the quantifiable environmental factors that will be incurred in building production and use, reducing them to equivalent terms and presenting them in meaningful categories. The purpose of the audit is to add an environmental dimension to design decisions.*
>
> *An environmental audit includes both energy and non energy factors, each of which has direct and indirect components.*

The data required to carry out a full environmental audit does not yet exist and there are many grey areas. Even when there have even been attempts to define what information is actually required the lists can not be said to be definitive or exhaustive (2). Most audit systems choose to limit themselves in scope and opt to try and deal with as many environmental impacts as possible while remaining relatively easy to understand. For all systems there is a trade off between ease of use and complexity.

There are a number of audit models and material databases either already available or currently in preparation. These are the first generation to become available and as such reflect the current imperfect state of research in this area. Examination of some of these models is problematic due to their commercial status and associated cost.

Three major models have been assessed from Canada, Scandinavia and the UK. Each of these models sets out to provide a detailed assessment of buildings and represent the 'second generation' of tools which use much more complex calculations than were used originally. Other 'first generation' models are also examined in less detail.

In this section, for the purposed of clarity an outline for all of the models which have been assessed has been provided initially, with some specific comments relevant to each.

5.1 Forintek

5.1.1 Background

The Canadian "Building Materials In The Context Of Sustainable Development" project, sponsored by Natural Resources Canada, has been ongoing for a number of years, and involved a range of partners headed by Forintek Canada Corporation. The reports examined were produced by Cole and Kernan (**3**) and the Environmental Research Group of the University of British Columbia (**4**)(**5**)(**6**). For clarity, this work is referred to in the text as Forintek. The project has three aims -

> *Developing a systems model to assess the environmental consequences of using alternative building materials in defined applications*
>
> *Providing objective, publicly available information concerning the relative fit of alternative building materials within a holistic sustainable development framework*
>
> *Providing direction for building products R&D which will minimise environmental impacts through more efficient use of natural resources and building materials.*

The main reasons cited for the project -

> *Increased environmental awareness, pressures from environmental activists and direct government regulation will increasingly combine to affect building material choices. Since most, if not all, building products offer certain environmental benefits while entailing environmental cost, one result is likely to be use of a wider mix of materials in any given structure...........Our model will help to identify opportunities by facilitating direct environmental comparisons between materials for specific buildings and designs.*
>
> *The price system may send perverse signals about the relative environmental benefits of costs associated with competing products, particularly when they are made of different materials...........Since efforts to reduce the environmental impacts of producing and using building products can result in product cost increases, the products making the greatest environmental gains may suffer in price competition against other products...........The building designer may be unaware of the extent to which higher costs for a product reflect environmental improvements and therefore be unable to make a true comparison on the basis of just cost criteria.*

These general principles are refined into four questions -

1) Are there significant differences between the embodied energy of wood, steel and concrete structural systems?

2) If differences occur between the embodied energy of wood, steel and concrete structural systems, are these differences significant in terms of total building embodied energy?

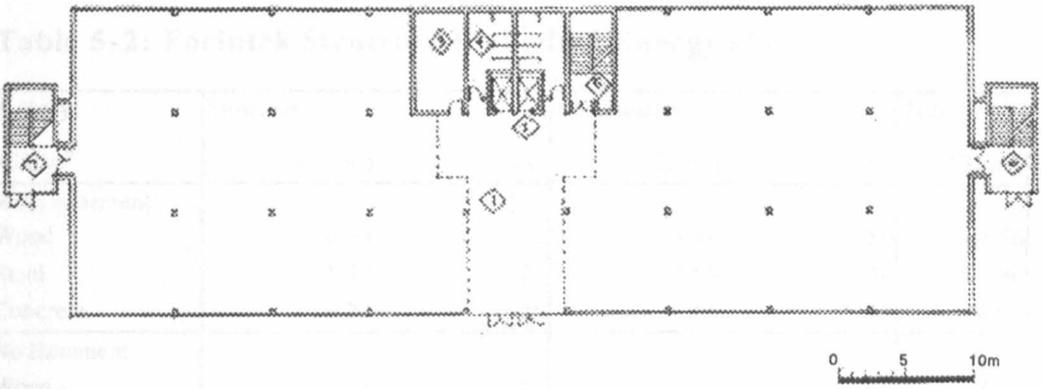
3) What is the relative order of magnitude of the initial embodied energy of buildings compared to that incurred through normal maintenance and replacement over their effective life and to the operating energy use?

4) For current and anticipated future levels of energy efficiency, is embodied energy and the differences created by alternative structural differences significant when compared to the total life-cycle energy used in buildings?

5.1.2 Approach

The questions raised were answered by examining the embodied and operating energy of a generic three stories office building of conventional design using wood, steel and concrete as frame materials. The building was given to different hypothetical geographical locations. A plan for the building studied is shown in Figure 5-1.

Figure 5-1: Forintek : Typical Floor Plan



To calculate the initial embodied energy a relatively small number of energy intensity figures (see Table 5-1), derived from published sources were used in conjunction with a material quantity take off to provide the embodied energy figures.

Table 5-1: Forintek Materials Embodied Energy (3)

		Embodied Energy MJ/kg
Concrete	Below Grade Horizontal	0.75
Timber	Glulam	8.90
	TJI Floor Joists	10.10
	12 mm Plywood	10.40
	TJI Roof Joists	12.96
Steel	Reinforcing Bars	15.43
	Beams	15.43
	Roof Joists	19.66
	Steel Deck	25.66
	Columns	25.91
	Column Base Plates & Anchors	27.00
	Reinforcing Mesh	41.22

The recurring embodied energy - that from repair and maintenance - and demolition were then calculated, also based on estimates obtained from the available literature. The operational energy was calculated using the Department of the Environment 2 (DOE -2) energy simulation program covering a number of different simulations. The Life cycle energy was then established by combining these figures. The summary results are give in Table 5-2 together with those from similar calculations in other reports. There is a wide range of variance between these sets of figures - this can be explained by a number of factors including differences in building design and finishing, the geographical location and the embodied energy figures used.

Table 5-3 shows the suggested energy requirement for demolition of different structure types. Concrete requires significantly more energy than steel. This is probably due to the factor that a concrete frame requires demolition where as the steel elements can be dismantled.

Table 5-2: Forintek Structure Embodied Energy (3)

3 Story,	Structure		Non Structure		Total
4620m^2	(GJ/m^2)	(%)	(GJ/m^2)	(%)	(GJ/m^2)
With Basement					
Wood	0.93	20	3.64	80	4.56
Steel	1.27	26	3.69	74	4.96
Concrete	1.27	26	3.66	74	4.93
No Basement					
Wood	0.51	12	3.61	88	4.11
Steel	0.98	21	3.68	79	4.66
Concrete	1.01	22	3.62	78	4.63

Table 5-3: Forintek Energy Demand For Demolition (4)

Material	Building		
	Small 500-1500m^2 MJ/m^2	Medium 5000-15000m^2 MJ/m^2	Large 50000-150000m^2 MJ/m^2
Wood	31.2	27.1	23.8
Concrete	176.0	136.2	119.2
Steel	105.6	81.7	71.5

5.1.3 Report Conclusions

This report reached a number of conclusions. These should be viewed in the light of some degree of possible differences with other systems. The most important of these conclusions for the purposes of this report are shown below.

Structure can represent a significant proportion of the initial embodied energy of a commercial building.

The difference between the embodied energy of wood, steel and concrete framed buildings designed to offer similar performance can also be significant.

As the energy efficiency of buildings improves, the amount of energy required to produce them - their embodied energy- represents an increasing component of total energy.

Current strategies for reducing the life cycle energy use should clearly progress first by introducing those design considerations which significantly reduce building operating energy

5.1.4 Discussion Of Forintek Model

The results provided by this study show similar embodied energy figures for steel and concrete structures - well within the errors which will occur within the calculations. Timber structures are shown as requiring a lower embodied energy for the whole structure - 92% of the figure for steel when an underground car park was required and 88% when it was not. When examining only the structural embodied energy the results for steel and concrete are again very similar, however the timber structure requires nearly 50% less energy than either, 52% when there is no car park and only 76% when the car park is present. These figures show the same trend as those from Buchanan and Honey detailed in section 4.2.10. As with those figures, the nature of timber production in this country is different from Canada and this will have an effect on the results. These results are based on a standard design of structure rather than one using an up to date green design.

Since this model is commercial, there is a lack of detailed data to assess and furthermore it is a closed model[1] . In broad terms however the model seems to provide a good guide to the environmental impact of buildings. The major limiting factor for the use of this model is the possible transfer of data from Canada to the UK. For the data to be used for this country it would be necessary to alter it to take account of the underlying differences in construction and materials provision culture as well as more specific differences in actual values.

With this in mind, this report has been used as a source of information and guidance, but the actual values have not been used.

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[1] A closed model is one for which the base data is unavailable except to the original creators

5.2 Oxford Brookes University

5.2.1 Background

The Doctoral Thesis of Alex Amato - A Comparative Environmental Appraisal Of Alternative Framing Systems For Offices (7) contains the outline of a system for evaluating the Life Cycle Energy implications of using steel and concrete frames. This work is supported by information gathered from a number of sources, including the Steel Construction Institute (SCI), British Steel, Davis Langdon & Everest and Oscar Faber Applied Research (8). Much of the data supplied to Amato from outside parties is of a commercially sensitive nature and is not included in the Thesis. Results and information stemming from this work have appeared through a number of channels other than the thesis document (9)(10), but mostly through the SCI. Since a large quantity of data is not included it is not possible to recreate the results. For clarity, this work is referred to as Oxford Brookes.

5.2.2 Building Models Used

The calculations made in this model are based on the design of two standard buildings (designated Building A and Building B) detailed by the SCI in 'Comparative Structure Costs of Modern Commercial Buildings'(10). These buildings have a simple rectangular plan, the larger of the two also possessing an internal atrium. No modifications have been made to take into account any design features, incorporated in some new buildings, which might have the effect of lowering the environmental impact. The buildings are configured in a number of ways as outlined below -

Building A "Small Building"

13.5m wide, 48m long and four stories high (2,600m2 gross floor area) with perimeter heating. The servicing zones are situated at either end of the building. The cladding is traditional brick and block with rectangular windows occupying 25% of the facade. There is a floor to ceiling height of 2.7m with a 150 mm raised floor. The foundations are pads bearing on sand and the ground floor is not suspended. A typical floor plan for this building is shown in Figure 5-2.

Building B "Large Atrium-Type Building"

45m wide, 60m long and eight stories high (18,000m^2 gross floor area) with a central covered atrium of dimensions 15m x 30m and full air conditioning. The servicing zones are situated at opposite ends of the building. The cladding is purpose made high quality cladding system with a thin granite veneer over medium density block work with dry internal lining. There is a floor to ceiling height of 3.0m with a 200 mm raised floor. The foundations are under reamed bored piles into clay. A typical floor plan for this building is shown in Figure 5-3.

Figure 5-2: Oxford Brookes Building 'A' : Typical Floor Plan

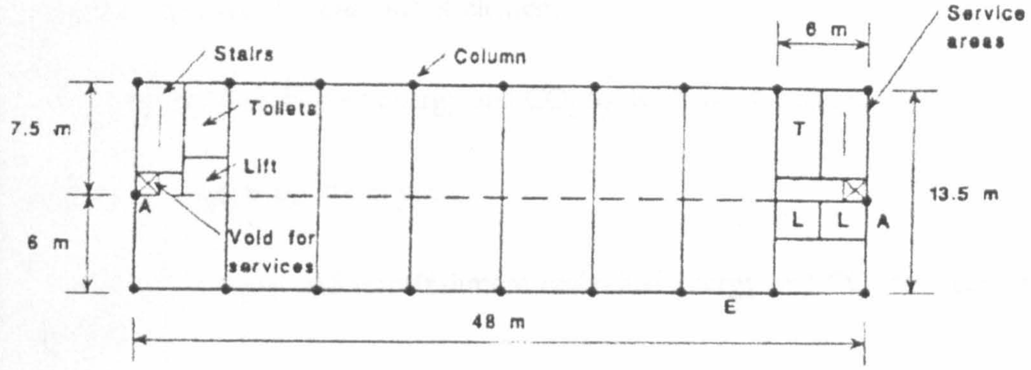
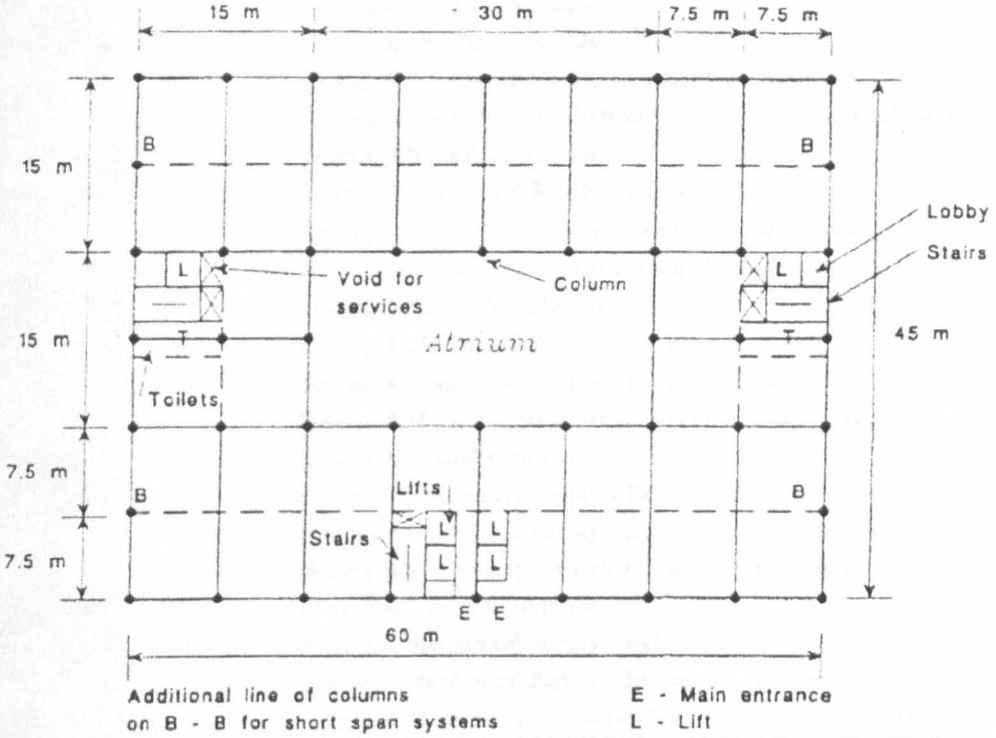


Figure 5-3: Oxford Brookes Building 'B' : Typical Floor Plan



Further details are given for other design details and assumptions such as occupancy patterns, required fire resistance and working energy requirements. The full range of heating and structural options used in the study are shown in Table 5-4.

The figures used for embodied energy were provided by Davis Langdon and Everest (DLE) with some modifications, specifically looking at the impact of steel recyclability and the transport element. Unfortunately the DLE database is not available for this study and so any assessment will therefore be limited. The embodied energy is calculated using a standard bill of quantities entering data for

- Value of material in tonnes/m^2 of element
- Values of initial embodied energy and CO_2 for each m^2 of element
- Values of component life in years
- Values of the repair and refurbishment embodied energy and CO_2 for each m^2 of element

Table 5-4: Building Options Examined (9)

Structure Type	Option
Building A	
Slim Floor Beams And Precast Slabs	Heating & Natural Ventilation
	Heating & Mechanical Supply + Extract
	Heating & Mechanical Supply + Extract Via False Floor
	Heating & Mech. Supply + Extract Via FF + Enhanced Heat Transfer
Composite Beams And Composite Slabs	Heating & Natural Ventilation
	Heating & Mechanical Supply + Extract
	Heating & Mechanical Supply + Extract Via False Floor
	Heating & Mech. Supply + Extract Via FF + Enhanced Heat Transfer
Reinforced Concrete Slabs	Heating & Natural Ventilation
	Heating & Mechanical Supply + Extract
	Heating & Mechanical Supply + Extract Via False Floor
	Heating & Mech. Supply + Extract Via FF + Enhanced Heat Transfer
Cellular Beams And Composite Slabs	Heating & Natural Ventilation
	Heating & Mechanical Supply + Extract
	Heating & Mechanical Supply + Extract Via False Floor
	Heating & Mech. Supply + Extract Via FF + Enhanced Heat Transfer
Precast Concrete Hollow Core Units	Heating & Natural Ventilation
	Heating & Mechanical Supply + Extract
	Heating & Mechanical Supply + Extract Via False Floor
	Heating & Mech. Supply + Extract Via FF + Enhanced Heat Transfer
Building B	
Slim Floor Beams And Precast Slabs	Heating & Mechanical Supply + Extract Via False Floor
Composite Beams And Composite Slabs	Heating & Mechanical Supply + Extract Via False Floor
Reinforced Concrete Slabs	Heating & Mechanical Supply + Extract Via False Floor
Cellular Beams & Composite Slab	Heating & Mechanical Supply + Extract Via False Floor
Precast Hollow Core Units	Heating & Mechanical Supply + Extract Via False Floor

The Oxford Brookes study uses the definition of Embodied Energy and CO_2 shown below which is then qualified with a number of clauses.

Embodied energy is '*the total primary energy that had to be sequestered from a stock within the earth in order to produce a specific good or service and return waste safely to earth*'

The definition of this statement is then qualified using a number of definitions

1) Feedstock energy - the calorific energy produced when a material is burned. This can remain locked into the materials (timber) or be lost in creation of a product. Feedstock energy has been excluded.

2) Partitioning - useful materials produced as a by product of the main material. A problem occurs in how to assign the embodied energy between the main and any secondary products. This could be done in a number of ways, for example by economic value, by mass or by the energy required to produce the nearest alternative. No allowance has been made for partitioning due to the complexity of this operation, but preliminary indications suggest that there is only a small impact on final energy figures.

3) Timber and sequestered CO_2 - the CO_2 locked into building materials (primarily timber). This can be deducted from the total for the material. The Oxford Brookes report argues that this should only happen when timber is actually a totally renewable resource (all timber used is replaced in a steady state system.) In addition methane is produced where timber is placed in landfill sites.

4) Transport And Embodied Energy and CO_2 - is the transportation of all materials involved in production of a product through all stages. This may involve several transport movements and of these the final movement to site is usually the most important. The data mainly comes from Department of transport information and is of a general (average) nature. [Figures are shown for transportation of raw materials - steel and cement].

5) Recycling and reuse - all recycled and reused materials have been assumed to have no embodied energy when they are removed from the building of which they were a part.

Renewable energy inputs - no energy generated from these sources has been included in the study, for practical reasons, although Amato suggests that it should be included in future.

Two areas were given specific attention in this report - recycling and transportation. These two elements were used to modify the data base of materials values supplied by DLE.

5.2.3 Transportation Calculations

The transportation figures used in this report are based on national averages for materials moved in the UK. The calculation was based on a range of vehicles ranging from 7.5 tonne rigid to 33 tonne articulated lorries. The figures came from analysis of DoT statistics and the work by Miller and Humby (see section 5.4.3.4) which looked at the differences in energy for concrete that is in situ cast and precast. The transportation values used (both primary and delivered) are shown in Table 5-6.

This study found that

> *"In general, the transport components are small compared with manufacturing energy consumption. For most materials, therefore, only small amendments to the DLC database were carried out except for aggregates, natural stone, hardcore and similar materials where transportation was a major contributor".*

For example the (primary) energy for hardcore is quoted as 0.28 GJ/t of which the transportation energy is 0.1 GJ/t - 36% of the total.

5.2.4 Recycling Calculations

One of the most important elements in the calculation of energy is the recycling element. Steel is a good candidate for recycling, and this report estimates that the split between new and recycled steel is around 50/50. However, within this there is variability on where recycled materials are used -

> *....nearly all structural sections manufactured in the UK originate from British Steel Commercial Steel Sections and Plates (primary process), while most steel reinforcement bar is produced by companies like Shearness Steel almost entirely using scrap steel as their feedstock.*

The report therefore suggests that a figure for steel could be derived for all steel assuming long term recycling and that this could be applied to all steel use situations. The equation used to derive these values is shown as Equation 1.

Equation 1: Derivation Of Recycled Steel Value

$$S_{ee} = (P_{ee} - R_{ee}) \times \frac{(1-r)}{(1-r^{n})} + R_{ee}$$

Where S_{ee} = Multi-cycle embodied energy

P_{ee} = Primary Embodied Energy

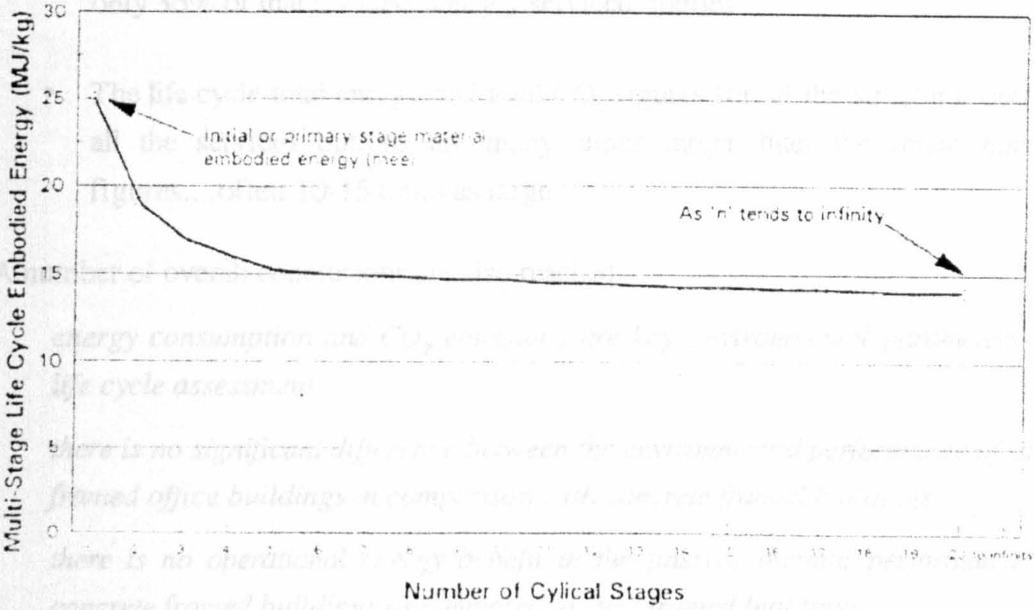
R_{ee} = Recycled Embodied Energy

n = Number Of Cycle Stages, With Primary $n = 1$

r = Recycling Yield Ratio

When used this equation produces a range of values for steel embodied energy over time. The curve is asymptotic so the greater the number of cycles, the less the value will tend to change and the closer it is to horizontal, but it will never actually stop changing. This curve is shown in Figure 5-4.

Figure 5-4: Variation Of 'Multi Stage Life Cycle Embodied Energy'



This analysis results in three values for steel - for the primary stage energy (i.e. the situation if only raw materials are used, shown as the left hand value in Figure 5-4), the multistage energy (all values over time taking into account all steel production) and the recoiled energy (the energy for steel using only recycled materials). These values, shown in Table 5-5, were used as parameters in calculation of the whole structure embodied energy results. The value for primary steel was used for calculations in the main section of the work (including the figures in Table 5-7).

Table 5-5: Steel Primary (Primary) Embodied Energy Values

	GJ/t
Primary Steel (from raw materials)	25.5
Recycled Steel (scrap is the main source)	17.3
Multicycle Steel (value over time)	18.9

5.2.5 Report Conclusions

The study reaches a number of conclusions the most important of these for the purposes of this thesis are shown below -

- There is no significant variation between the various types of construction

a) in the embodied energy or embodied CO_2 values

b) in the operational energy or operational CO_2 values

c) in the total life cycle or CO_2 values

- The operational energy consumption for naturally ventilated office buildings is only 36% of that for mechanically serviced options

- The life cycle total energy and total CO_2 figures for all the structural options and all the services options are many times larger than the initial energy/CO_2 figures....often 10-15 times as large.

A number of overall conclusions are also reached

> *energy consumption and CO_2 emissions are key environmental parameters for life cycle assessment*
>
> *there is no significant difference between the environmental performance of steel framed office buildings in comparison with concrete framed buildings*
>
> *there is no operational energy benefit in the passive thermal performance of concrete framed buildings as compared to steel framed buildings*
>
> *the relationship between embodied energy and operational energy is now understood and this understanding can assist with assessing future energy implications arising from improvements in the building fabric*
>
> *a comparative life cycle assessment methodology now exists that is 'transparent' and this could be further developed for other LCA studies*

5.2.6 Selected Data From The Thesis

Table 5-6 shows some of the data which has been used in the report. This work is notable for explicitly separating both transportation and primary energy requirements. It is probable that this data is based on figures calculated for the UK, however this is not certain because the DLE database uses information from many sources.

The periods after which operational energy becomes equal to and then exceeds embodied energy are shown in Table 5-7. This can be as quickly as 4 years in the case of heavily mechanised buildings, increasing to 11 years where only heating is employed.

Table 5-6: Oxford Brookes Embodied Energy and CO_2 Values (9)

	Transport EE		Total EE		Total CO_2
	Delivered	Primary	Delivered	Primary	
Element	GJ/t	GJ/t	GJ/t	GJ/t	kg/t
Excavation & Disposal	0.09	0.10	0.09	0.10	7
In-Situ Concrete Substructure	0.06	0.07	0.64	0.84	119
In-Situ Concrete Superstructure	0.06	0.07	0.85	1.09	163
Common Bricks	0.05	0.05	2.70	5.80	490
Facing Bricks	0.05	0.05	5.60	11.70	878
Mortar	0.06	0.07	0.64	0.84	122
Hardcore	0.09	0.10	0.16	0.28	15.8
DPM/DPC	0.60	0.67	75.00	120.00	8280
Reinforcement	0.40	0.44	25.00	26.80	2030
Concrete Blocks	0.13	0.14	1.04	1.31	203
Precast Concrete	0.20	0.22	1.07	1.36	208
Timber	3.40	3.80	6.40	13.00	1644
Chipboard	3.40	3.80	16.00	36.00	2560
Plywood	3.90	4.30	8.20	17.00	1465
Mandolite	0.06	0.07	14.00	63.00	1400
Vicuclad	0.13	0.14	20.00	70.00	2000
Structural Steel	0.40	0.44	25.00	26.80	2030
Sheet Steel	0.31	0.34	29.00	34.00	2698
Stainless Steel	0.40	0.44	12.00	33.00	1656
Roofing Felt	0.13	0.14	38.00	75.00	3800
Roof Insulation	0.40	0.44	22.00	35.00	2606
Wall Insulation	0.40	0.44	22.00	35.00	2606
General Insulation	0.40	0.44	22.00	35.00	2606
Asphalt	0.40	0.44	3.30	5.00	330
Stone Chippings	0.05	0.06	0.27	0.30	22
Natural Slate	0.10	0.11	0.14	0.16	12
Crushed Slate	0.10	0.11	0.18	0.20	15
Concrete Tiles	0.06	0.07	1.04	1.30	203
Paving	0.06	0.07	1.04	1.30	203
Resin	0.60	0.67	124.00	200.00	21400
Plaster	0.06	0.07	1.03	1.40	93
Plaster Board	0.13	0.14	2.00	2.70	180
Paint	0.60	0.67	50.00	70.00	5350
PVC	0.60	0.67	75.00	120.00	12840
Softwood	3.40	3.77	6.40	13.00	1644
Hardwood	5.80	6.44	8.95	16.00	2136
Wood Stain/Varnish	0.60	0.67	36.00	50.00	5350
Glass	0.25	0.28	12.00	15.00	1130
Aluminium (In Windows)	0.30	0.33	84.00	200.00	29200
Steel (In Windows)	0.60	0.67	26.00	31.00	2441
UPVC (In Windows)	0.60	0.67	75.00	120.00	12840
Rubber Seals	0.60	0.67	93.00	150.00	16050
Mastic Sealant	0.60	0.07	124.00	200.00	22200
Concrete Screed	0.06	0.67	1.24	1.55	249
Nylon (In Carpets)	0.60	0.67	118.00	190.00	20330
Polyester (In Carpets)	0.60	0.67	118.00	190.00	20330
Bitumen (In Carpets)	0.60	0.18	39.00	50.00	5000
Wool (In Carpets)	0.16	0.67	2.00	3.00	250
Rubber Underlay	0.60	0.67	87.00	140.00	14980
Vinyl Tiles	0.60	0.06	75.00	120.00	12840
Clay Tiles	0.05	0.15	5.64	11.71	878
Terrazzo Tiles	0.13	2.22	1.20	1.40	118
Marble	2.00	0.44	1.80	2.00	180
Mineral Fibre Tiles	0.40	0.28	30.00	37.00	2700
Ceramic Fittings	0.25	0.67	10.00	20.00	1440
UPVC Pipework	0.60	0.67	75.00	120.00	11770
Copper Pipework	0.30	0.33	90.00	137.00	8640
Steel Pipework	0.54	0.60	30.00	35.00	2800
Stainless Steel Pipework	0.54	0.60	11.00	33.00	1518
Cast Iron Pipework	0.54	0.60	30.00	35.00	2800
Plastic	0.60	0.67	93.00	150.00	16050
PVC Wire Insulation	0.60	0.67	75.00	120.00	9652
Steel Wire	0.54	0.60	28.00	35.00	2800
Lifts & Escalator	0.56	0.62	28.00	35.00	2700
Natural Stone	0.13	0.14	0.36	0.40	32
Reconstituted Stone	0.13	0.14	1.20	0.40	118
Sheet Aluminium	0.30	0.33	84.00	200.00	12321
GRP Panel	0.60	0.67	71.00	100.00	8071

Table 5-7: Operational Energy and Initial Embodied Energy (9)

Periods When Operational Energy (OE) Equals Initial Embodied Energy (EE)	Primary Energy (Years)	Delivered Energy (Years)	CO2 (Years)
A1 Slim Floor Beams And Precast Slabs			
Heating & Natural Ventilation	11.3	14.8	14.3
Heating & Mechanical Supply + Extract	7.8	10.1	9.8
Heating & Mechanical Supply + Extract Via False Floor	7.7	10.0	9.8
Heating & Mech. Supply + Extract Via FF + Enhansed Heat Transfer	7.7	9.9	9.7
A2 Composite Beams And Composite Slabs			
Heating & Natural Ventilation	11.6	15.0	14.4
Heating & Mechanical Supply + Extract	7.9	10.1	9.8
Heating & Mechanical Supply + Extract Via False Floor	7.9	10.0	9.8
Heating & Mech. Supply + Extract Via FF + Enhansed Heat Transfer	7.8	10.0	9.7
	7.8		
A3 Reinforced Concrete Slabs			
Heating & Natural Ventilation	11.2	14.0	15.1
Heating & Mechanical Supply + Extract	7.7	9.8	10.4
Heating & Mechanical Supply + Extract Via False Floor	7.6	9.5	10.3
Heating & Mech. Supply + Extract Via FF + Enhansed Heat Transfer	7.6	9.4	10.3
A4 Cellular Beams And Composite Slabs			
Heating & Natural Ventilation	11.8	15.5	14.7
Heating & Mechanical Supply + Extract	8.0	10.4	10.0
Heating & Mechanical Supply + Extract Via False Floor	8.0	10.3	10.0
Heating & Mech. Supply + Extract Via FF + Enhansed Heat Transfer	8.0	10.2	9.9
A5 Precast Concrete Hollow Core Units			
Heating & Natural Ventilation	11.7	14.9	16.2
Heating & Mechanical Supply + Extract	7.9	10.0	11.0
Heating & Mechanical Supply + Extract Via False Floor	8.0	10.1	11.0
Heating & Mech. Supply + Extract Via FF + Enhansed Heat Transfer	8.0	10.1	11.0
B1 Slim Floor Beams And Precast Slabs			
Heating & Mechanical Supply + Extract Via False Floor	4.5	6.6	5.5
B2 Composite Beams And Composite Slabs			
Heating & Mechanical Supply + Extract Via False Floor	4.6	6.6	5.4
B3 Reinforced Concrete Slabs			
Heating & Mechanical Supply + Extract Via False Floor	4.1	5.8	5.6
B4 Cellular Beams And Composite Slabs			
Heating & Mechanical Supply + Extract Via False Floor	4.5	6.5	5.4
B5 Precast Concrete Hollow Core Units			

5.2.7 Discussion Of Oxford Brookes Model

This model represents the first major environmental impact assessment tool available and specific to the UK and covers a wide range of materials and ideas, including assessment of operational energy. It does not cover any of the more current green design ideas and this restricts the applicability of all the conclusions reached. The conclusion that steel and concrete framed buildings are broadly similar in terms of environmental performance agrees with the data from Forintek, although this excluded operational energy.

The transportation calculations are based on average Government figures and can not be expected to have the same degree of certainty that actual local figures would have. Since the model is not available and neither is most of the base data, or the parameters for the calculation of the data, it is difficult to assess how good the performance of the model actually is.

The published data shows a number of interesting facets including pointing up the large variation in the transport component of embodied energy (Table 5-6) especially for items such as aggregates. Other significant findings show that the initial embodied energy is only a small proportion of the total energy used during the complete life cycle of the building - typically the initial embodied energy used is surpassed by the operational energy used in 10 -15 years, with the longer period being taken in naturally ventilated buildings.

The recycling model proposed should be treated with care and is overly complex, suggesting a fuller knowledge than is actually the case. It is problematic to suggest that steel will be recycled using the same technology as now in say 100 years time. It is likely that much more of the energy produced at that point would be produced using renewable energy, which would significantly alter the energy equation.

Although this is a relatively small detail, because of the large numbers of such details, deviations in the formulae used could result in errors. A comparison of the embodied energy data (shown in Figure 5-5) for the Forintek and Oxford Bookes studied show the range of data available.

A distinction is made in this study between the embodied energy in the building after completion (termed '*initial building embodied energy*' *(ibee)*) and the embodied energy when the building is deemed obsolete (termed '*Life-cycle building embodied energy*' *(Lcbee))*. The operational energy requirement is the energy required for the building to fulfil its function and is in addition to the life cycle embodied energy requirement.

The embodied energy values are then multiplied out for each element and married to the estimates for the operations energy.

5.3 Chalmers University Model

This model, originating in Scandinavia, analyses the life cycle impact of building frame material over the life cycle (**11**).

5.3.1 Background

The authors identify a number of reasons for the production of this model in particular the current lack of tools for assessing environmental impact. It notes that these methods should be so transparent that it is possible for the user to find out on what basis the results have been obtained. These broad aims are refined into two statements

> *To analyse and assess the environmental impact of structural concrete and steel frames in buildings during the whole life cycle using the method of LCA as a tool*
>
> *To create a computerised model structure for environmental assessment of framed structures, that may be used as a tool for improvement analysis*

The study looked at a representative segment of offices and dwellings with several stories. The frame designs were chosen to be representative of current building technology in the Nordic countries.

The designs chosen were examined using a modular system, defined below, including both horizontal and vertical elements and supplementary materials needed to make each frame case deliver an equivalent minimum function.

5.3.2 Design Criteria

The building design uses a number of broad design guidelines and is based on a "Functional Unit". The design parameters and functional unit definitions are shown below.

Design parameters

- The building is 'externally long' and 12/10m wide for offices/dwellings.
- The floor to ceiling height is 2.7/2.4m for offices/dwellings.
- A cladding system is included.
- Only the third floor in a six storey building is analysed.
- Gables, stair cases etc. are not included.

Functional unit

- The Functional unit includes the floor deck, one internal wall for the room and one internal wall separating the hallway and room, and two external walls. The "Functional Unit" floor area is derived from this. The dimensions for the functional unit are shown in Table 5-8.

Table 5-8: Functional Unit Definition

	Width (m)	Length (m)	Facade Height (m)	Internal Height (m)	Window Area (m^2)	External Wall Area (m^2)	Deck Area (m^2)	Internal Wall Area (m^2)
Office	2.4	12.0	3.0	2.7	2.5	9.2	28.8	32.4
Dwelling	2.4	12.0	2.7	2.4	1.7	9.6	24.0	24.0

5.3.3 System Boundaries

To somewhat simplify the calculation, a range of items was identified which could be used to provide a representative sample of the environmental impacts associated with these forms of construction. The factors identified are listed below.

- *Use of raw materials*
- *Energy use*
- *Emissions to air and water*
- *Waste*

Within these definitions data gaps have been identified where information was sub standard or simply missing. These data gaps included the use and impact of infrastructure, accidental spills, human resources and their impacts, work environment, noise and odour. The calculations made use of average, rather than specific transportation distances and average current performance was used rather than a current best practise or improved future standard.

The building life span was taken to be 50 years. The analysis of waste materials ended at land fill stage and so does not consider impacts after disposal - for example visual impact of landfill sites. Materials where it is not possible to study all the "upstream" or "downstream" flows or where data is lacking have been designated "Non-elementary". Packaging materials are not considered nor are non structural steel items (nails, screws, etc.) except were specifically stated.

Data collection occurred from a number of sources including environmental reports, manufacturers' data, trade associations, building contractors and engineers and housing administration organisers. The research was 'conducted in close co-operation' with '..the building material industry, especially producers of cement and concrete products'.

The data used in the inventory may be specific, i.e. represent a specific process, or general, and represent an average of processes in a country, within an industry etc. Where there was considered to be a large uncertainty, for example with building life span, alternative scenarios have been calculated and results presented (a sensitivity analysis).

5.3.4 Calculation Methods

There are three statements which define how the calculations have been made and these are listed below.

1) The mass balance is solved with the functional unit as the basis for calculation.

2) Energy use of the system is calculated, specified according to different energy sources, by first calculating the contributions from each process and then adding them together.

3) Emissions of the system are calculated by first calculating the contributions from each process and then adding them together.

Only direct energy has been calculated (the energy needed to produce that energy is excluded) and feedstock energy (where raw materials have a calorific value and could be used as fuel) has been accounted as energy use. Where emissions are not calculated directly default figures were used. The standardised transportation data is shown in Table 5-9.

Table 5-9: Transportation Energy Data (11)

Type	Energy MJ/ton-km
Lorry, Long distance	1.00
Lorry, local distribution	2.70
Railway, Electrical	0.30
Railway, Diesel	0.33
Coastal Shipping	0.47
Ocean Going Shipping	0.20
Tankers	0.11

In some stated cases, data has been aggregated under broader definitions than those generally used because of the non common terminology used by manufacturers. Gross flows in and out for any given process do not always balance because they are calculated over a year and neglect possible changes to stocks.

5.3.5 Demolition

This study assumes that all materials become filler and/or waste after demolition except constructional steelwork as is current practice in Sweden. The figures used are shown in Table 5-10. These are significantly lower than the values quoted in the British Columbia study (see table Table 5-3) the concrete rate being 136.2 compared with 51.5 MJ/m^2 and the steel rates being 81.7 compared with 18.7 MJ/m^2/ There is no suggestion that either of the reports is wrong - the differences could simply be due the methods employed, factors included or differences between Scandinavia and Canada.

Table 5-10: Chalmers Energy Demand For Demolition (11)

Frame Alternative	Energy Demand (diesel MJ/m2)
1-2 (in situ concrete)	51.5
3-7 (other material options)	18.7

Table 5-11 shows the percentage of waste materials assumed to result from demolition.

Table 5-11: Composition Of Demolition Waste (11)

Type	% (Weight)
Concrete	27
Wood	10
Ceramics	34
Stone	8
Lightweight Concrete	3
Plaster	8
Gravel, Sand, Crushed Limestone	2
Steel	1
Coke Ash	5
Other	5
	103

5.3.6 Impact Assessment Methods Utilised

The Chalmers study made use of three methods of assessing environmental impact.

1) Environment Priority Strategy in Product Design (EPS)

This system is based on the willingness to pay to restore reference conditions for

- Biological diversity
- Human health
- Production
- Aesthetic value
- Natural resources

This results in an index (ELU) assessing these five parameters, with lower being better

2) Environmental Theme Method.

Data is converted to contributions to know environmental problems, weighted against each other based on Swedish environmental policy.

3) Ecological Scarcity

Ecological scarcity is defined as the ratio between total environmental impact and critical impact within a geographically defined area.

5.3.7 Report Conclusions

The Chalmers University document provided three main conclusions relevant to this study. These are listed below.

- As the energy use related to service life of the building far exceeds the energy use during the other steps, frames should be constructed so that service use energy is minimised.

- Recycling of demolition masses is important to reduce the impact of buildings over their life cycle.
- Energy use from cradle to grave does not differ very much between frames.

5.3.8 Discussion Of Chalmers Model

The data provided for the calculations and scope of emissions in this study is far greater than that in either the Forintek or Oxford Brookes work and includes categories for emission to air and water as well as simple energy use. These factors include items such as emissions of formaldehyde, arsenic, methane and many others.

The use of a functional unit provides a method of assessment simpler than looking at the building as a whole. This simplicity may also be a drawback because, although most buildings contain repetitious patterns which could be used as a functional unit, there are also many areas where non standard plans are used. This is particularly the case with concrete framed buildings (see Chapter 4)).

The overall conclusion is that there is very little difference between concrete and steel and this agrees generally with both the British Columbia and Oxford Brookes works. However no consideration was given to timber as a construction material and this was shown to have the least impact in the British Columbia work.

It is difficult to use this data in a UK model due to the problems, already outlined, in importing data from abroad.

5.4 Additional Systems

5.4.1 Eco Labelling

Eco labelling does not provide an overall assessment for a building, rather it provides detailed environmental information in terms of energy, CO_2 and wider environmental impact for individual materials. This information can then be used in a wider environmental audit or simply when selecting which material is preferable from an available range. This process can also be used to help eliminate waste through a better knowledge of 'best practise'. Each material has progressed a different amount along this path and, while for some there is a large amount of information in one area (for example for materials which are subject to a detailed British Standard such as cement), overall the information available is limited and subject to debate.

5.4.2 International Audit Models

There are a number of audit methods available for different countries, all of which have advantages and drawbacks. Of these methods, possibly the best known is the Building Environmental Performance Assessment Criteria (BEPAC) which has similarities with the Building Research Establishment Environmental Assessment Method (BREEAM).

All these audit models have the drawback, when looked at from a UK perspective, of using base data which may not be directly applicable to construction in this country. One example of this difference in data is electricity, with each country having different proportions of output produced by each type of fuel source (e.g. hydroelectric is more often used in Canada than the UK) and even this varies with location within the country. This problem is not intrinsically insuperable but most of the systems assessed are 'closed' in as much as changing the input variables is not possible without detailed knowledge of the model. One of the main problems any environment model faces is the need for immediate results, when by the very nature of construction only a very long term study could reasonably provide true accuracy of data.

5.4.2.1 BEPAC

The BEPAC model (**12**) is specific to Canada and offers assessment in five major areas; Ozone layer protection, environmental impact of energy use, indoor environmental quality, resource conservation and site and transportation. These are further subdivided into more detailed categories where required. These categories are all accorded equal importance. For each section points are awarded in two areas - design and management. This system contains no detailed assessment of the building frame except in so far as this connects with other criteria. The calculations are feature specific and subjective within the framework. It does not assess the complete design in detail.

5.4.2.2 An Object Oriented Model For The Assessment Of The Environmental Quality Of Buildings

This French method proposed by Peuportier, Polster and Sommereux (**13**) uses a simplified elemental approach coupled with a database to evaluate the building impact. It uses an algebraic expression for the quantity of recycling which increases accuracy for materials where this is applicable. This system is thought to be the best available in the medium term until there is more real data. Output is in the form of an environmental profile which can be thought of as an expanded form of material eco labelling encompassing the complete building.

5.4.2.3 Building Material Assessment System

The Building Material Assessment System (BMAS) system proposed by Partridge and Lawson (**14**) uses a weighting system to assess the environmental impact of materials using 14 parameters ranging from the damage suffered by the environment during extraction to the recyclability of the demolished material. The parameters and weighting are shown in Table 5-12.

These weightings are then used in conjunction with a score from 1 (least bad) -5 (worst) for each material for each parameter. All these factors are used to produce an Ecological

Factor, which can be used to rank materials with higher score indicating a worse performance.

Table 5-12: BMAS Parameters & Weighting (14)

Element	Parameter	Weighting	Total
Mining	Damage During Extraction	3	
	Damage Relative To Quantity Of Materials	2	
	Renewability Of Raw Material	4	
	Recycled Content	3	12
Manufacture	Waste From Manufacture & Production	3	
	Air Pollution From Manufacture & Production	4	
	Embodied Energy	5	12
Construction	Energy For Transport To Site	3	
	Energy On Site For Assembly & Erection	1	
	On Site Waste & Packaging	2	6
Use	Maintenance Requirement	3	
	Environmental Impact During Life Cycle	3	6
Demolition	Energy & Associated Effect During Demolition	2	
	Recyclability Of The Demolished Material	4	6

The system has the advantage of being able to cope with different geographical locations and the flexibility to cope with areas where systems requiring numbers might be unable to provide any results. The disadvantage is that because the weight of a material is determined by 'straw poll' of 'environmentally aware professionals and building designers' and averaged, the result is subjective.

No results are given for standard buildings.

5.4.2.4 Other Systems

There are a number of other systems which provide partial assessment. The Netherlands has produced the "Environmental Preference Method For Building Materials" which looks to provide the least polluting material from any given selection thus providing the designer with a simple lookup table of 'best' materials from this point of view.

The "Environmental Declaration Of Building Materials' system suggested in Denmark **(15)** would result in a database of facts on materials with each having an environmental profile including information on raw materials, emissions and other related factors.

The Athena package **(16)** is produced by Forintek and based on the data already discussed.

5.4.3 UK Audit Models

5.4.3.1 BREEAM

The most widely used audit method in the UK is BREEAM **(17)**, which provides a method of assessing buildings - including offices, supermarkets and homes - using three broad areas of concern which are designated as Global, Local and Internal. Global issues involve factors such as CO_2 emissions resulting from energy use and designing for longevity, local issues include noise and use of contaminated land and internal issues assess the thermal comfort and lighting. Credits are gained by showing improvement on design in terms of the environment from the 'best' normal practice and are appraised on a range from fair to excellent. No credits are awarded for simply fulfilling legal requirements. An overall award is made based on the minimum credits gained over all three sections. To gain maximum effect the assessment should take place in conjunction with the design, however buildings are also assessed after the design is completed.

The strength of this approach is in its relative simplicity and ease of application. The simplicity is also the major drawback, because evaluation of factors occurs on a uncomplicated level and excludes some areas altogether. For example a building gaining the highest credit award would have all the following features according to Yates, Bartlett & Baldwin (**18**)

- Improved insulation
- No air conditioning
- Good use of daylight
- Energy efficient artificial light with effective controls
- Efficient appliances

The use of 'Improved' and 'Good' reveals the imprecise nature of the assessment and there is no reflection of the interaction of different aspects in the way that a more quantitative assessment might. In addition it is possible for a building to gain maximum points (**19**). This is obviously limiting to design and does not reflect the full range of possibilities available. Despite these drawbacks, this approach has considerable merit as a first step approach to environmental assessment.

5.4.3.2 Environmental Design Manual

This suite of tools is gathered from a number of different sources, mainly the CIBSE guide and Building Research Establishment data, which has been placed on computer and linked together. The system is not yet available commercially, but should provide more information than BREEAM although still less than would be required for a full environmental audit.

5.4.3.3 Office Toolkit

The Office Toolkit (**20**) is a computer model package which provides assessment of existing buildings. It is a tool for office managers rather than designers. The package comes in the form of a spreadsheet.

5.4.3.4 Brighton University

This work, carried out by Humby and Miller (**21, 22**), is not a complete evaluation model, but rather seeks to assess the differences between pre cast and in situ cast concrete in terms of construction. The production of insitu concrete includes activities including batching, delivery of concrete, timber and reinforcement to site and site construction up to vibration of the concrete. The precast analysis included a similar range of activities.

The report provided a range of calculations and values for placing of concrete (pump, skip and dumper) and transportation distances and these are shown in Table 5-13 and Table 5-14. These are calculated using primary energy figures.

Table 5-13: Concrete Placing Energy (21)

Activity	Energy MJ/m^2
Crane & Skip	3.00
Pumping	27.38
Dumper	4.10
Average	10.59

Table 5-14: Assumed Transportation Distances (21)

Element	Distance (Miles)
Precast Units To Site	180
Ready Mixed Concrete To Site	5.2
Steel Reinforcement To Site	31.5
Timber Shuttering to Site	20.3

Overall the report concluded that in situ casting had a significantly lower total assembly energy (33.4 MJ/m^2) compared to precast (62.5 MJ/m^2), although it did acknowledge that transportation distances had a major influence on this result. Transportation was estimated as 40 - 60% of the total energy. These figures are given to highlight the differences between insitu cast and precast concrete, and as such are not comparable with models which assess all energy demands.

5.5 Comparisons and Assessment of the Available Models

The conclusions presented by the three major works for which results are available broadly agree, although there is much room for uncertainty in the variables and calculations allowed by all sets of research. The results presented in the Oxford Brookes work represent probably the first in depth analysis for the UK of the environmental impacts for commercial buildings and are certainly of great interest.

It is difficult to accurately assess both the Oxford Brookes and Forintek models on a micro level because of a lack of data. The Chalmers model is the most detailed but in common with the other reports, limited in its assessment of on site (both construction and demolition), activities. The Brighton study looks in most detail at on site activities (both the Chalmers and the Oxford Brookes study use elements from this report). The data provided by Buchanan and Honey (Table 4-13) has also been considered in this section because it provided data on a whole building basis, but was not considered to be an audit model. The data for Linacre college (Table 4-14) has not been included because of the relatively small size of the structure.

Figure 5-5 and Figure 5-6 show the frame and total structural energy cost for three reports and clearly illustrate the wide range of figures available. The data from which these graphics are derived, shown in Table 5-15, are taken from two of the main studies - Forintek and Oxford Brookes. This has been supplemented by results from Buchanan And Honey. No results have been used from the Chalmers report because these are not quoted in whole building embodied energy terms and are also filtered using weighting systems.

Clearly there are big differences between the results from each report. The highest results for each material come from Buchanan and Honey. This is the oldest work and seems to have been carried out in the least detail. In each case the Forintek report provides the lowest results.

The relationship between the frame and the total embodied energy varies with, in some cases, the frame providing as much 61% of the total (concrete) or as little as 12% (wood). Given the wide differences between the report results, an average figure was not calculated over all the results. The Oxford Brookes figures are primary energy, while the other two are delivered energy.

Table 5-15: Comparison Of Frame and Total Embodied Energy

Study	Option	Frame Energy GJ/m^2	Total Energy GJ/m^2	Frame:Total %
Concrete				
Forintek	No underground parking	1.0	4.6	22
Forintek	Inc. underground parking	1.3	4.9	26
Oxford Brookes Building B*	Flat Soffit	2.1	7.3	29
Oxford Brookes Building A*	Flat Soffit	2.5	8.7	28
Buchanan & Honey	Concrete	3.4	5.6	61
Precast Concrete Frame				
Oxford Brookes Building B*	Hollow Core Units	1.7	6.9	25
Oxford Brookes Building A*	Hollow Core Units	2.7	9.0	30
Steel Frame				
Forintek	No underground parking	1.0	4.7	21
Forintek	Inc. underground parking	1.3	5.0	26
Oxford Brookes Building B*	Cellular Beams & Composite Slab	2.6	8.8	29
Oxford Brookes Building A*	Slim Floor Beams & Precast Slab	2.6	7.8	33
Oxford Brookes Building A*	Composite Beams & Composite Slab	2.6	8.9	29
Oxford Brookes Building B*	Slim Floor Beams & Precast Slab	2.7	7.9	34
Oxford Brookes Building B*	Composite Beams & Composite Slab	2.7	7.9	34
Oxford Brookes Building A*	Cellular Beams & Composite Slab	2.9	9.1	31
Buchanan & Honey	Steel	4.4	6.6	67
Wooden Frame				
Forintek	No underground parking	0.5	4.1	12
Forintek	Inc. underground parking	0.9	4.6	20
Buchanan & Honey	Wood	1.5	3.7	41

* This model makes an allowance for the installation of different types of plant and servicing - 0 GJ/m2 for heating and natural ventilation and around 0.20 - 0.27 GJ/m2 for fully serviced buildings. The figures given are for the heated and natural ventilation option.

Figure 5-5: Comparison Of Frame Embodied Energy By Material

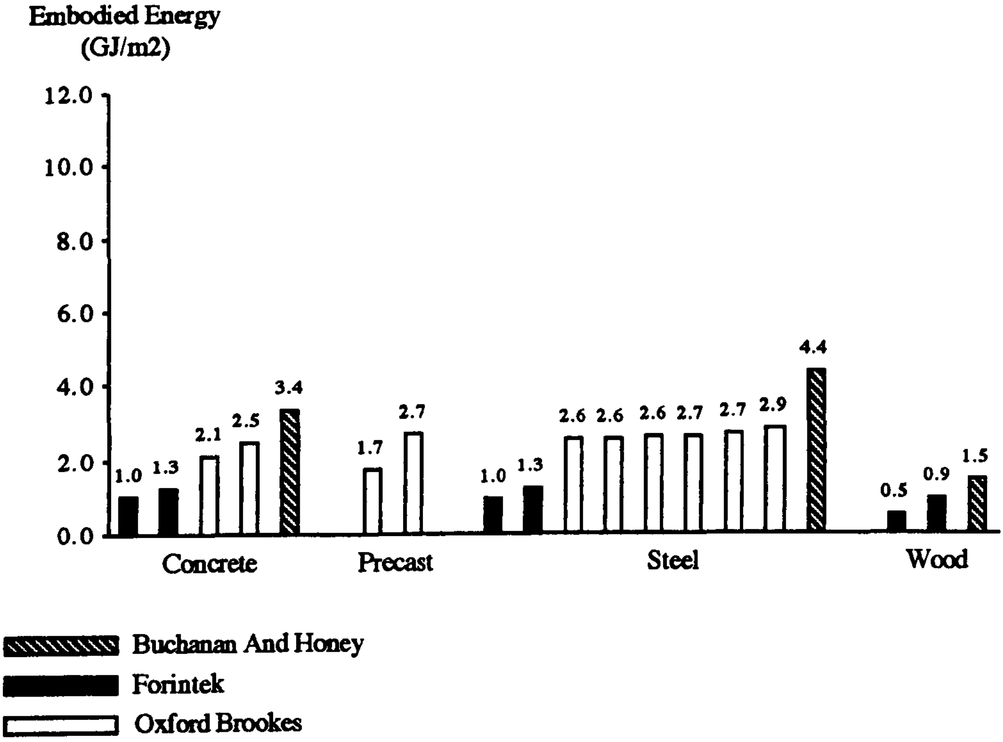
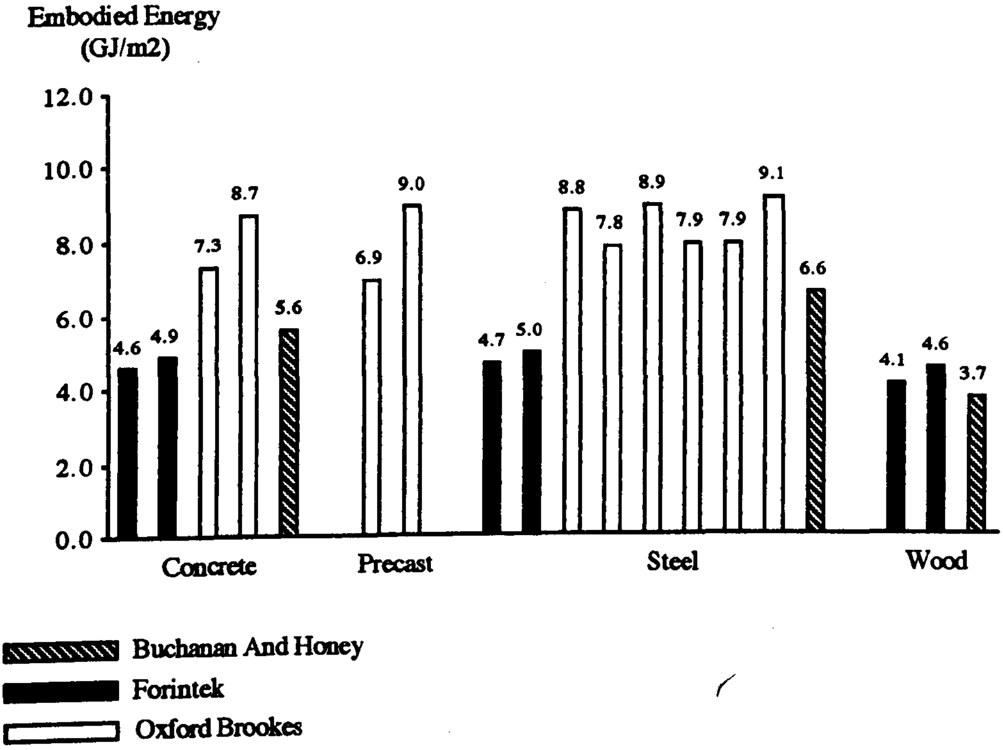


Figure 5-6: Comparison Of Total Embodied Energy By Material



5.5.1 Concrete Frame

There are five examples for concrete frames with a spread of 1.0 - 3.4 GJ/m^2 for the frame and 4.6 - 8.7 GJ/m2 total embodied energy. The frame energy is given as between 22 - 28% of the total energy for all except Buchanan and Honey where the result was much higher at 61%.

5.5.2 Precast Concrete Frame

Only the Oxford Brookes study examines a precast frame and these results are slightly irregular. The buildings examined use the same precast system, and the figures produced (1.7 and 2.7 GJ/m^2 respectively) show a greater difference than in any other interstudy comparison. While it is acknowledged that concrete can be a more variable material than steel in terms of construction, precast solutions should be similar to steel. Elements are factory produced and should be as predictable as steel in on site conditions. The steel frame solutions, using three different designs are much more uniform (within 0.3 GJ/m^2 for six examples). The Oxford Brookes report makes no mention of these differences. The precast solutions result in a lower frame energy than the insitu cast alternatives. This is the opposite of the results found by Humby, which found that the precast frame used nearly twice the energy of insitu, partly due to the increase transportation distances. The ratio of frame to total embodied energy were 25 and 30% respectively.

5.5.3 Steel Frame

The results for steel frames are generally slightly higher than for the concrete alternatives. This is not carried through to the total energy, with the results being approximately comparable. The steel frame is generally a higher proportion of the total energy being 21 - 34% (excluding the value of 67% quoted by Buchanan and Honey). The Oxford Brookes frame energy results are remarkably consistent, with five of the six results falling within 0.1 GJ/m^2 and the final result being only 2.5 GJ/m^2 higher than the average.

5.5.4 Wooden Frame

The wooden frames have by far the lowest energy requirements, although the other energy requirements are higher, making the total comparable within the Buchanan and Honey and Forintek results. The reports came from Canada and New Zealand respectively and the impact of this on the production of timber compared with the UK is not known.

5.5.5 Comparison Between Frame Materials

None of the models are able to assess differences that might occur in specific buildings between, for example, geographical locations - a building in Sheffield could be expected to return different embodied energy values to one in central London. Along with other differences which could occur (source of materials, methods employed, recycling, etc.) it would be unwise to suggest that one result will be correct in all situations. In particular there has been little differentiation between types of concrete. Using a single value for steel may be acceptable because it is a relatively homogeneous material, but using one value for concrete suggests that C20 blinding concrete has the same impact as high strength C80 or lightweight C40 and this is clearly inappropriate for anything other than a simple assessment.

The differences between the ratio of frame to total energy is interesting because many of the differences between frame materials are not relevant when considering, for example, cladding, since most systems can be applied to all frames.

The Oxford Brookes report concludes that there is very little differences between frame materials, which is slightly dubious given the results. A difference of 2.1 and 2.6 GJ/m^2 represents a 24% increase and is not insignificant over a complete building. Using the Oxford Brookes 'B' building as an example 18,000m^2 x 0.5 GJ/m^2 = 9 000 GJ. Assuming a value for recycled steel of 17.6 GJ/t, this represents a saving in energy equal to 520 tonnes of steel production. This is not insignificant, especially if the result is applied to all new buildings. Set against this, is the fact that these results are subject to errors derived from both the basic embodied energy values used and the limits on calculation. It is possible that these errors could be larger than the differences. However, all the results are subject to these errors, so this criticism, while certainly valid, should not be given too much weight.

The buildings considered in all the studies are simple and not designed to maximise advantages of each material for low impact design, for example through the use of curved soffits. The Oxford Brooke study looks at only one in situ cast concrete frame, which uses a flat soffit, although it does include hollow cores, which can be used in conjunction with thermal mass. None of the case studies examined in Chapter 4 use a flat soffit design.

The Oxford Brookes model is the only one which is specifically UK based and is therefore the one which has been most closely studied.

The final point which should be remembered is that no study produces results that are necessarily any better than the others - they could all be equally correct for the circumstances in which they were created. However, all reports acknowledge possible flaws and these areas should be improved upon where possible.

5.6 Conclusions

Analysis of the available models should be used to guide the creation of any new models. Overall, it is clear from looking at the available detail there are significant gaps in the detailed information available in calculating life cycle energy figures, and that there is still significant room to improve the accuracy of results. Although detailed information is available from some sources, especially the Chalmers report, it is localised for Sweden, which limits the applicability in the UK. The differences in results for frames are acknowledged to be relatively small and should be qualified by the errors which are unavoidably included via variable base data.

When looking at the current models it becomes apparent that that there is a need for a simple to use and truly transparent impact assessment model. The results currently available are from Canadian, Scandinavian and UK models and these, unsurprisingly given the ranges of input data, yield varying results. These results are difficult to compare due to the differences in data from region to region and the different designs used to provide the baseline information.

The work presented here in should produce a localised impact assessment model which is open to inspection both in terms of the basic data and the uses to which that data is put. The model should also be able to accept different data sets to enable the parameters to be examined and suggest the sensitivity to change of different values. This adaptability should also enable the model to be improved as new information becomes available and/or be tailored to specific company data. Once created a new model can be used to assess structures already used in other models to compare values, but also use designs from the next generation of low impact buildings. The data used to produce any results should be clearly available to ensure that possible confusion is minimised.

Fundamentally, any conclusions provided are strictly limited by the data and calculations used. When assessing different works some simple questions should be used to question the results and conclusions -

1) What figures were used and were these produced in the same way as other models?

2) Do the calculations include the same range of data. How have partitioning, uneconomic carbons and other parametric items been handled?

3) Could other figures reasonably have been substituted which would affect the results?

4) Are all the assumptions which have been used explicitly stated. Could other reasonable assumptions have been made which would have produced different results?

5.7 References

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6. STRUCTURAL EMBODIED ENERGY ASSESSMENT MODEL: DEFINITIONS AND PARAMETERS

The information gathered from the literature and available reports, discussed in the preceding chapters, reveals the areas where work is progressing and where gaps exist and more work is required. Overall, while there is broad agreement that environmental issues will continue to grow in importance in the construction industry and many new ideas and tools are being suggested, there are still many areas where detailed agreement has not been reached. Looking at the current 'state of the art' it is very possible that some concepts will be superseded.

In the area of embodied energy there are clearly several areas where there is a significant gap in the available data, specifically in construction and subsequent demolition of structures. The data on transportation is increasing in quantity but is still very generalised and lacking on specialised pieces of plant and equipment.

There are also gaps in knowledge of operational energy, although this is where much of the work is currently being carried out. The work carried out up to this point has used computer models, however there is now data emerging from green buildings in use. This data should prove extremely valuable to designers of future projects. The conflict between the theoretical and practical sides of the work mean that there is likely to be significant changes in design over the next decade. Most of the buildings up to this point have been limited in scope using relatively well known ideas - double to treble glazing, increased insulation, low energy equipment - and linking them to relatively simple designs. As confidence in the new types of design grows it is possible that the design ideas will become increasing divergent.

When looking at the current models it becomes apparent that that there is a need for a simple to use and truly transparent impact assessment model. Currently available results give widely different results which are difficult to compare due to the differences in work practises from region to region and the different designs used to provide the baseline information.

None of the models studied look at the human energy requirement in construction processes or the energy associated with people such as housing, travel or food. There are a number of reasons for this, primarily the difficulty in accurate assessment. In addition consideration should also be given to the fact that humans will consume energy whatever activities they are pursuing. In this work the energy expended by the human operatives has not been considered. The increasing use of computers and robotics will reduce the need for this type of assessment, however construction still needs a large work force.

6.1 Background To Data Gathering

The factors outlined in the preceding chapters will inform the parameters within which the new model operates and the data which is used in processing. This background information can be summarised into the guidelines discussed below.

The work should produce a localised impact assessment model which is truly open to inspection. Any model produced should be adaptable enough to accept as much as possible of the variable grades of data which are currently available. It should also be able to accept different data sets for any given parameter depending on the situation. This adaptability should enable the model to be improved as new information becomes available and be tailored to specific company data. Once created, a model can be used to assess a number of the structures already discussed in other studies.

Data can be used from as wide a range of sources as possible, but preferably that which comes from direct observations and measurements, usually in the collaboration of the companies involved. New data should be concentrated in the areas where there are currently gaps and should supplement that already available. When combined, the new and existing data will form the basis for the calculations carried out by the Structural Embodied Energy Assessment Model .

In general the level of knowledge within companies approached for information about environmental issues was disappointing. Although in most instances there was a recognition that "the Environment" was important, the knowledge did not extend much beyond this level. No general operatives, sales or technical staff in non specialised[1] companies recognised the term embodied energy. Although this was expected in smaller local companies, it is surprising in the larger ones. In some cases 'environmental benefits' were claimed for a company, for example a reduction in fuel consumption by using a specific product, however when this was followed up, data was unavailable. This data may have been withheld for reasons of a commercial nature and this is regrettable, albeit understandable in some situations.

The lack of data is reflected in the values used in some places in the Structural Embodied Energy Assessment Model. No values have been used which are not thought to be at least realistic. In each case the source of the information and some background information has been included although some of the companies from which data was gathered have asked to remain unnamed, and this is reflected in the text.

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[1] The range of companies approached for information was very large, including plant and tool manufacturers, plant hire companies, concrete suppliers, steel fabricators and erectors, contractors and waste management and recycling. The only firms considered to be specialising in energy and the environment were those with a dedicated department or team.

6.1.1 Primary Data Sources

New data has come from direct contact with plant and materials manufacturers, visiting trade fairs and gathering literature for specific processes or equipment. Where direct measurements have been the source of data this has been carried out in conjunction with commercial companies in a range of areas concentrating on local firms.

This section also includes information which has been derived from published sources where the data has been repurposed - for example guides on good construction techniques. In many cases using good construction techniques will also minimise the energy requirements

Most, if not all companies have a good knowledge of the costs involved in continuing business in their area of work. This knowledge may well extend to the energy required during operations - mainly in the form of fuel bills, however in the case of a number of firms contacted, the link between fuel and energy was not made. In other cases little or no care was taken noting fuel expenditure, especially in smaller local companies, on the grounds that this was not a major source of monetary cost. In a limited number of cases, examination of the operations and fuel bills of a company made it possible to gain a good understanding of the energy flows involved. In a number of other cases, data exists but was deemed of a commercially sensitive nature and unavailable to those outside an organisation.

In the majority of remaining cases, such energy information did not explicitly exist, although a certain knowledge of the area was apparent, for example, general fuel consumption figures for plant.

6.1.2 Secondary Data Sources

The secondary data comes from information already published and detailed in the preceding sections, for example the values for steel and cement.

6.1.3 Primary And Secondary Data

The use of the terms primary and secondary does not imply that some data is of a lower quality, but rather to show by what route the information arrived in the model. However, where data has not been directly gathered or calculated, there is, of necessity, less control over how the calculation was made. In some cases a combination of both types of data has been used - for example the energy figure for aggregate has been calculated and used in conjunction with published data for cement. In some cases, for example plant and equipment, the data comes from both primary and secondary sources. Where this occurs, the primary data has been used in preference.

6.1.4 Process Hierarchy

Both primary and secondary data must be organised and processed if it is to be of use in calculation, other than on a very basic level, of structural embodied energy. The

Structural Embodied Energy Assessment Model uses a pyramidal structural organisation (Figure 6-1). Although 'lower' level processes are shown as feeding into 'higher' levels, it should not be assumed that these will have a lower energy cost or are less important. In addition, at all levels, a unit rate or process can feed into a process not directly above it.

The most obvious multi level interaction is for what have been termed 'office energy overheads'. Every product, be it a tonne of 10 mm aggregate or an office block is produced by people who require ancillary equipment - office space, lighting, computer, telephones and so on.

6.1.4.1 Unit Rates

At the lowest level are the simplest components - unit rates. These consist of energy consumption figures for single items of plant and machinery and are quoted as energy (gallons of diesel consumed) per hour or miles per gallon. As previously noted, items of plant will themselves have an embodied energy figure and will be the result of a complex series of events (the manufacturing process), however, in this context, they have been assumed simply to exist. This is a reasonable assumption for a number of reasons - the long life span of most items of plant and the highly recyclable materials from which they are made (metals). In addition, the data is simply not currently available.

Also included in the unit rate class is an item which is used at all the other process levels. Transportation will occur in conjunction with every process at every level and will range from movements of hundreds or thousands of miles to small distances around a building site. The process diagrams for both concrete and steel identifies a number of the major transportation steps - for example the movement of aggregates from a quarry to a batching plant - and these are the ones that have been directly calculated as part of the structural embodied energy. However a myriad of smaller movements will take place, which are not directly identified, because they are small and because they are unpredictable. An example of this type of movement would be reusable formwork - in some cases forms and moulds might be left in place until they are required, in other cases they could be moved to an intermediate storage place, or moved several times as required. In addition the method of movement will vary, possibly using a wide range of plant such as tower crane or tipper truck, or even by hand.

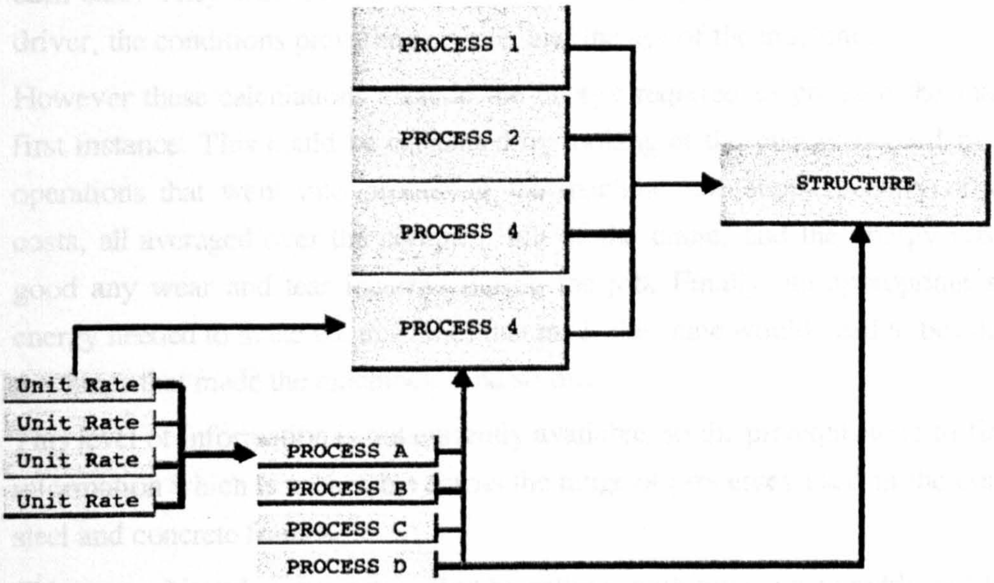
6.1.4.2 Basic Processes

At the next step up in the hierarchy are the first processes. These are built up from combinations of the unit rates. For example, the energy requirement for land acquired aggregates is made up of the rates for any diggers, loading shovels, crushing machines, screens, and tippers, and transportation around the site. To this must be added a figure for the office energy overhead requirements. In addition, explosives might be required where the source material was rock rather than alluvial materials. Explosives are the product of a process of their own, however this has been excluded.

6.1.4.3 Higher Level Processes

The higher level processes uses the lower level processes and unit rates to build up rates. For example the energy figure from the aggregate process becomes part of the concrete batching process which will also include the energy for all the materials used in concrete including the transport energy cost, the energy used in the batching plant and the office energy overhead. The outcome of this process assessment is a unit rate for a cubic metre of batched concrete. The parameters can then be altered for different concrete mixes. Processes may occur separately for both steel and concrete or may be used by both. These factors are discussed in the next section.

Figure 6-1: Process Hierarchy



6.2 Energy Data Parameters

There are two basic methods of obtaining energy figures for materials and processes - independent evaluation, for example by this study, or internal evaluations by the relevant industries.

Since there is currently a large quantity of research being carried out in the area of embodied energy, the Structural Embodied Energy Assessment model has been designed to accept the full range of data currently available and has the ability to be updated when required. The functioning of the model is discussed in Chapter 8.

6.2.1 Limits On The Range Of Data

An overall calculation of embodied energy should include all energy that has gone into producing that item. This means that, for example, when assessing the environmental cost of using a mobile crane, to make a very accurate reading it would be necessary to know a number of specific and supplementary items.

This is best illustrated in terms of an item of plant, for example a mobile crane working erecting steel on site. The first item which must be known is the quantity of completed work over the job, in this case in tonnes of steel erected and the fuel used to complete this work (excluding any additional but unrelated jobs which might have been undertaken whilst on site). Also needed is the fuel used in travel to and from the site and other oil and lubricants during the job. Supplementary information then needed includes the energy used in support of the cranes operation including, but not limited to, computers, light and equipment in the site office and hire firm office (office energy overhead). These figures, if known will give a good indication of the energy directly used to erect a given tonnage of steel. To get a figure for other operations these figures would need to be reworked in each case. They will also vary depending on other parameters including the skill of the driver, the conditions prevailing on site, and the age of the machine.

However these calculations exclude the energy required to produce the machine in the first instance. This could be calculated by looking at the energy needed by each of the operations that went into producing the machine, the supplementary office overhead costs, all averaged over the complete life of the crane, and the energy cost of making good any wear and tear incurred during the job. Finally, an appropriate share of the energy needed to make the machines that made the crane would need to be added. And the machines that made the machines. And so on.

This level of information is not currently available, so the prerequisite is to find a level of information which is achievable across the range of processes used in the construction of steel and concrete frames.

This was achieved in two ways, first by setting, with reference to published literature and recommendations, the minimum requirement to get worthwhile results and a realistically achievable maximum level of data. The second method was to canvas appropriate companies to see the level of data that was already or could become available through data gathering and analysis. At this stage, the preferred method of data gathering was to cooperate with individual companies to assess the energy uses and requirements in a wide range of situations.

The analysis revealed a number of points -

- The level of knowledge and available data was surprisingly low in a large number of cases. In many instances initial contact was not responded to or with simple negative responses.
- Some manufactures have made more progress in self evaluation and environmental data gathering than others. British Steel for example, has, along with other major European steel manufacturers, commissioned a major study into the environmental costs of steel. When this is published, in early 1998, assuming that the calculations involved are visible, these values will clearly be the most accurate. This work has been publicised and announced (1), however, when British Steel were approached to

see if any information could be made available for use in this project they declined to comment further. The general tone was that when the information was available, it could be provided on a case by case basis to those who demonstrated a need and were prepared to accept guidance on the data use.

- For the most complex operations, cement and steel manufacture, the most realistic methods of evaluation would appear to be either for an external examination of the operations with the co-operation of, and full access to, the industry. Alternatively the manufacturers involved could commission a study or carry out their own work. Generally the second approach has been taken and the values used in these areas in this study are therefore either those provided by the manufacturers themselves (an "imported" value) or the very broad values provided by, for example, the Building Research Establishment (see section 4.2.10).
- In addition to the difficulty involved in the calculation, there is a question of fairness to the materials involved. Therefore 'equivalent' sources of data are used wherever possible to ensure an even handed approach. It is recognised that each individual item or process will have its own specific value for embodied energy, even down to individual batches and that using one 'all in' evaluation will reduce the accuracy of the model when compared to bespoke calculations. It is not possible to partially calculate a figure, by taking known values for individual items, for example by adding office overheads, and adding it to an all in value to 'improve' the data because the exact parameters (items included and excluded) of the data is not known. Any addition might therefore duplicate an item already included.
- Some figures in segments of the construction industry, for example the requirements of the people in charge of purchasing decisions for major plant, did not feel that energy was a significant issue. In carrying out the survey for information everyone involved in purchasing plant stated that the most important consideration was either cost or durability/reliability. This was, in part, attributed to ownership and use of plant in this country. Often plant is owned by plant hire firms, which rent items to contractors on a short terms basis. The plant is hired with two main issues in mind - ability to do the job and cost. The decision about which hire company to use is often made with reference to 'preferred' subcontracts. In this system the plant hire firm has no particular incentive to consider energy, since fuel is provided on site by the contractor, and the contractor is generally simply interested in low hire charges. In situations where the contractor used their own plant, fuel use was often noted, but not then further analysed and considered insignificant.
- Some manufacturers expressed the opinion that productivity and thus indirectly energy, is primarily effected by factors such as driver comfort and good machine design. Driver ability was also cited as a major contributory factor.

- Manufacturers, when questioned, were often reluctant to produce energy figures stating, with a degree of justification, that this information is not required by them or their clients and difficult to produce due to the range of operations and variables involved. A straw poll of full page advertisements placed in the November 1997 issue of Plant Managers Journal (**2**), found no mentions of energy or environment (see Table 6-1).

Table 6-1: Requirements For Plant

	Reliable/ Durable	Power	Research/ Technology	Comfort/ Productivity	Cost/ Economy	Service/ Maintenance	Energy/ Environment
Cummins	X	X	X			x	
Hyundai	X	X	X	X	X		
Samsung	X	X	X				
JCB		X		X	X	X	
Twaites			X				
Case					X		
Hanix			X	X			
Volvo	X				X		
Bobcat					X		
New Holland		X					
Komatsu		X	X	X	X		
	3	6	6	4	6	2	0

6.3 Compiled Energy Data

The target data for the Structural Embodied Energy Assessment model was set, acknowledging the factors previously outlined, to using simple average fuel consumption and energy rating figures. These are supplemented, where applicable, by an assessment of the office overhead cost.

The data shown in the tables in this section has been presented as simply as possible for clarity, for example plant type A, average fuel consumption B litres per hour, work done C tonnes.

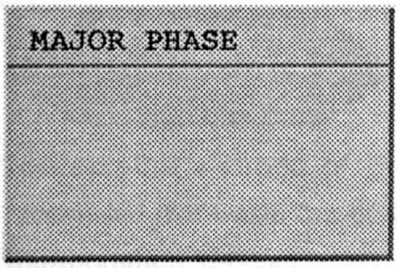
For each section a background statement is included about the origin of the data and the use to which it is put. In some cases data has been calculated from actual figures from plant and equipment used, in others it represents information from manufacturers. Where possible, where manufacturers' data has been used, a discussion was held with a company representative about use and limitations, although in most cases explicit operative knowledge of this area was limited.

6.4 Process Diagrams

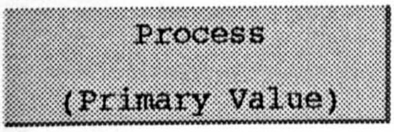
Process diagrams have been created for both concrete (Figure 6-2) and steel (Figure 6-3). These show the range of operations that have been considered for each material in this report. They also show how the processes will flow and interconnect for steel and concrete in a structure.

Although concrete and steel have been detailed separately, they are fundamentally linked - concrete is used in 'steel' framed buildings and visa versa, and the two chart system is used simply for clarification purposes. In each case, the charts are, of necessity, simplified. It is simply not possible to show all the possible variations for each variable. Each of the elements shown has been identified as an item which requires analysis in order to perform an accurate embodied energy calculation.

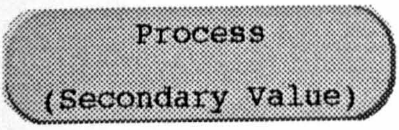
To help with identification of processes, the charts use shape coded boxes for each general situation. These are explained below.



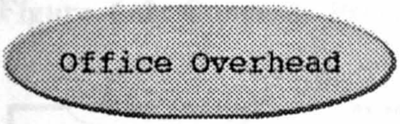
These boxes cover the major headings for phases in the frame life cycle. The 'Site Operations' box indicates a large number of processes, the majority of which have been assessed. During construction many interactive processes will be taking place simultaneously and while some of these are frame related, others are not. Where an overlap occurs in energy terms, for example in the work being carried out by site management and operatives, an estimate has been made about the relative weights for each activity. The Occupation box, which covers repair and maintenance, is shown because this is the most important phase of the building life cycle and links the construction and demolition phases, rather than because it has been assessed. The reasons for this have been noted previously.



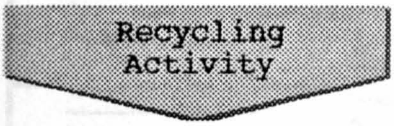
These boxes show where a process calculation has been made, based on primary data. In some cases where both primary and secondary data has been used in building up a process rate, these are shown as being primary values for clarity. This will include items such as batched concrete where, for instance, cement is a secondary figure, but batching energy is primary.



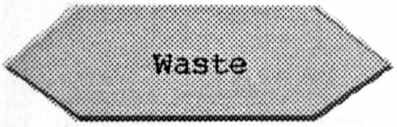
These are processes for which a secondary value has been used.



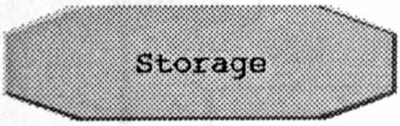
This box shows that an assessment has been made of the office energy requirement and that this has been included in the process embodied energy calculations.



This indicates where a recycling activity may take place. Whether or not this occurs will depend on the specific job.



Indicates that a stream of waste materials is generated. As with transportation, it is recognised that waste can be generated at any point in the life cycle, however, also like transportation, this can be very unpredictable. An allowance for waste has been made, at standard rates, for most material streams.



This box indicates that materials may be moved to storage at this point. In most cases there is an option for materials to either be used directly or moved to store and then used (double handling). An example of this is the off loading of steel members, which ideally can be done straight from the lorry to the structure, but in many cases will be moved to store. Well managed stores will suffer only small losses, however waste can be significant if the conditions are other than optimum.

Figure 6-2: Concrete Processes Overview

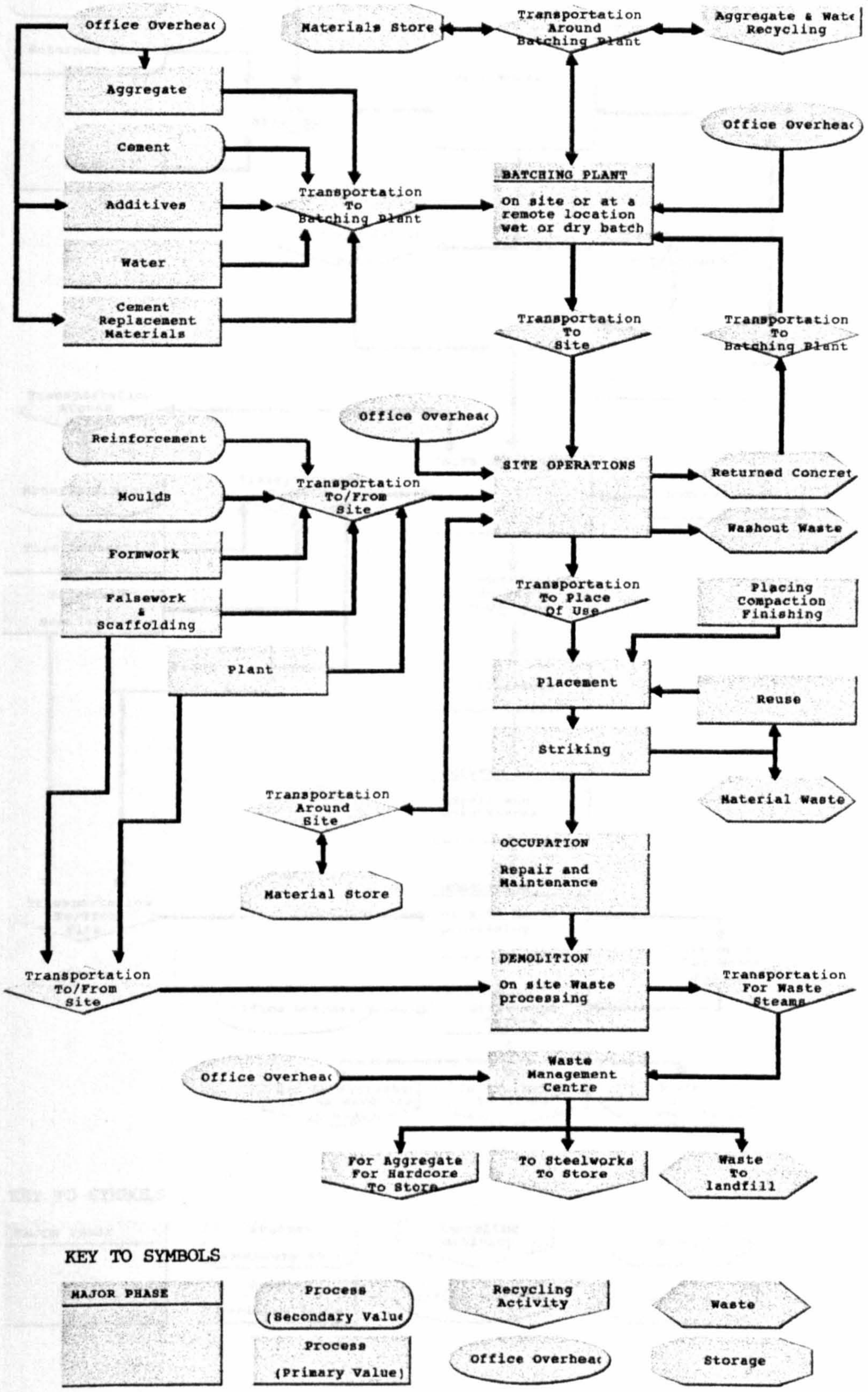
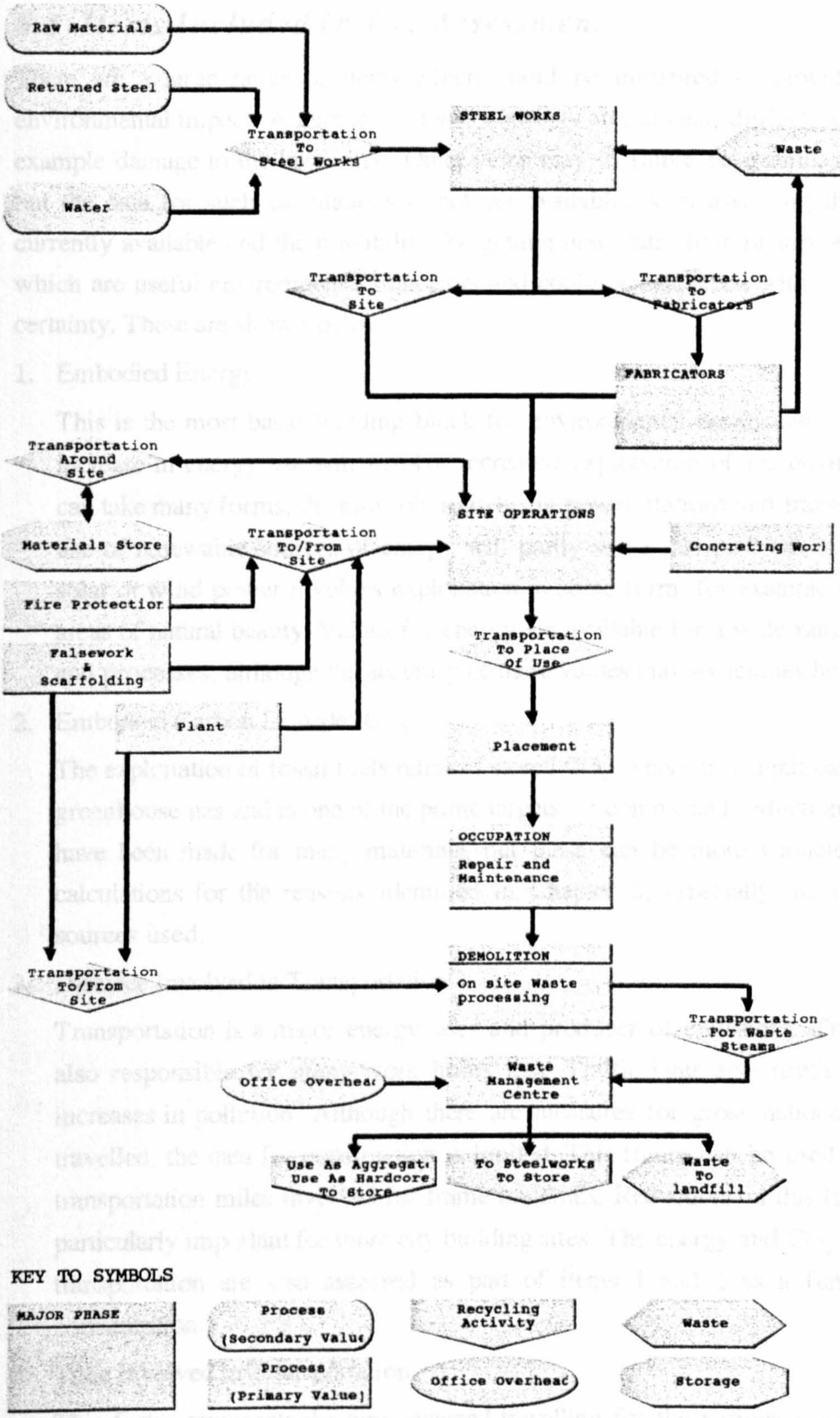


Figure 6-3: Steel Processes Overview



6.5 Items Included In The Assessment

There are a large range of items which could be measured to provide a guide to environmental impact. A number of these concepts are, at best, difficult to quantify, for example damage to the landscape. Other items may in future be quantitatively assessed but the data for such calculations is not yet available. After assessing the information currently available and the possibility for getting new data, four factors were identified which are useful environmental indicators and could be calculated with some degree of certainty. These are shown below.

1. Embodied Energy.

   This is the most basic building block for environmental assessment. Currently any increase in energy use will involve increased exploitation of the environment. This can take many forms, the most obvious being power stations and transportation. The use of renewable sources of energy will partly solve this problem but even use of solar or wind power involves exploitation in some form, for example wind farms in areas of natural beauty. Values for energy are available for a wide range of materials and processes, although the accuracy of these values may sometimes be limited.

2. Embodied Carbon Dioxide (CO_2).

   The exploitation of fossil fuels released stored CO_2. This has a significant impact as a greenhouse gas and is one of the prime targets for control and reduction. Calculations have been made for many materials, but these can be more variable than energy calculations for the reasons identified in Chapter 2, especially the mix of power sources used.

3. Distance Involved in Transportation.

   Transportation is a major energy user and producer of emissions. Traffic jams are also responsible for many work hours lost. Traffic jams also result in significant increases in pollution. Although there are measures for gross national traffic miles travelled, the data for construction is limited. This figure can be used to assess the transportation miles involved for frame materials. Reductions in this figure could be particularly important for inner city building sites. The energy and CO_2 emissions for transportation are also assessed as part of items 1 and 2 as a function of fuel consumption.

4. Time Involved in Transportation.

   This factor represents the time incurred travelling for the various materials options. This factor will relate to the distance travelled, but this need not necessarily be on a 1:1 ratio.

Although there are other factors which could be included, these four values represent information which is both useful and within the range of data which was available. The time and distances involved are related factors, but only the distance travelled is used in the calculation of energy and CO_2 emissions - using a fuel consumption figure in miles per gallon..

6.6 Parameters of Data

Generally when making calculations a number of basic principles have been applied

- Where specific data is not available calculations have been carried out on the basis of what would be considered 'good practice' and 'what is reasonable'. So for example while it is possible that materials could be moved around site a number of times due to bad organisation, calculations have been made for only one handling movement in excess of that required for final placement.

- The allowance for partitioning, feedstock and other embodied energy factors is dealt with on a case by case basis. In terms of frame materials, these factors apply to waste products and the analysis has been made in favour of waste reduction. The general consensus is that waste should be minimised and lower embodied energy values encourage this.

Where data has been specifically gathered for this thesis, an assessment has been made for these items:

- The energy in production of the material.

- The transportation required.

Where possible this has been supplemented by:

- The number of people required for the process and the related office energy.

For the purposes of illustrating the additive natural of embodied energy, an estimate for the transportation requirements for people and the embodied energy of plant has been made for quarrying. The level of data used has been noted with each item.

6.7 Presentation Of Data

The data has been presented using the standard format, shown in Table 6-2. Where intermediate calculations are required they are shown in supplementary tables. The units for energy measurements are always quoted in gigajoules, usually per tonne or per week, but in some cases others have been employed where appropriate. The use of gigajoules rather than megajoules is a reflection of the relative contributions although in many cases the calculations have been made in more detail. The figures are quoted to a maximum of three decimal places. 0.001 GJ/t is equal to 1 MJ/t. Where figures have values lower than 0.5 MJ the value is quoted as 0.000 GJ. CO_2 calculations are quoted to two decimal places because they are an order of magnitude greater than energy. Transportation distance calculations are shown to two decimal places, while transportation time is shown to three decimal places.

Table 6-2: Standard Data Presentation

Material or Process	Embodied Energy (units)	Embodied CO_2 (units)	Transportation Distance (units)	Transportation Time (units)
Processing Fuel	x	x	x	x
Transportation	y	y	y	y
Total	x + y	x + y	x + y	x + y

For the columns headed 'embodied energy' and 'embodied CO_2' the figures refer to the contribution to the total embodied energy and CO_2 from using the material or process in the units given.

6.8 Conclusions

A method has been identified which will increase the depth of analysis in some areas. When applied to the items identified, in the process diagrams, the analysis will provide significantly more information than has been available up to this point.

The method of data build up will allow delivered, primary and transportation energy, time and distance to each be analysed separately. While the range of factors is more limited than other studies, specifically the work at Chalmers University, it was not possible to increase the scope without being able to analyse, in detail, all the industrial processes involved in construction. That level of involvement was not achievable in this study. This work also provides figures which have not previously been calculated for transportation

The analysis of construction processes in detail has shown that there is a lack of environmental knowledge in many areas. The information for construction plant was particularly lacking in depth although in some cases the information was available after discussion with each company involved.

By assessing the factors involved in embodied energy calculation, for example feedstock energy, on a case by case basis, more control can be achieved over the results than an overall inclusion or exclusion would allow.

6.9 References

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7. STRUCTURAL EMBODIED ENERGY ASSESSMENT MODEL: ASSEMBLY OF DATA

The gathered data has been split into three basic categories for concrete, steel and generic items. The generic section covers items that are common to both steel and concrete frame construction or are used in other areas of construction, but might in some cases be used in the context of the structure. The generic items are presented first because these rates are used in subsequent calculations. All items are presented in the order in which they were built up. Although concrete is used in significant quantities in steel structures and visa versa, for simplicity these items are only discussed once.

7.1 Generic Data

There are a significant number of plant items and operations which are used in the construction of both concrete and steel frame construction of which the most obvious are transportation and office environmental impacts. Also presented in this section are the basic rates of conversion for energy and the production of CO_2.

7.1.1 Energy Data

The basic energy data and conversions used are shown in Table 7-1. This table shows the primary to delivered energy ratio and the CO_2 production for each fuel. So, for example, every 1 GJ of gas delivered is equal to 1.11 GJ of primary energy which releases 1.11 x 51.3 = 56.9 kg of CO_2.

Table 7-1: UK Energy Conversion And CO_2 Factors At 1996 Rates

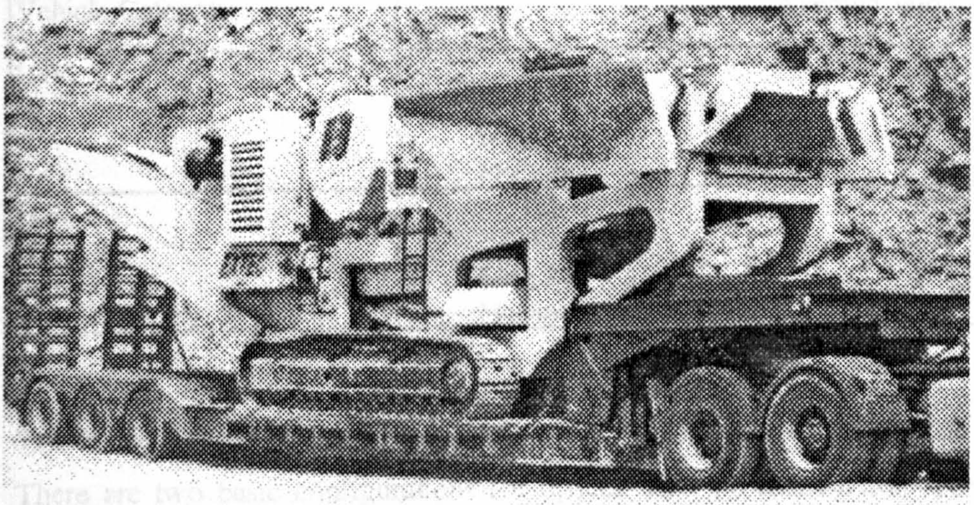
Fuel	Delivered Energy GJ	Primary Energy GJ	CO_2 kg/GJ
Electricity	1	2.72	53.6
Coal	1	1.02	91.7
Gas	1	1.11	51.3
Oil	1	1.08	69.7
Diesel	1	1.17	65.7
Petroleum	1	1.12	64.0

The data in this table has been complied from the information contained in chapters 2 and 3. The CO_2 production figure for electricity is based on a weighted average for all fuels used in the UK to generate electricity in 1996. Nuclear, renewable and imported energy sources have been taken as producing zero CO_2 emissions. Petrol and diesel are produced from oil, but are given separate values because the data was calculated especially for transportation and is therefore more specific than the general figure for oil. This data table is used in the build-up of all the rates which have been calculated in this thesis.

7.1.2 Transportation

Transportation of materials and plant can involve movements over long distances and incur high volumes of traffic. Most of the major environmental impacts are for material movements, but plant movements can also involve very long distance travel, especially with high cost items, for example large capacity mobile cranes. For these machines round trip distances of over 500 miles are not uncommon and given that they typically travel only 2 or 3 mile per gallon and will incur large energy costs. Not only are plant items slow, they are often wide or long (see Figure 7-1) which can result in a significant reduction in the speed of other traffic. Frame materials would not usually move such long distances, although some do, but generate larger volumes of traffic.

Figure 7-1: Transportation Of Plant



The travel data has been taken from three sources and these are given, in order of use priority, below.

1. Direct observation and discussion with company representatives.
2. Specific information from published sources directly relevant to construction operations.
3. Generic data. Where no other information is available, the data from the sources quoted in chapter 3 is used (Table 3-4 in particular). This data has been ranked as the third choice not because of any perceived flaw, but because it has not been derived from construction sources.

In a number of cases, the companies canvassed were able to make estimates of the travel distances involved, but not the fuel expenditure. In this case the priorities detailed above apply.

Calculation of travel speed is the most difficult aspect of these calculations due to the variability in road transportation as a whole. The data shown in Table 7-2 has been derived from the data in Table 3-3 and includes an item for a ‘long run’. The long run calculation makes allowance for the fact that most longer trips will cover a number of different road types and conditions. Most longer trips will make use of a motorway at some point while starting or finishing in urban areas. In this case the rate has been built up by using a weighting system of 60% motorway, 20% rural and 20% urban. A long run has been assumed to be any transportation over 50 miles, and is used unless more specific data is available.

The values used in this thesis have been standardised on miles (MPG, MPH) rather than kilometres and the tables reflect this. This was done because all the data gathered from field work was in this form, which is more readily assimilated by the majority of people in the UK construction industry.

Table 7-2: Assumed SEEAM Travel Speeds

Vehicle Category		Average MPH
LGV	Urban	22.5
	Rural	35
	Long Run	41.5
	Motorway	50
HGV	Urban	12.5
	Rural	25
	Long Run	37.5
	Motorway	50

7.1.3 Office Overhead Energy Costs

There are two basic configurations for offices used in construction: permanent office buildings and temporary site accommodation. These will contribute both embodied and operational environmental impacts.

The simplest measurement are for running costs, but to increase the accuracy of assessment any embodied energy should be included, however not enough information was available to make this viable in this thesis. An attempt was made to get both the materials and the energy used in manufacture for the site accommodation from Portakabin. Unfortunately the information was not available for two stated reasons - commercial sensitivity and time taken to gather the information. The office energy that has been calculated is therefore limited to that for transportation and operation.

7.1.3.1 Permanent Office

There are as many possible rates for office energy consumption as there are offices. For example, an Architect working on the design of a building might work in a prestige office with full air conditioning and have an area allocation of 20m^2. Alternatively they might work from a naturally ventilated office and share a work area, giving a space per person of 10m^2. The energy requirement for these two situations would be expected to be very different, while the actual work done in each could be expected to be roughly similar.

No transportation or embodied energy element has been calculated for this type of office.

7.1.3.2 Temporary Office

For temporary and site work the situation is simpler, with portable offices being used. While there is a significant range of designs available[1] the range of options is much more limited than for office buildings. Observations on site have also revealed that the units used are generally at the small end of the possible scale, with use made of more smaller rather than fewer larger units. This occurs for a number of reasons, but in particular the flexibility offered by a larger number of smaller units (which can be split up and sent to different sites) and the ease of transportation (smaller units can be transported without special permissions). It was also observed on site that there tended to be two types of office fit out - basic unit and office level. The basic units provided only shelter and heating, usually for operatives and engineers. There was usually no equipment in these units beyond the basics of light, heat, seating and possibly workspace for drawings. The office level units tended to be of the same basic design, but had been fitted out to a much higher level and included fax, telephones, computer and other general office equipment. These units were used by the site managers and administrators. Given this split, two levels of site accommodation have been recognised - basic and site office.

The transportation calculations for this type of office were based on an average travel distance of 100 miles, suggested by Portakabin. This distance will vary depending on the site and the company involved.

7.1.3.3 Energy Partitioning

In the same way that embodied energy can be split between different products, the office energy needs to be split between different activities. Activities on-site are an obvious example of this where operatives would be actively doing a number of jobs, so an engineer might spend x hours setting out columns and y hours supervising internal finishes. An approximation of all the hours devoted to each activity is required to split the office energy costs. This applies to both the operational and transportation cost, so that an office brought on site and devoted initially to structural aspects might then be used for other activities after the structure was completed and before the office was moved again.

This differentiation has been made through discussion with the relevant people for the purposes of calculation, but would be different for each site.

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[1] Information on 'instant accommodation' was acquired from Portakabin Ltd - the largest supplier of this type of equipment in the UK. They have a range of accommodation ranging from 7.36m^2 to 35.95m^2 internal floor area and these can be combined to give greater areas.

7.1.3.4 Temporary Accommodation In Semi Permanent Situations

In some situations, accommodation is placed at a site and left there for extended periods of time - years rather than months. In these cases no allowance has been made for transportation since the offices are effectively permanent.

7.1.3.5 Office Energy Use

The permanent office energy requirements have been made for a single person and based on an average office. In some cases the office overhead is included in the overall data and where this occurs no further analysis has been made.

The site office requirements have been worked out as if use was made solely of a two person unit set up for both a basic and office configuration. This unit was used because it provides flexibility in calculation and because, as noted, site units tend to be small. This limit may cause a slight over estimate in transportation cost, but is not thought to be significant. An allowance for transportation has been made for a 'one way' journey so the return trip is expected to be accounted for by other operations.

The energy levels and equipment found in each office type are shown in Table 7-3. The low and high range for permanent offices are taken from the energy efficient office best practice programme (1). The high value is for a typical fully air conditioned prestige office and the low value is for a good practice naturally ventilated structure.

Table 7-3: SEEAM Average Office Energy

Item	Basic	Site Office	Office Low	Office High
Heater (W)	2000	2000		
Lights (W)	116	116		
Computer (W)		117		
Printer (W)		75		
Photocopier		126		
Day (9 Hours) Heating/No Heating (kWh)	19.1 / 1.0	21.9 / 3.9		
Year (268 Days) (108/160 Heating Split)(kWh)	2223	2989		
Assumed Area (m^2)	12.3	12.3	10	15
People per unit area	4	2	1	1
Area Per Person (m2)	3.1	6.2	10	15
Per Unit Area Floor per annum (kWh/m^2)	181	243	150	600
Per Unit Area Floor per annum (GJ/m^2)	0.651	0.875	0.540	2.160
Per Unit Area Floor per week (GJ/week)	0.013	0.017	0.011	0.043
Per Person Per Week Delivered (GJ/week)	0.040	0.108	0.108	0.648
Delivered To Primary Conversion Factor	2.72	2.72	1.43	1.92
Per Person Per Week Primary (GJ/week)	0.109	0.293	0.155	1.241

The values given in Table 7-3, have been arranged to provide a figure for energy per person per week in each of the different accommodation types. Given the wide spread of values for the permanent office accommodation, a value of 25 GJ/week will be used. The breakdown between energy types is assumed to be 80% gas to 20% electricity for the low energy building and 50:50 for the high energy building. This will vary between buildings.

The relatively high energy use for the site accommodation relates to the use of electric heating. A transportation distance of 100 miles has been assumed at a rate of 37.5 MPH and with a fuel consumption of 9 MPG. This gives a two way transportation energy of 4.4 GJ/unit. The units are assumed to be for two people sharing therefore the energy per person is 2.2 GJ/unit

This transportation energy has been split over 50 weeks. A longer stay on site would decrease the energy per week and visa versa. Table 7-5 makes no allowance for moving office equipment off and onto the site.

Table 7-4: Environmental Impacts: Basic Site Accommodation

Site Accommodation: Basic per person	Embodied Energy (GJ/week)	Embodied CO_2 (kg/week)	Transportation Distance (miles/week)	Transportation Time (hours/week)
Transportation (To)	0.022	1.44	1.00	0.027
Operation	0.109	5.83		
Transportation (From)	0.022	1.44	1.00	0.027
Total	0.153	8.72	2.00	0.053

Table 7-5: Environmental Impacts: Office Site Accommodation

Site Accommodation: Office per person	Embodied Energy (GJ/week)	Embodied CO_2 (kg/week)	Transportation Distance (miles/week)	Transportation Time (hours/week)
Transportation (To)	0.044	2.89	2.00	0.053
Operation	0.293	15.69		
Transportation (From)	0.044	2.89	2.00	0.053
Total	0.381	21.47	4.00	0.107

Table 7-6: Environmental Impacts: Permanent Office

Permanent Office: per person	Embodied Energy (GJ/week)	Embodied CO_2 (kg/week)	Transportation Distance (miles/week)	Transportation Time (hours/week)
Operation	0.698	36.55		
Total	0.698	36.55		

7.1.4 Mobile Cranes

Mobile cranes may spend large periods of their working life travelling long distances. Small cranes may well travel locally and will probably travel to and from a depot each day. The larger cranes travel further but will often stay on site for a few days and some may spend long periods on site not working, while waiting for other operations.

Small mobile cranes (approximately less than 60 tonne lift capacity) have only one engine, which is used for both driving on the roads and to operate the crane when on site. Cranes over this size tend to have two engines - one relatively large for travel and one smaller for crane operation on site. This improves the efficiency of overall operation, but will increase the capital cost, both in monetary and environmental terms.

Mobile cranes will tend to have a working life of around 20 years depending on use and maintenance, but this will be split over a number of operators. Large operators tend to buy equipment from new and then sell them to smaller operators after 5 - 10 years.

Mobile cranes can perform all the operations that a tower crane can, but are usually used for specific tasks, such as steel frame erection, although concrete pours can also be achieved. A mobile crane will usually be limited in reach over the site unless special luffing jibs are used. Table 7-7 shows travel fuel consumption for a range of cranes, this information was gathered from Emsley Crane Hire. All of the cranes in this table use separate engines for road and site operation. There is little information about energy use while on site which will depend on the type and quantity of work carried out. An estimate has been made for this figure based on discussions with mobile crane operators and these figures should be regarded with caution.

Table 7-7: Mobile Crane Fuel Consumption

	General		Transport	Averages		Site
Model	Max. Lift	Weight	Distance One Way	Speed	Fuel	Fuel
	Tonne	Tonne	Miles	MPH	MPG	G/hour
Large						
Liebherr LTM 1160/2	160	80			2.7	
Liebherr 1090/2	100	73			3.1	
Demag	120	74			3.0	
Average	130		150	30	3.3	2.5
Medium						
Krupp KMK 4080	90	62			3.3	
Krupp KMK 4070	70	62			3.2	
Grove AT685	70	58			4.1	
Average	77		50	35	3.5	2.0

Using the data in this table it is possible to work out a figure for average energy use per day. For simplicity the energy has been calculated for two crane types, large and medium, based on the average figures for those crane types. A measurement for a small crane was not required for frame calculations. The large crane is assumed to spend three days on site excluding travel time, while the medium crane transportation is calculated for a single day cycle. A working day is assumed to be 9 hours (exluding travel). The energy is given pro rata for each day rather than per tonne - jobs can either be measured by placing rates, for example tonnes of steel per hour, or time on site, for example 2 days for tower crane erection, but time on site allows for more flexible calculations.

Table 7-8: Environmental Impacts: Large Mobile Crane

Large Mobile Crane	Embodied Energy (GJ/day)	Embodied CO_2 (kg/day)	Transportation Distance (miles/day)	Transportation Time (hours/day)
Operation	4.453	292.50		
Transportation	5.997	393.94	100.00	3.33
Total	10.450	686.44	100.00	3.33

Table 7-9: Environmental Impacts: Medium Mobile Crane

Medium Mobile Crane	Embodied Energy (GJ/day)	Embodied CO_2 (kg/day)	Transportation Distance (miles/day)	Transportation Time (hours/day)
Operation	3.562	234.00		
Transportation	5.654	371.43	100.00	2.86
Total	9.216	605.43	100.00	2.86

Clearly the transportation element is considerable for both types of machine. It is certainly possible that sites could make use of cranes from a depot much nearer than the distances used, lowering the environmental impact. However, the hire of large items of plant is usually done on the basis of cost rather than distance and even when a local depot is available there is no guarantee that plant would be sourced from there. In situations where plant stays on site for longer periods, the energy per day would fall accordingly.

To place these energy requirements in context, the energy has been allocated for an average councrete pour using the data calculated by Alkoc et al (**2**). The times were observed on a water treatment project in Turkey using a 40t SWL truck mounted mobile crane with both a 0.5 and 1.0 m^3 bucket. The analysis has been carried out using the 1.0 m^3 bucket because, for the size of crane in this analysis, the 0.5 m^3 bucket would be significantly undersized. The crane motor is assumed to be running over the complete range, including discharging. The total rate of movement for columns and slab of 12.31 and 4.41 minutes would allow 44 and 122 such actions respectively to be performed in a nine hour day.

Table 7-10: Alkoc Concrete Pour Rates (2)

	Slab min.	Column min.
Fill 1m^3 Bucket	1.20	1.20
Swing 1m^3 Bucket	0.88	0.88
Return 1m^3 Bucket	0.58	0.58
Pour 1m^3 Bucket	1.75	9.65
Total	4.41	12.31

Table 7-11: Environmental Impacts: Concrete Pour, Medium Mobile Crane

Medium Mobile Crane Concrete Pour Using 1m^3 Bucket	Embodied Energy (GJ/day)	Embodied CO_2 (kg/day)	Transportation Distance (miles/day)	Transportation Time (hours/day)
Total	9.216	605.43	100.00	2.86
Actions	44/122	44/122	44/122	44/122
Column Per Cycle	0.209	13.760	2.27	0.065
Slab Per Cycle	0.076	4.963	0.82	0.023

There is no UK data of this kind, so these rates might well be inappropriate for an office building in this country. Using the large mobile crane to pour concrete would be inappropriate in both energy and cost terms. The overall environmental impact calculations do not take into account the manufacturing or maintenance energy for this equipment which could be considerable. It is therefore unlikely that the energy has been over estimated.

7.1.5 Tower Cranes

The tower crane is possibly the single most useful item of plant on site and virtually all buildings of the type assessed in this thesis will make use of one. A tower crane will be used for off loading, moving materials around the site and possibly placing both steel and concrete.

The information in this section was acquired from three sources - technical data from Liebherr, site observation of tower cranes in action and discussions with crane retailer Vansen Crane. For the purposes of calculation, two crane types were assessed - a Liebherr 154 EC - H6 and a 280 EC-H. The configurations used are shown in Table 7-12. The two cranes were configured to the same height and jib length, but with different lifting capacities.

Table 7-12: Crane Configuration (3,4)

Item	154 EC-H6	280 EC-H
Jib Length (m)	60	60
Max. Lift @ Jib End (kg)	1650	4100
Hoisting Height (m)	41.4	41.4
Hoist Motor (kW)	37.5	65
Hoist Rate (m/min)	1.7-100	1.4-100
Slew Motor (kW)	10	10
Slew Rate (sl./min)	0.9	0.7
Trolley Motor (kW)	5.5	7.5
Trolley Rate (m/min)	0-96	0-138
Packing List		
Tower Sections (no@m)	10@4.14	10@4.14
Tower Dims (m)	1.9 * 1.9	2.3 * 2.3
Jib Sections (no@m)	2@12, 2@5, 2@10, 1@6.4, 1@11.1	2@12, 2@5, 2@10, 1@6.4, 1@11.1
Platform and Head	1 Lorry Load	2 Lorry Loads
Other Items	2 Lorry Loads	2 Lorry Loads
Total Loads	20	21

There are three major elements that need assessing for tower cranes which are the transportation, erection and use. Transportation is made more difficult to assess by the wide range of permutations possible in crane size, however some generalisations can be made. The average travel distance is between 100 - 150 miles, with the cranes broken up into sections of around 2.2 tonne and carried on low loaders. The concrete blocks for use as counterweights are carried with the steel sections. To erect the crane on site a mobile crane is required with the capacity to lift the heaviest member safely into position. The attending mobile crane would be required for two days with a large tower crane but only one day for a smaller version. The mobile crane will be working intermittently. In some cases tower cranes can 'self erect' or 'climb' (that is increase the height without the need for a slave crane), however, even in this case a mobile will be required for the jib assembly.

The tower crane is secured on a base which can come in a number of varieties, the simplest being made of expendable concrete. When the tower crane is disassembled the base can be incorporated into the structure, left insitu or removed. Other base types, for example with a rail mounted crane, can be fully recovered. For the purposes of calculation a static recoverable base is assumed to have been used.

The energy requirement while the crane is in use comes from the three electric motors used to hoist and lower the load, slew the jib and run the trolley. The motors for these need to be sized for peak loads, which can make them less efficient at lower loads. Generally more than one movement will be carried out at a time, so for example a load could be lifted and turned at the same time. The hoist is far larger than the slewing or trolley motors. Since the motors are electrical, they use no energy when not actually working. Tower cranes which run on rails will additionally require a motor for movement and this will be a similar size to the slewing motor.

Tower cranes perform a wide range of tasks on site moving most materials. A tower crane will possibly be more useful for concrete frames because of the large number of small lifts required. Performing fewer heavy lifts might require the crane to be relatively oversized for non structural work.

7.1.5.1 Movements Using A Tower Crane

Some assumptions have been made when assessing the movements using a tower crane. No allowance has been made for positioning errors which require extra movement or for movement into atria. They also assume that there are no obstacles to the movement path, other than the building rising one floor at a time.

The amount of slewing and trolleying that a tower crane is required to do will depend on the relative location of the crane to the building and the area from which materials are moved (the off loading zone). This was carried out using a relatively simple measuring system, which used a weighting system to asses the average distances involved.

The crane was assumed to be at the centre of a 'target' shape which was mapped into zones up to the outer reach of the jib. A silhouette of the building was then superimposed. Each of the 16 radials covers 22.5° of the complete circle and each of the concentric rings marks off 5 metres along the crane jib. The inner most 5 meter circle was assumed not to be used due to the proximity to the tower and crane base. This gives 176 sections. An assessment was made of how much of the building falls within each section, based on visual inspection using a simple proportional (0.1, 0.5, 0.75 etc.) system. To find the degree of movement required by the crane, an example building was used (see Figure 7-2). This was basic design was chosen for three reasons - the basic rectangular plan is often used, the atrium design is often used in green buildings and the atriums allowed two different crane positions to be assessed. Figure 7-3 shows the tower crane located in the building atrium and includes the area calculation overlay.

Figure 7-2: Example Building

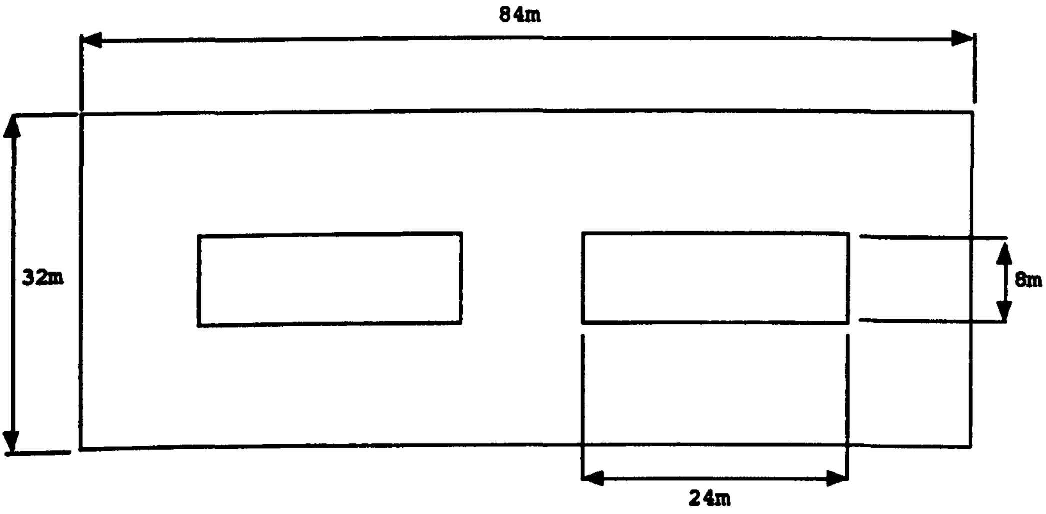


Figure 7-3: Tower Crane Location Example 1

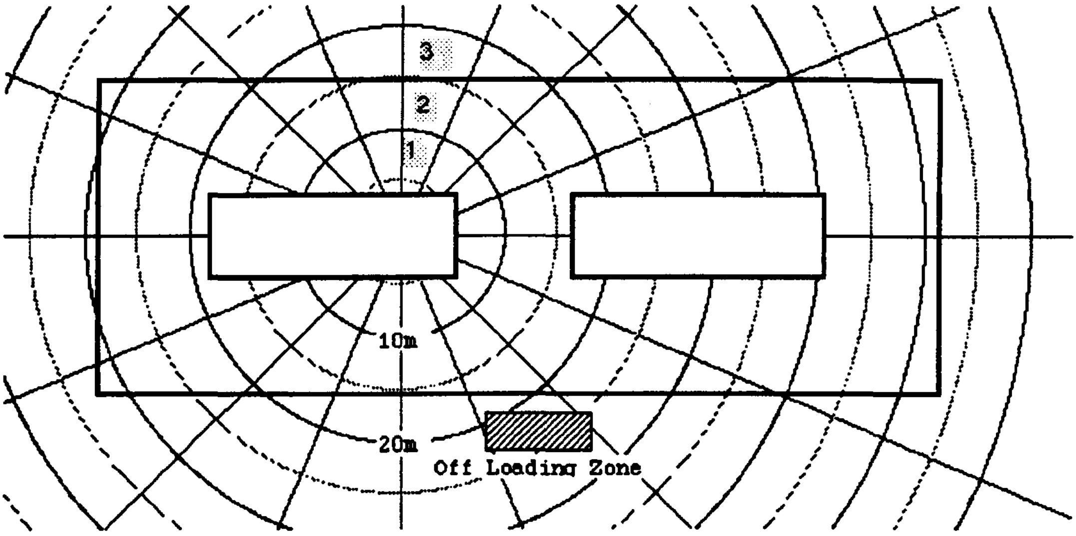


Table 7-13: Example 1 Slewing and Trolley Estimates

Loading Area Band	4											
Band	1	2	3	4	5	6	7	8	9	10	11	
Trolley Distance	15	10	5	0	5	10	15	20	25	30	35	
Segment Area	14.7	24.5	34.4	44.2	54.0	63.8	73.6	83.4	93.3	103	112	
0.0	1	1	0.5									56
22.5	1	1										39
45.0	1	1										39
67.5	1	1	0.5									56
90.0	0.5	1	1	1	0.5							137
112.5				0.5	1	1						140
135.0				0.5	1	1						140
157.5		0.5	1	1	1	0.5						177
180.0	1	1	0.5									56
157.5	1	1										39
135.0	1	1										39
112.5	1	1	0.5									56
90.0	1	1	1	1	0.5							145
67.5	1	1	0.5	0.5	0.8	0.8	0.8	1	1			408
45.0	1	1	0.5	0.5	0.8	0.8	0.8	1	1			408
22.5	1	1	1	1	0.5							145
Area Weight	184	331	241	265	329	262	118	167	187	0	0	2083
Average Slew (°)												84.6
Average Trolley (m)												10.1

Using this graphic the information in Table 7-13 was compiled. The 22.5° section and ring band containing the off loading zone were assumed to require no slewing or trolleying (that is, it was the starting point). Each section further away from that requires 22.5° more slewing and each ring in or out requires more trolleying.

This example shows the building as having an area of 2083m^2 which compares reasonably well the correct figure of 2112 m^2 and the closer these two figures the better the result. From this data , two results are derived - the average slew and trolley distances. Lower values will incur lower energy requirements. These are used for the energy calculation for this building set up. This calculation assumes that all areas of the building require equal crane time, however it is possibly to provide a weighting for each area. It would also be possible from this data and the hoisting equations to work out the actual energy for each sector and floor, but to do so without more study of on-site activities would imply a degree of knowledge which is currently not available. The same analysis was carried out for the same building but with the crane in three different positions.

Figure 7-4: Tower Crane Location Example 2

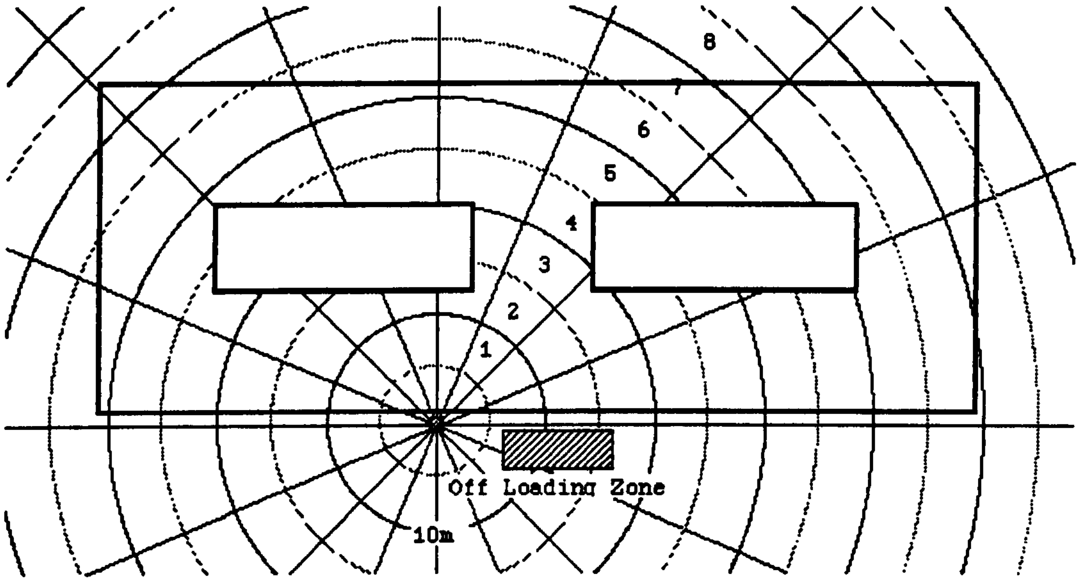


Figure 7-5: Tower Crane Location Example 3

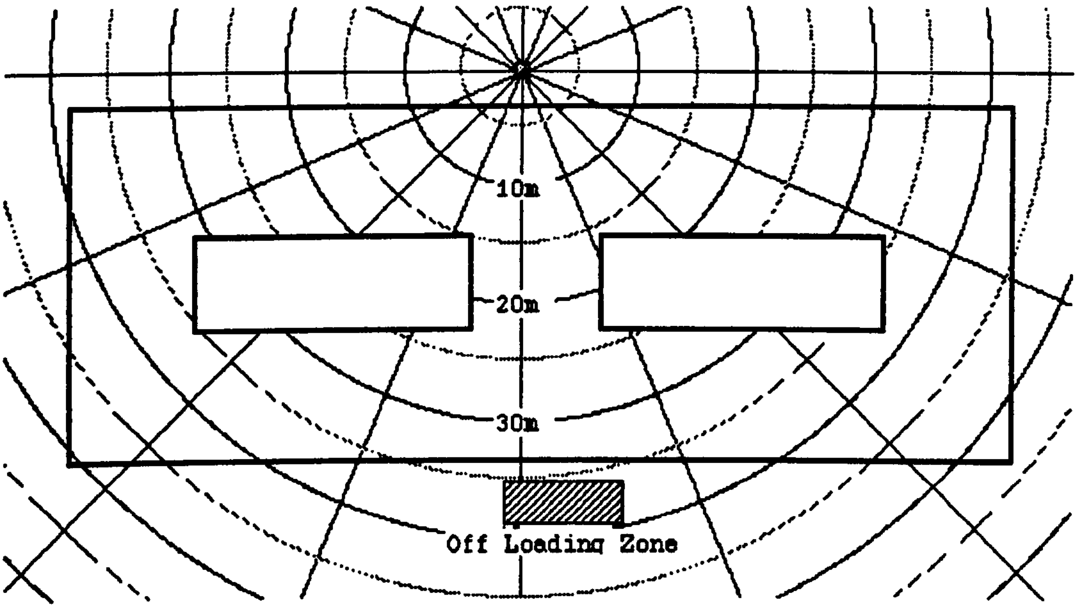
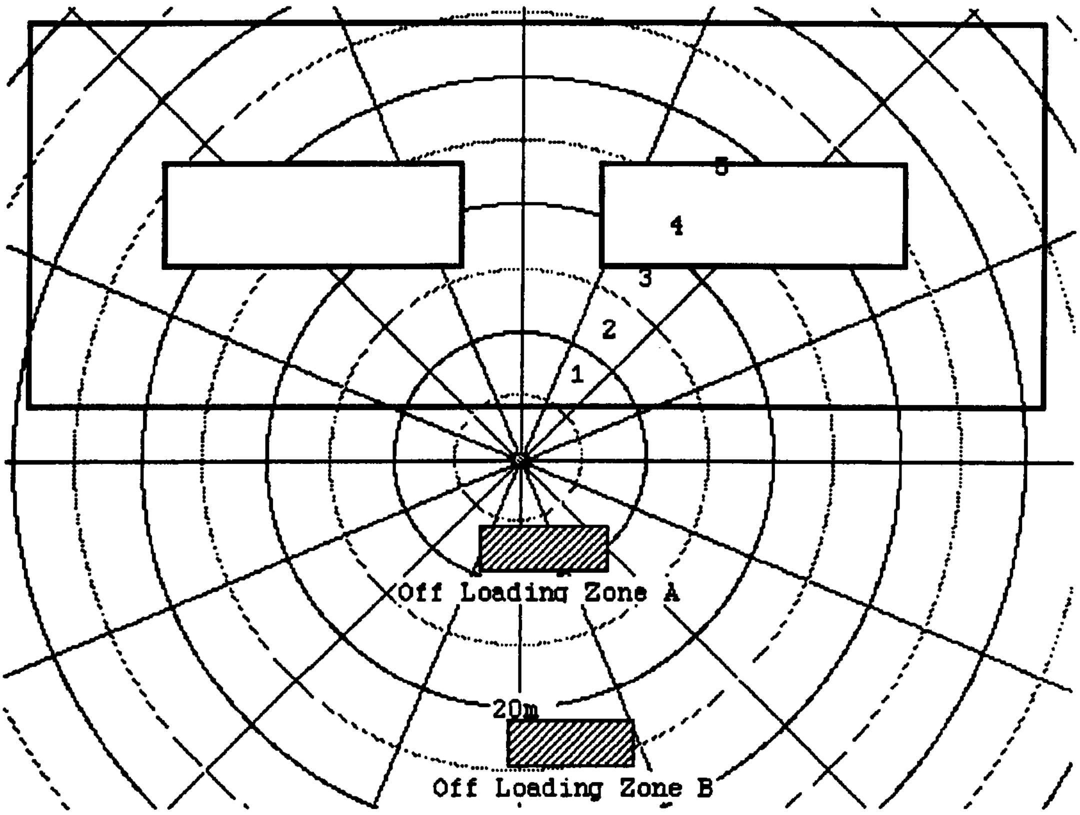


Figure 7-6: Tower Crane Location Example 4



It is notable that in example four, moving the off loading location towards the building actually increased the average trolley requirements significantly. These different locations are noted in Figure 7-6 as A (closer to the building) and B. This analysis takes no account of the limitations imposed on tower cranes by over swing rights, or the speed limits required on the object being moved[2].

Table 7-14: Summary Of Slewing and Trolleying

Example	Average Slew (°)	Average Trolley (m)
1	84.6	10.2
2	85.9	17.2
3	53.5	10.1
4a	134.9	23.1
4b	134.9	11.5

Table 7-14 provides a summary of the calculated average horizontal movements. Example 3 shows the least movement requirements for both slewing and trolleying. This makes no allowance for the fact that for much of the time when off loading the crane driver would be unable to see the hook. In normal circumstances an operative would be employed to

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[2] The further out along the jib an object is, the greater will be the speed with which it moves during slewing. For a crane slewing at 0.9sl/min (slews per minute) an object held at 60m from centre will be travelling at 7m/s while one held at 10m will be travelling at 1.2m/s.

work with the crane to fasten loads (a 'banksman') and this person would direct the crane movements. The movement energy is calculated in conjunction with the hoisting required.

7.1.5.2 Crane Operation Speeds

The distances calculated in the previous section must be used in conjunction with movement speeds and motor ratings, to allow calculation of energy used.

Each of the three movements types analysed uses a dedicated motor and each of these has a range of speeds. The hoist and trolley motors have a quoted range of speeds for each gear ratio. The slew rate is expressed simply as complete rotations (360°) per minute. The hoist motor speed is mainly determined by the load being lifted. The movement rates are shown in Table 7-12. Each movement generally consists of a short period of low speed, then acceleration, top speed, deceleration and then stop, however for shorter movements the crane may not reach full speed. When hoisting and lowering, the area designated for clearance would usually be travelled at low speed for safety reasons. To make the calculation for speed, quoted movement rates have been assessed in conjunction with the crane movements observed on site.

7.1.5.2.1 Slewing

The calculations for slewing speed have been made using the information provided in Table 7-15. There are three elements to the slewing movement - initial acceleration, steady movement and deceleration. From on site observation the acceleration was observed to be around 3 seconds and the deceleration a slightly shorter time. These were observed on the slower crane, so the times for the faster crane have been assumed to be slightly higher. These times have been converted into the number of degrees travelled during acceleration (and deceleration). When these times and angles are subtracted from the total arc required, they leave the element which will be travelled at full speed. There are two 'legs' to each movement in this assessment, out and return. Although many movements around site will be point to point, for the purposes of off loading activities, the movement is circular. The motor load will be different for the out and return leg, with more power being required when the crane is loaded and the actual energy required will depend on the load being moved. Since the two legs are equal in length, an average value can be used. For a point to point movement the higher value should be used.

The results for this analysis for both cranes are shown in Table 7-16 and the values for each are very similar. The smaller crane actually has the faster movement rate, while the quoted engine rating is the same for each which is probably to limit the speed with which heavier loads can be moved.

Table 7-15: Details For Crane Slewing

	154EC-H6	280EC-H	
Motor Rating	2.5	2.5	kW
Slew Rate	0.9	0.7	sl./min
Max. Slew Rate	324	252	°/min
Acceleration Time	4	3	sec.
Deceleration Time	3	2	sec.
Acceleration Degree	12	9	°
Deceleration Degree	9	6	°

Table 7-16: Energy For Crane Slewing

	154EC-H6				280 EC-H			
One Way								
Arc (°)	45	90	135	180	45	90	135	180
Accelerating (°)	12	12	12	12	9	9	9	9
Top Speed (°)	24	69	114	159	30	75	120	165
Decelerating (°)	9	9	9	9	6	6	6	6
Time Moving (sec.)	11.4	19.8	28.1	36.4	12.1	22.9	33.6	44.3
Energy (kWh)	0.008	0.014	0.020	0.025	0.008	0.016	0.023	0.031
Two Way								
Energy (kWh)	0.016	0.027	0.039	0.051	0.017	0.032	0.047	0.062

7.1.5.2.2 Trolley

The calculations for the trolley speed have been made in the same way as for slewing. The information used in the calculations is shown in Table 7-17, and the results in Table 7-18. The values are of a similar order to the values for slewing.

Table 7-17: Details For Crane Trolley

	280 EC-H	154 EC-H6	
Top Speed	138	96	m/min
Acceleration	4	3	sec.
Deceleration	3	2	sec.
Motor Rating	3.75	2.75	kW

Table 7-18: Energy For Crane Trolley

	280 EC-H		154 EC-H6	
One Way				
Total Distance (m)	10	20	10	20
Distance Decelerating(m)	4.60	4.60	2.40	2.40
Distance At Top Speed (m)	1.95	11.95	6.00	16.00
Distance Decelerating (m)	3.45	3.45	1.60	1.60
Time Moving (seconds)	11.21	21.21	9.20	19.20
Energy (kWh)	0.012	0.022	0.007	0.015
Two Way				
Energy (kWh)	0.023	0.044	0.014	0.029

7.1.5.2.3 Hoisting

The hoisting energy required will not be affected by the relative location of the crane and building. Table 7-19 shows the basis for the calculations for hoisting energy requirement. The calculation for hoisting is more complicated than for the other movements. The movement is split into several phases - slow speeds near ground, increasing to maximum. Just before the load reaches the level required for horizontal movement it will slow and the lowering of the load will be slower than the accent for safety reasons. Pouring concrete into columns should require less energy than movements to the slab, because of the discharge height. This is offset by the increased movement which would occur between columns unless the volume of concrete required for each was equal to the skip volume.

Table 7-19: Details Of Crane Hoisting

General	Building Height	20	metre
	Floor To Floor Height	4	metre
	Required Clearance	5	metre
	Hoisting Top Speed	100	m/min
	Hoisting Low Speed	10	m/min
Half Cycle	Distance At Low	2.5	metre
	Average Lift	15.0	metre
	Slowing Distance At Lift Top	1.0	metre
	Clearance At High Speed	5.0	metre
	Lift At Full Speed	19.0	metre
	Lift At Slow Speed	6.0	metre
Full Cycle	Lift At Full Speed	38.0	metre
	Lift At Low Speed	12.0	metre
	Time At Slow	1.20	minutes
	Time At Full	0.38	minutes
Hoist Time		1.58	Min/Cycle

Table 7-20 shows the energy requirements for the cranes for three heights of building. These results are an order of magnitude above the energy for other movements. There is also a great difference between the energy requirements for each motor. The calculation has been made for the average hoisting requirement. This is why the average energy for the different building heights varies so little for each crane, although larger buildings will require more energy in total.

Table 7-20: Average Energy Of Crane Hoisting

Building Height m	154 EC-H6 kWh	280 EC-H kWh
8	0.46	0.79
20	0.49	0.86
40	0.56	0.96

The total energy requirement for each movement type are totalled in Table 7-21.

	Best Case	154 EC-H6	280 EC-H	Worst Case	154 EC-H6	280 EC-H
nce (m)	10	0.014	0.023	23	0.034	0.050
)	53	0.018	0.020	135	0.039	0.047
ing Height (m)	20	0.494	0.856	20	0.494	0.856
red Total (kWh)		0.512	0.875		0.533	0.902
red Total (MJ)		1.843	3.150		1.912	3.247
y Total (MJ)		5.013	8.568		5.201	8.832
y Total (GJ)		0.005	0.009		0.005	0.009

nergy requirement is shown for both the best and worst cases calculated for crane oning and use the hoist values for the 20m case. This table illustrates a number of . The hoist energy is the major component of the total energy being between 93 - f the total. The proportion for the 154 EC-H6 is lower than for the 280 EC-H due smaller motor on this model. Clearly the energy use for the larger model is based assumption that larger loads would be lifted. The effect of lifting the same load h the same movement with different motor sizes is not known. In spite of this, it is le that over sizing of the motor could have an effect on energy requirement.

3 Tower Crane Energy

e tower cranes examined in this analysis will require significant transportation. h the 280 EC-H requires tower and jib members which are both larger in section vier than for the 154 EC-H6, there is unlikely to be any difference in the vehicles d and thus the fuel consumption of the transportation would be similar. viest section requiring lifting is, for both cranes, the slewing platform and cab, n some configurations is heavier for the smaller crane! The mobile crane ent has been taken for a medium model, as previously defined in Table 7-9.

odied energy for each tower crane has been calculated (Table 7-22) for on with the erection energy. This calculation was carried out by simply adding l weight for all the sections in each crane. Of the total weight for each crane the s steel and where other materials have been used, they are assumed to have the odied energy as steel. The calculations have been made assuming a crane life of nd 50 weeks of use on each site. The steel calculations are made using an energy figure of 26.8 GJ/t and embodied CO_2 of 2030 kg/t (Table 5-6). he energy required for tower crane fabrication is not known, a figure was or structural steel fabrication and this is similar enough in nature to provide a e relative levels for energy. The calculation of the fabrication energy is detailed .3.4.

Table 7-21: Environmental Impacts: Crane (One Cycle)

	Best Case	154 EC-H6	280 EC-H	Worst Case	154 EC-H6	280 EC-H
Distance (m)	10	0.014	0.023	23	0.034	0.050
Arc (°)	53	0.018	0.020	135	0.039	0.047
Building Height (m)	20	0.494	0.856	20	0.494	0.856
Delivered Total (kWh)		0.512	0.875		0.533	0.902
Delivered Total (MJ)		1.843	3.150		1.912	3.247
Primary Total (MJ)		5.013	8.568		5.201	8.832
Primary Total (GJ)		0.005	0.009		0.005	0.009

The energy requirement is shown for both the best and worst cases calculated for crane positioning and use the hoist values for the 20m case. This table illustrates a number of points. The hoist energy is the major component of the total energy being between 93 - 96% of the total. The proportion for the 154 EC-H6 is lower than for the 280 EC-H due to the smaller motor on this model. Clearly the energy use for the larger model is based on the assumption that larger loads would be lifted. The effect of lifting the same load through the same movement with different motor sizes is not known. In spite of this, it is probable that over sizing of the motor could have an effect on energy requirement.

7.1.5.3 Tower Crane Energy

Both the tower cranes examined in this analysis will require significant transportation. Although the 280 EC-H requires tower and jib members which are both larger in section and heavier than for the 154 EC-H6, there is unlikely to be any difference in the vehicles employed and thus the fuel consumption of the transportation would be similar.

The heaviest section requiring lifting is, for both cranes, the slewing platform and cab, which in some configurations is heavier for the smaller crane! The mobile crane requirement has been taken for a medium model, as previously defined in Table 7-9.

The embodied energy for each tower crane has been calculated (Table 7-22) for comparison with the erection energy. This calculation was carried out by simply adding the quoted weight for all the sections in each crane. Of the total weight for each crane the majority is steel and where other materials have been used, they are assumed to have the same embodied energy as steel. The calculations have been made assuming a crane life of 30 years and 50 weeks of use on each site. The steel calculations are made using an embodied energy figure of 26.8 GJ/t and embodied CO_2 of 2030 kg/t (Table 5-6). Although the energy required for tower crane fabrication is not known, a figure was available for structural steel fabrication and this is similar enough in nature to provide a guide to the relative levels for energy. The calculation of the fabrication energy is detailed in section 7.3.4.

Table 7-22: Tower Crane Embodied Energy

		154 EC-H6	280 EC-H
Weights (kg)	Slewing Platform	8910	10120
	Tower Head		2340
	Tower	18500	22600
	Jib	6370	9950
	Jib Heal	2850	7400
	Jib Head	500	280
	Hoist Unit	3230	4100
	Trolley And Hook	915	1150
	Total (kg)	41275	57940
	Total (t)	41.3	57.9
		GJ	kg
Assumed Figures	Steel Energy	26.8	2030
	Fabrication Energy	1.0	53
	Total	27.8	2083
Energy	Total (GJ)	1147	1611
	Energy (GJ/year)	38.2	53.7
CO_2	Total (kg)	85976	120689
	Energy (kg/year)	2866	4023

The erection energy for both cranes is shown in Table 7-23 and Table 7-24 while the cost for dismantling is assumed to be the same.

Table 7-23: Environmental Impacts: Crane Erection 154 EC-H6

Tower Crane Erection 154 EC-H6 Primary Energy	Embodied Energy (GJ/erection)	Embodied CO_2 (kg/erection)	Transportation Distance (miles/erection)	Transportation Time (hours/erection)
Mobile Crane (1 day)	9.216	605.43	100.00	2.86
Transportation	79.160	5200.00	4000.00	96.39
Total	88.376	5805.43	4100.00	99.24

Table 7-24: Environmental Impacts: Crane Erection 280 EC-H

Tower Crane Erection 280 EC-H Primary Energy	Embodied Energy (GJ/erection)	Embodied CO_2 (kg/erection)	Transportation Distance (miles/erection)	Transportation Time (hours/erection)
Mobile Crane (1 day)	9.216	605.43	100.00	2.86
Transportation	93.453	6138.89	4250.00	102.41
Total	102.669	6744.32	4350.00	105.27

While the energy for erection is similar for both cranes, the embodied energy for each reveals larger differences. The relationship between the erection and embodied energy will depend on the number of sites the cranes are installed on and the life span, but represents a significant proportion of the total.

Table 7-25 shows the total energy for each tower crane excluding the operation. The calculations are based on a six month cycle of site use. The tower crane is the only item where the embodied energy has been included in the calculation (although an estimate has been made for quarried aggregates, it was for example only and thus not used in the building calculations). This has been done for two reasons, firstly because the tower crane is relatively simple compared with other plant and an estimate for fabrication energy was available and secondly, the tower crane is used on all types of site so there is little danger of biasing overall results.

Table 7-25: Environmental Impacts: Crane Erection and Transportation

Tower Crane Primary Energy	Embodied Energy (GJ/erection)	Embodied CO_2 (kg/erection)	Transportation Distance (miles/erection)	Transportation Time (hours/erection)
154 EC-H6	126.625	8671.29	4100.00	99.24
280 EC-H	156.360	10767.28	4350.00	105.27

To estimate the effect of the transportation and erection it is necessary to estimate the length of time the crane is on site, the percentage of work which is frame related and how many lifts per day the crane performs. On site observation suggested that a figure of around two minutes should be allowed for hooking and unhooking (although the maximum rates for these actions is significantly lower, there are also periods when no actions occur for long periods). The calculations for the average movement time suggest that 150 seconds should be allowed, based on a 16m tall building. This gives a total time per movement of 6.5 minutes, which allows 83 actions per nine hour day and 457 for a 5.5 day week. There are 50 working weeks per year which gives a total of around 23000 movements. The figures in Table 7-28 have been divided by this number to give the figure per cycle.

Table 7-26: Environmental Impacts: Crane Total 154 EC-H6

Tower Crane 154 EC-H6	Embodied Energy (GJ/cycle)	Embodied CO_2 (kg/cycle)	Transportation Distance (miles/cycle)	Transportation Time (hours/cycle)
Operation	0.005	0.281		
Embodied	0.002	0.125		
Trans & Erection	0.004	0.228	0.18	0.004
Dismantling & Trans	0.004	0.228	0.18	0.004
Total	0.015	0.862	0.36	0.009

Table 7-27: Environmental Impacts: Crane Total 280 EC-H

Tower Crane 280 EC-H	Embodied Energy (GJ/cycle)	Embodied CO_2 (kg/cycle)	Transportation Distance (miles/cycle)	Transportation Time (hours/cycle)
Operation	0.009	0.480		
Embodied	0.002	0.176		
Trans & Erection	0.004	0.295	0.19	0.005
Dismantling & Trans	0.004	0.295	0.19	0.005
Total	0.019	1.247	0.38	0.009

In this analysis the operational energy is of a similar order to the erection, transportation and embodied energy, however for a smaller crane the difference would be greater. Changing the period on site from one year will clearly have an effect on this balance.

7.1.6 Excavation

The rate required for excavation will vary depending on the site, the materials to be moved and the equipment employed. To get a basic assessment of the rates, a simple excavation contract was examined.

The site was in Sheffield and required a quantity of approximately 1960m^3 of earth moved to a site 9.7 miles away. A single excavator was used for excavation, with the transportation being performed by 6 tipper trucks. These averaged 15 miles per hour and 6 trips per day. The material was deposited at a site operated by the contractor, however, in other cases material would be taken either to a landfill site or to a depot for storage until required. At the place of disposal a second machine was used to distribute materials.

The contract took nearly 5 days to carry out, which was regarded as slightly better than average. The period required would have been increased if the material was harder to excavate. The equipment was left on site overnight, but an allowance has been made of delivery of the plant to site and removal at the end.

Table 7-28 shows the energy calculations both with and without transportation. The majority of transportation impact occurs when moving the earth away from site, although there is a small element for delivery and removal of the plant to the site. If there was no machine at the point of disposal then the energy excluding transportation would be reduced by around a significant amount.

Table 7-28: Environmental Impacts: Excavation

Excavation	Embodied Energy (GJ/m^3)	Embodied CO_2 (kg/ m^3)	Transportation Distance (miles/ m^3)	Transportation Time (hours/ m^3)
Plant To Site	0.001	0.05	0.04	0.003
Excavator (x2)	0.040	2.65		
Transportation	0.034	2.23	1.76	0.118
Total	0.075	4.93	1.80	0.120

7.1.7 Waste Disposal

Although the majority of waste disposal from frame materials occurs during the demolition phase, there is inevitably some during the construction phases which will be dealt with using skips.

Skip hire firms can function as recycling centres transporting waste materials back to a central depot, from where sorting can occur. The local company that provided the data for this study did this using a fleet of 11 skip wagons to service over 100 individual skips. The waste is returned to a central point where high value items are removed by hand and other material split into two streams, active and inert. The inert stream contains the concrete and brick waste which is taken to a waste site and can be recycled. There was no difference in the disposal charges made whether the waste was recycled or not.

Table 7-29 shows the fuel consumption of medium and large skip wagons and the larger tipper trucks that move waste from the skip depot to the quarry.

Table 7-29: Waste Removal By Skip And Lorry

	Average Speed (MPH)	Average (MPG)
Skip Removal		
16t Truck	22	12.1
7.5t Truck	24	13.0
Tipper Truck Removal		
31t Tipper	23	8.2
24t Tipper	23	9.6

Table 7-30: Environmental Impacts: Waste Removal By Skip

Waste Removal	Embodied Energy (GJ/t)	Embodied CO_2 (kg/ t)	Transportation Distance (miles/t)	Transportation Time (hours/t)
Transport From Site	0.080	5.25	4.89	0.222
Sorting	0.006	0.41		
Basic (Transfer Station)	0.000	0.01		
Office (Transfer Station)	0.000	0.02		
Move To Landfill	0.022	1.44	1.00	0.043
Basic (Landfill)	0.000	0.00		
Office (Landfill)	0.000	0.02		
Total	0.109	7.15	5.89	0.266

7.1.8 Small Plant Items

There are several small, but potentially significant, sources of power consumption. Compressors are used in a number of situations, for example to run breakers and drills. Use of these might be expected to occur more in a concrete than in a steel frame because there are more potential uses. Given the relatively high rates of fuel consumption (more than some small skid steer excavators for example), compressors have been included.

The analysis for small items excludes any transportation distance because they will usually be hired locally and stay on site for some time. There are many other small items of plant, for example grinders and power saws, which have been considered to use too little energy to be considered in the overall analysis. Table 7-31 shows the environmental impacts for small items.

Table 7-31: Environmental Impacts: Small Items

Compressor	Embodied Energy (GJ/hour)	Embodied CO_2 (kg/ hour)	Transportation Distance (miles/hour)	Transportation Time (hours/hour)
Compressor (CFM 70)	0.178	11.72		
Compressor (CFM 145)	0.326	21.45		
Weldmaker (KVA 2)	0.065	4.29		
Weldmaker (KVA 4)	0.118	7.72		

7.2 Concrete Design And Construction

7.2.1 General Principles

The processes in producing concrete involve a wider number of companies and individuals than for steel production. Whether this will result in higher energy cost will depend on the actual values for each of these items. The data included in this section includes aggregates, concrete specific items of plant such as truckmixers and concrete pumps. All the items shown in the process diagram (Figure 6-2) have been considered in calculating the embodied energy requirement for concrete.

7.2.2 Design

The design energy cost will depend on the type of structure and the depth of design work required. This figure should also include an element for both architectural and structural design time and the energy to travel to meetings and in supervision. This information is not available in any detail, and so no evaluation has been made.

7.2.3 Quarrying And Recycling Operations

Quarrying and recycling, while at opposite ends of the life of a concrete building life cycle, can be closely linked - recycled demolition material may replace newly claimed aggregates in some cases and the plant used in this processing is very similar. A quarry in Yorkshire, the BFI at Barnsdale Bar (see Figure 7-7), was used for the data calculations but other quarries were visited to get a better idea of the range available.

Quarrying represents one of the most visible faces of environmental damage, generating large quantities of traffic and causing scars on the landscape. Equally, without the aggregates thus generated, the possibilities for construction would be extremely reduced -

aggregates, either as concrete or fill material are one of the most basic materials in building.

7.2.3.1 General Issues

The Barnsdale Bar quarry is used for both extraction of materials, as a landfill site and a small amount of recycling. Figure 7-7 shows these operations occurring in a relatively small space, with landfill in the foreground, materials recycling in the middle distance and quarry at the rear. The multi purpose use of a site for a number of operations is not possible in all situations, but where it can be carried out represents a good attempt to minimise environmental impact.

The use of a quarry as a recycling centre for inert materials, such as concrete, rather than using on site operations may be an environmentally sound option in some cases. The figures which must be balanced are the energy cost of moving the materials to the recycling centre and the ease of disposal once screening has taken place. If a use can be found for resultant recycled materials more conveniently from a static base rather than individual sites, then this operation will make sense. This was the case at BFI, with some of the recycled material being used to provide the lining for the 'waste cells'[3]. The BFI site is adjacent to the A1M motorway and away from any major housing site, limiting the 'additional' environmental damage. In spite of this the best method of recycling materials will probably be to do so on the site where waste was created. The reasons for this are as follows -

1) To limit the contamination of the waste streams that may occur (the possibility of recycling concrete and brick waste as aggregate is much more limited if the waste is contaminated with soil or organic materials) The quantity of these contaminants need not be very high to place doubt on the quality of the finished product and the extra screening required to eliminate this taint might well double the energy cost.

2) To limit the traffic generated by moving materials. This involves placing the materials in wagons, transportation to the recycling point, dumping of materials to a store, rehandling materials to crusher and screen and removal to store before transportation to site of reuse. When on site recycling occurs, demolished materials can often simply be moved by excavator to the crusher and processed directly. In addition, if reuse is to be on the same site that generated the waste, transportation is minimal.

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[3] As required by current legislation, water must be prevented from flowing through waste material. A Cell is formed by placing impervious materials as a 'bed' for waste. The cells "walls" are then raised ahead of the waste disposal.

7.2.3.2 Plant requirements

The BFI quarry is relatively small and has a limited range of plant and equipment. Table 7-32 shows the energy required in the process used to produce new aggregates. The energy calculations are based on a calculated daily average - the expected quantity of materials moved in one full working day.

Figure 7-7: Barnsdale Bar Quarry & Land Fill Site

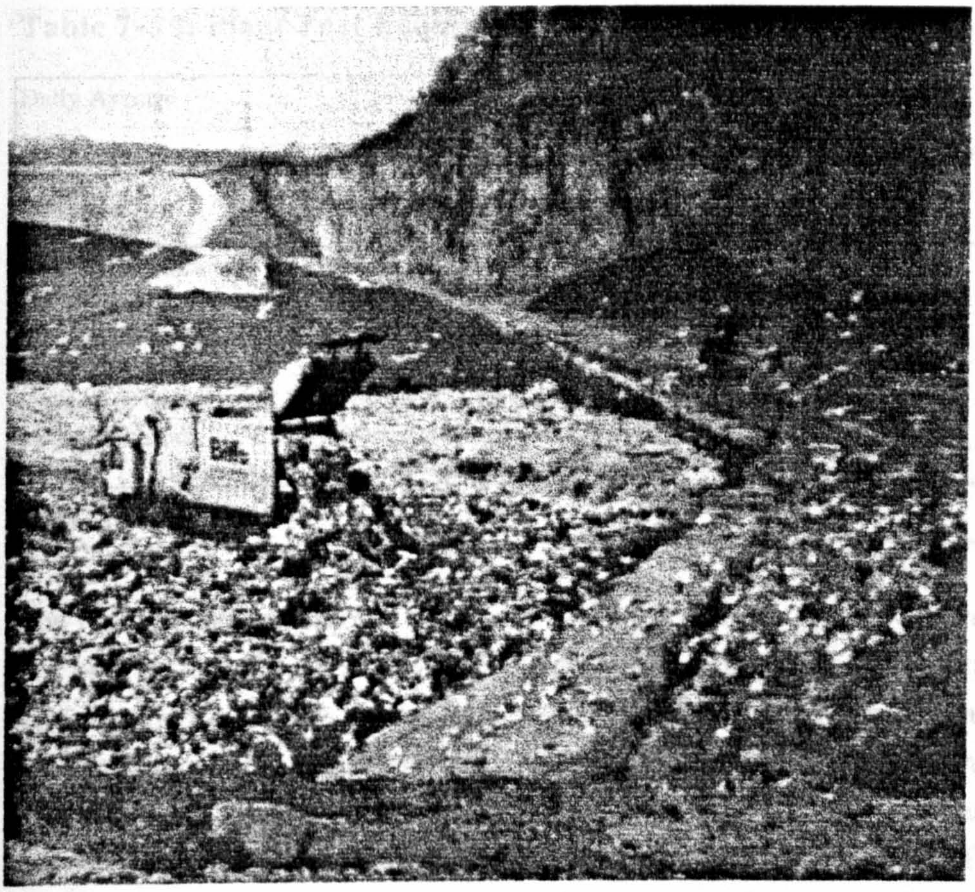
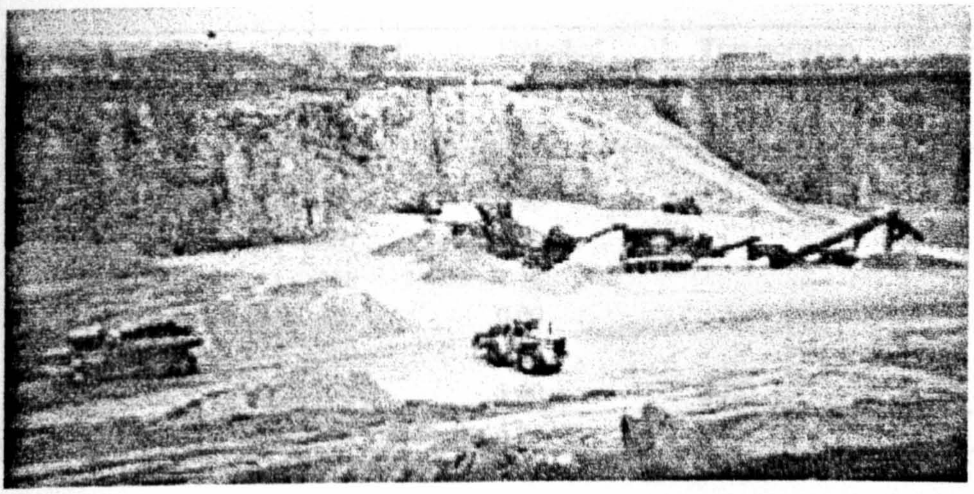


Figure 7-8: BFI New Materials Processing



The averages shown - 1200 tonnes per day for new aggregate was calculated over one year's operation, however the fuel consumption is based on daily plant refuelling records over one month.All the major items of plant used in processing new aggregate materials are shown in Figure 7-8. An allowance was also made for the explosive energy requirement, as calculated by MacSporran et al (5), however the transportation fuel energy requirement has been considered as zero due to the small quantities involved.

Table 7-32: Plant Fuel Requirements - New Aggregates BFI

Daily Average		Average Material	Average Diesel	Fuel /Tonne
Operation	Plant	(t)	(lt.)	(lt./t)
Drilling & Blasting		1200	0	0.00
Loaded Into Tipper	Wheel Loading Shovel	1200	100	0.08
Moved To Crusher	Tipper	1200	200	0.17
Loaded Into Crusher	Wheel Loading Shovel	1200	100	0.08
Crushed & Graded	Crusher & 3 Screens	1200	500	0.42
Moved To Stock	Wheel Loading Shovel	1200	100	0.08
Loading To Transport	Wheel Loading Shovel	1200	100	0.08
Total				0.83

The fuel requirements shown have been converted into energy and CO_2 values. To this has been added values for the office energy requirement and the transportation energy. These components form the basis of the energy value which has been used for both concrete aggregates and fill aggregates. The requirement for washing the crushed material before it can be used for concrete has been taken as zero. To further illustrate the additive nature of energy calculations values for both the embodied energy of plant and a component for operatives travelling to site have been made to assess how these compare with the basic figure.

Table 7-33: Environmental Impacts: New Aggregates

BFI New Aggregates	Embodied Energy	Embodied CO_2	Transportation Distance	Transportation Time
Primary Energy	(GJ/t)	(kg/t)	(miles/t)	(hours/t)
Explosive	0.001	0.00		
Wheeled Loader (x4)	0.015	0.95		
Tipper	0.007	0.48		
Crusher And Screens	0.018	1.19		
Basic (Landfill)	0.000	0.00		
Office (Landfill)	0.000	0.02		
Transportation	0.052	3.40	2.35	0.118
Total	0.093	6.04	2.35	0.118

For these calculations a round trip distance of 40 miles at an average speed of 20 MPH for lorries carrying 17 tonne loads at an energy cost of 9 MPG has been assumed. The transportation component will vary depending on the relative location of the site and quarry, but in this case was found to be more than half of the energy total.

The calculated figure for new aggregate is in the middle of suggested values. The BRE quote a range of 0.02 - 1.0 GJ/t (Table 4-4), and MacSporran (Table 4-1) suggested a value of 0.054 GJ/t. The Oxford Brookes (Table 5-6) study quotes a value of 0.28 GJ/t (primary), of which 0.1 GJ/t is transportation, for hardcore. The estimate for CO_2 is 15.8 kg/t. The distances and the fuel consumption are both different than those used in other calculations and has a major impact on the values.

The MacSporran analysis goes further than simple calculation of plant fuel and transportation. It also includes the embodied energy for the plant, both on site and transportation, including an estimate for maintenance. No estimate was made for the fabrication costs of plant. This analysis found that the combined embodied energy for plant was 0.0089 GJ/t, which gave a total energy of 0.063 GJ/t. The plant embodied energy was therefore around 14% of the total.

For this thesis there was an initial desire to extend the calculations further than this to include two extra factors - the fabrication energy for plant and offices and the operatives transportation energy. As already noted, it was not possible to find fabrication energy for either plant or mobile offices, however information was gained for the travel to site for operatives, and this is shown in Table 7-33. The values for time taken were calculated over a one week period. It was not possible to get figures for fuel consumption for the cars involved, so these calculations assume an average fuel consumption of 35 MPG.

Table 7-34: BFI Travel To Site

Method	People In Car	Distance (2 Way) Miles	Time (2 Way) Minutes	Average Speed MPH
Car	2	60	70	51
Car	1	48	70	41
Car	1	10	14	43
Car	3	50	54	56
Car	1	4	10	24
Car	1	20	40	30
Car	1	24	52	28
Car	1	44	70	38
Car	1	46	80	35
Car	1	36	110	20
Car	1	8	14	34
	14	350	584	399

The variation in average speed is due to the possible routes which can be used to assess the site - faster times were recorded for travel along the A1M than travel over minor roads. No significant traffic jams occurred during this period and travel times were all within ±5 minutes. This calculation can be made with much more certainty than can the assessment of plant embodied energy because it can be directly measured and makes use of information already available.

A second extension of the data was made for the embodied energy of the plant involved in the processes. This was undertaken as per the analysis by MacSporran, but with the calculations localised for the BFI. The embodied energy for steel was taken as 35 GJ/t (primary) and the CO_2 2698 kg/t, which are from the Oxford Brookes work (Table 5-6). This value is lower by 4 GJ/t than the value used in the MacSporran analysis. The total weight of machine has been assumed to be steel and the initial machine weight has been used to calculate both the maintenance and refurbishment requirement. The maintenance figures have been calculated simply on the basis of a set percentage of the initial weight of steel at set points and takes place every year except on years when refurbishment is carried out. The calculations have been made for both the site plant and road vehicles and are shown in Table 7-35. The extended total aggregate impact, including both operative travel and plant embodied energy is shown in Table 7-36.

Table 7-35: Plant Embodied Energy

Item Of Plant	Site Plant Crusher	 Tipper	 Loading	Transport	Total
Number	1	1	4	1	
Total Weight (t)	48	21	40	16	
Expected Life (years)	30	15	14	15	
Refurbishment Cycle (years)	5	3	7	3	
Refurbishment Rate	25%	30%	15%	20%	
Requirement	48	19	0	10	
Annual Maintenance	10%	5%	2%	5%	
Requirement	125	13	11	10	
Total Tonnage	221	53	51	35	
Steel/Year	7.4	3.5	3.7	2.3	
Annual Materials Handled	400000	400000	400000	21216	
Steel/Tonne	0.000018	0.000009	0.000009	0.000111	0.000147
Steel Energy	35		Energy	GJ/t	0.005
Steel CO_2	2698		CO_2	kg/t	0.40

Table 7-36: Environmental Impacts: New Aggregate (Extended)

New Aggregates BFI, Extended	Embodied Energy (GJ/t)	Embodied CO_2 (kg/t)	Transportation Distance (miles/t)	Transportation Time (hours/t)
Plant	0.041	2.62		
Office	0.000	0.02		
Transportation	0.052	3.40	2.35	0.118
Operative Travel	0.001	0.08	0.22	0.006
Embodied	0.005	0.40		
Total	0.099	6.51	2.57	0.124
% Increase From Basic	107%	108%	109%	105%

The increase from the basic to the extended calculation ranges from 5 - 9%. The transportation results should be regarded with caution because the figures for materials and operative travel use different vehicle types and could be viewed as being not strictly comparable. In this case the figures have been aggregated to contrast with the standard data set and are not used for calculations. Clearly the increases are significant, especially when it is remembered that these are values per tonne. The plant fabrication impacts might be expected to be significant given the complexity involved in manufacture. All these values could be expected to vary with different sites.

The largest contributor in both cases is the on site plant energy at around two thirds of the total. The direct transportation energy is around 21% but this would fluctuate with each quarry and site combination. The BFI site is quite isolated and consequently the travel distances are relatively high. The office energy makes a significant contribution, with the plant embodied and operative travel contributing approximately 3% between them (although the operative travel element contributes significant amounts to the traffic figures, which is not represented by these figures). Other elements for which no calculation has yet been made may add to the total. Based on these results, the most important aspect to study further is the plant, both in terms of fuel use and fabrication costs.

The relative contributions from each of these elements to embodied energy and CO_2 are shown in Figure 7-9.

7.2.4 Concrete Batching

The input values for the aggregates can be determined from the data in the preceding section, when added to the average transportation values. The value for cement is a secondary item.

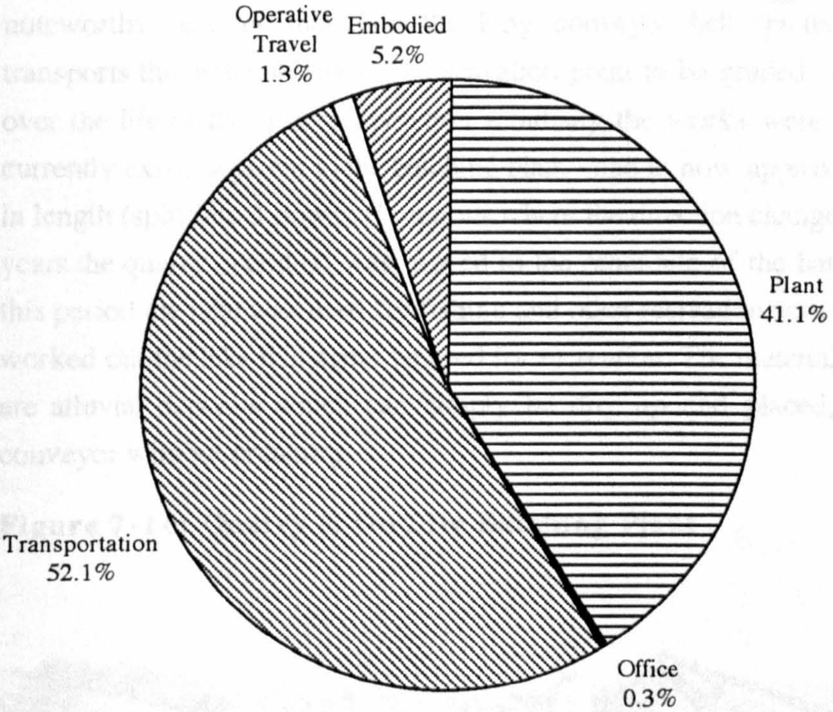
The energy values for batched concrete require the material value to be added to that for batching, any plant required (usually only a single wheeled shovel), the office overhead and the truckmixer for transport to site. A truckmixer is designed to keep the wet concrete agitated during transportation but can be used for primary mixing purposes.

7.2.4.1 Ready Mixed Batching Plants

Batching plants can be situated at a wide range of locations and the method of transportation of raw materials to site will depend on this. In a small number of cases plants are located either at a quarry site, or where marine aggregates are used, at the wharf and where this is the case the aggregates will have a lower transportation energy cost. In many cases plants are located in built up areas, with a view to being close to the potential market. However, in these cases the plants are of necessity small and with limited expansion capacity. Rural plants will generally be able to cope better with expansion, but suffer from being further from sites.

Figure 7-9: Contributions To Embodied Energy And CO_2

Contribution To Aggregate Embodied Energy



Contribution To Aggregate Carbon Dioxide

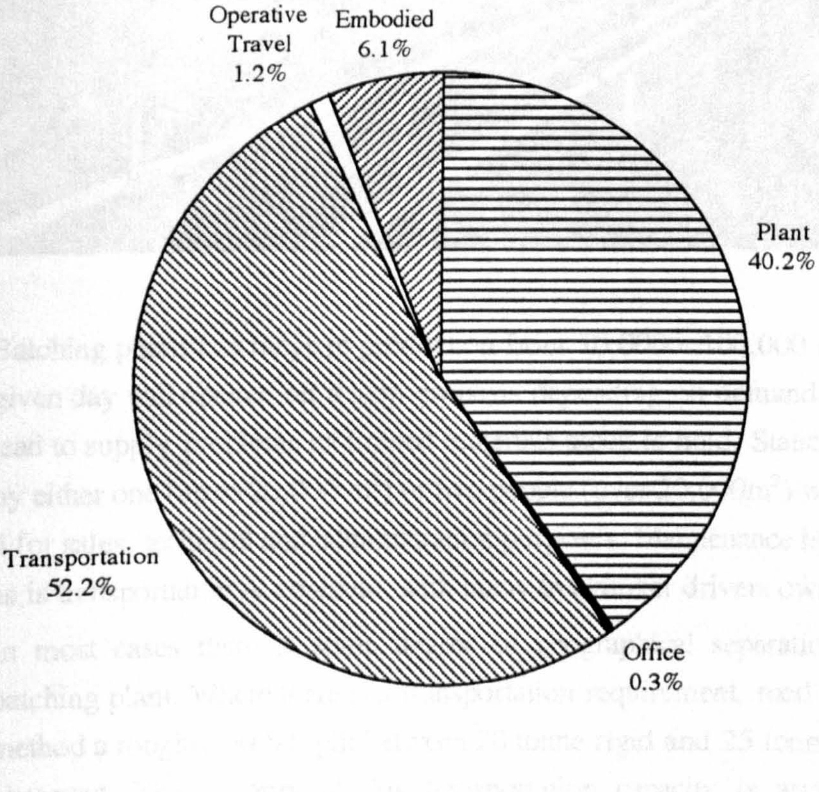
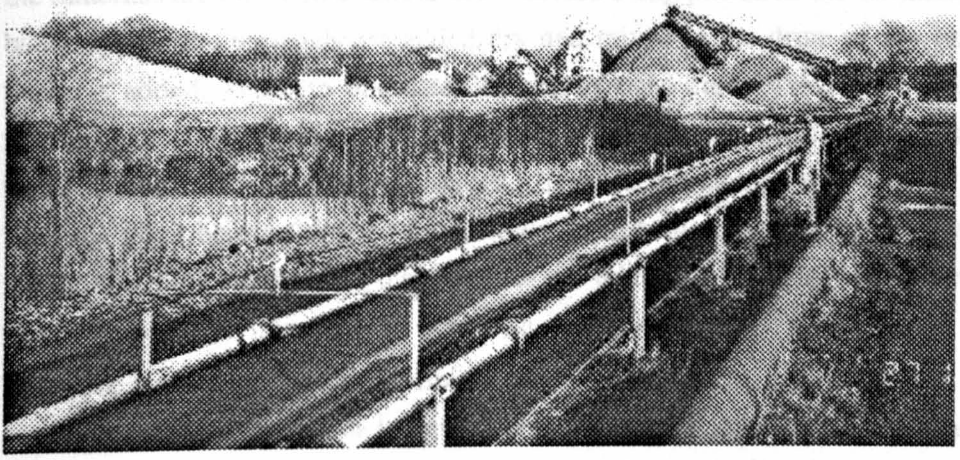


Figure 7-10 shows a quarry with on site batching plant. This site is in open country, but only four miles from the local town centre. The plant also has a number of other noteworthy features including the long conveyor belt (pictured foreground) which transports the materials from the excavation point to be graded. This belt has lengthened over the life of the quarry operation - initially the works were situated where the lake currently exists adjacent to the batching plant - and is now approximately half a kilometre in length (split into 3 powered sections where the direction changes). For a period of five years the quarry operation was moved to the other site of the batching plant, and during this period the lake was used for fishing and other recreation activities. After the quarry is worked out the lake will again be used for recreation. The materials quarried from this site are alluvial deposits which can simply be dug up and placed, via a hopper, on the conveyor without crushing.

Figure 7-10: Quarry & On Site Batching Plant



Batching plants can range in production from 10,000 - 100,000 m^3 per year, but on any given day will operate on a stop go basis depending on demand. In some cases this can lead to supply problems as limited materials stock is held. Static plants may be operated by either one (up to 20,000 m^3) or two people (over 20,000m^3) with a support staff of 3-4 for sales, technical and administration purposes. Maintenance is generally subcontracted as is transportation of concrete, with many truckmixer drivers owning their own vehicle.

In most cases there is some degree of geographical separation between quarry and batching plant. Where there is a transportation requirement, road haulage is the preferred method a roughly 50/50 split between 20 tonne rigid and 25 tonne articulated lorries was observed. The majority of this transportation capacity is arranged by the materials supplier, although some may be provided by the concrete producer.

Once on site, aggregate can either be placed directly in a holding silo from where it can be directly used for concrete production or placed in a stock pile for use as an emergency back up. The preferred method is to place materials immediately in a silo because this reduces the amount of double handling required. This may not be possible in all cases depending on a number of factors including

- The capacity of the silos for each type of aggregate (i.e. the plant size and capacity). This is generally limited to about 20 tonne each.
- The 'call off' of concrete by the end user
- The scheduling of materials delivery to the batching plant

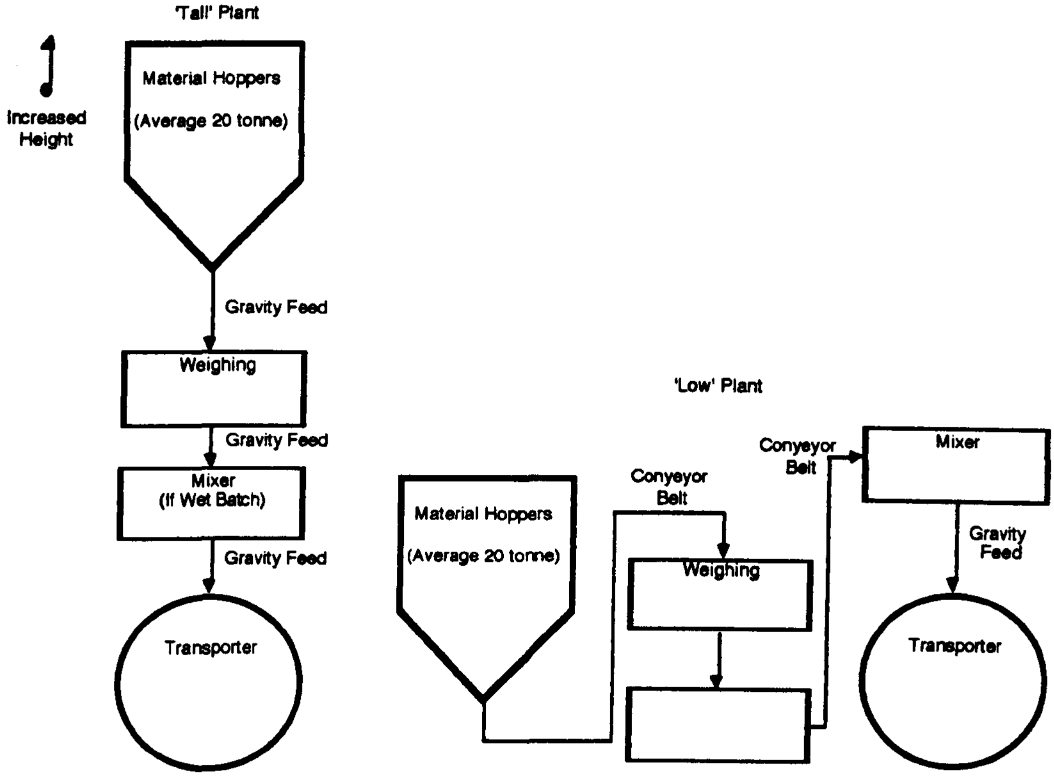
Cement is delivered in sealed silos directly from the manufacturer. The range of materials held on site will depend on the plant and demand from end users, but is generally limited to 20 mm and fine aggregate, OPC and GGBS. This basic mix of materials can be augmented in a number of ways, for example by adding 10 mm aggregate. A limited number of plants may have facilities for heating the mix water in cold weather. This will add to the energy requirement for the concrete, but is only used in a limited number of cases.

There are many possible batching plant configurations depending on the situation and plant output. There are two basic mixer types - wet and dry batch. In a wet batch system the materials are mixed in a central drum before being placed in the truckmixer. For a dry batch system the materials are added dry and mixed in the drum of the truckmixer after water is added. Where a dry batch system is used care is required to ensure that the materials are correctly mixed before placing given that, depending on mix, it may take up to 10 minutes to fully mix the material. It is recommended that mixing occurs at the batching plant before transportation, however in some cases the truckmixer may set out for the site immediately after the materials are added. If the materials are mixed on route an energy saving will accrue, but concrete quality may suffer.

There are also many possible combinations of silo capacity, mixer size, and layout. There are two possible extremes of layout - the high and low configurations. These are shown in Figure 7-11.

The energy requirements between two plants of a similar output capacity will be greater for the low configuration but only by a small amount. The high configuration requires one long conveyor belt to move the materials to the silo, after which they are gravity fed. The low configuration requires two separate belts to do the some job, and although the two smaller motors will be less efficient than one larger one, the actual work done (the weight of materials by the height lifted) is similar. A plant in the tall configuration may produce more dust pollution than a low one, because particles produced at high level will tend to travel further than those at a lower level.

Figure 7-11: Batching Plant Configuration



In urban locations, where there are a number of competing ready mix suppliers, the supplier selected is often determined by the cost rather than distances involved. Concrete for each given specification from different batching plants can be regarded as the same material, so buying from a plant further away from site will increase embodied energy costs without any increase in quality.

7.2.4.2 On Site Batching Plants

There are occasions where a contractor will opt to batch concrete on site rather than use a separate plant. This may only be possible where there is adequate space available. The impact on the energy requirement for concrete will depend on the relative locations of the source materials and the methods of transportation involved.

Even when concrete is batched on site, truckmixers may well be required to move the concrete around the site - if the concrete is pumped a constant supply is required rather than discrete loads of, for example 0.5m^3. Even in situations where the concrete is to be placed by crane, relative positioning of the crane and the plant might necessitate an intermediate movement, although adequate preplanning should avoid this.

Mobile batching plants used on site will normally be of the wet batch variety rather than the dry batch method often found at permanent sites. In addition they will usually be of the low rather than high variety to make transportation easier. The power consumption of mobile plants will be of the same order as that for permanent plants, given that similar equipment is employed. On very large projects, a permanent batching plant with specialist transportation facilities may be built, however this is outside the range of this work.

7.2.4.3 Mix Design

The mix design will have a large effect on the embodied energy of the batched concrete. This is mainly due to the varying proportion of cement, which is the major energy item in concrete. The implication of mix design for the total energy in the building will be tempered by a number of issues - the change in total concrete required for any given change in specification or design, transportation requirements and smaller items such as formwork and placing. Although it is possible to make concrete with characteristic strength[4] ranging from 20 - 80 N/mm^2 with little problem (and higher grades if required), most of the concrete used in the UK falls into two basic bands - low strength blinding (around 20 N/mm^2) and structural grades (30 - 40 N/mm^2) referred to as C20, C30, etc.

It is possible to produce concrete with a given characteristic strength in a number of different ways, depending on the relative proportions of cement, cement replacements, water, aggregate and additives. Generally, a higher slump will require more water and will have a lower strength for any given quantity of cement. There may also be a requirement to produce two different variants on the same strength concrete depending on the method of placement - pumping concrete may require a high cement and fine aggregate content (referred to as pump mixes).

A mix specified as having a characteristic strength of, for example, 40 N/mm^2 may actually perform above that specification so there may be a difference in the environmental impacts of concrete mixes which are ostensibly the same grade. This could occur, for example, when concrete is ordered from ready mix suppliers who over specifies the mix in order to avoid any possibility of failure during testing. The greater the consistency of results, the lower any margins would need to be.

The SEEAM model considers a range of concrete mix designs, shown in Table 7-37, which have been used to illustrate the relative material quantities. These mixes are either actual site mixes or have been designed after discussion with the manufacturers and reference to the relevant literature (6,7). The range of possible combinations for materials is so great that this work can only hope to provide a representative sample and mixes used in any specific instance may well be different.

Of particular interest in energy terms is the use of materials as substitutes for cement in the design. Both PFA and GGBS have significantly lower environmental impacts than cement (see calculations later in this section). The broad effects of these materials, when used as a cement replacement, are shown in Table 7-38. The suggested effects, while correct in general terms, will vary with the situation. PFA has a water reducing effect

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[4] The characteristic strength is the level above which 95% of all cube crushing results will fall

which can either be used to increase strength, by reducing the water content, or as an aid to pumping if the water content is held. PFA is less effective as a cementitious material than GGBS and can not be used in such high quantities. Both materials reduce initial setting time and lower initial strength gain and this may affect striking times. Both materials provide a lower heat gain than cement which is a benefit when heat is a problem, but may be a drawback in cold weather concreting.

The overall environmental impacts for batched and placed concrete are considered in a later section which includes an analysis of the effect of mix design.

Table 7-37: Mix Designs

Mix Name	OPC (kg/m^3)	GGBS (kg/m^3)	PFA (kg/m^3)	Lytag (kg/m^3)	Agg (kg/m^3)	Water (kg/m^3)	Admix (l/m^3)
C20	240				1943	195	
C20 PFA	160		90		1940	190	
C20 GGBS	120	120			1950	190	
C30	295				1880	192	
C30 GGBS	150	150			1900	190	
C30 GGBS Pump	160	155			1895	192	
C30 Lytag	360			800	600	190	
C30 Lytag Fines	360			1275		190	
C30 Lytag GGBS Pump	205	205		670	730	190	1
C30 Lytag PFA	280		130	800	560	190	
C30 Lytag PFA Pump	290		130	620	750	190	1
C30 Lytag Pump	410			600	730	190	1
C30 PFA	210		100		1900	190	
C30 PFA Pump	200	110			1890	192	
C30 Pump	320				1880	192	
C40	340				1812	190	
C40 GGBS	190	190			1814	177	
C40 GGBS Pump	200	200			1830	190	
C40 Lytag	460			800	505	190	
C40 Lytag Fines	460			1175		190	
C40 Lytag GGBS Pump	275	275		640	620	190	1
C40 Lytag PFA	360		160	800	440	190	
C40 Lytag PFA Pump	390		170	640	590	190	1
C40 Lytag Pump	550			600	620	190	1
C40 PFA	240		120		1810	170	
C40 PFA Pump	240	115			1850	190	
C40 Pump	360				1792	190	
C60	470				1780	180	

Table 7-38: Effects of Replacing Cement with PFA or GGBS

	PFA	GGBS
Design Stage		
Cement Substitution	30%*	50%*
Cementitious Action	82% Pozzolanic	100% Pozzolanic, Cementitious
Fresh State		
Setting Time	Increased	Increased
Heat Generation	Reduced	Reduced
Air Entertainment	Reduced (depends on carbon)	
Water	Reduced need (approx 5% lower)	Slight reduction
Pumping	Better for given water content	
Cohesion	Improved	
Hardened State		
Early Strength	Slower gain	Slower gain
Long Term Strength	Equal to OPC	Slightly higher
Permeability	Lowered (if correctly cured)	

* Higher proportions may be used in some situations (80% for GGBS, 40% for PFA), but not normally in concrete used for frames.

7.2.4.4 Waste And Pollution

Wastage during batching is minimal compared to the gross quantities of materials involved. Some waste occurs during washing out of the truckmixer after each delivery and at the end of the day, although this is again small compared with gross volumes. At most plants there is a restriction on disposal of water used for washing out, so generally it is moved through settling tanks and reused as wash out water. In a limited number of more advanced plants, the slurry material can be reused in a new mix, after being stored overnight in the truckmixer, with the cement hydration retarded. This may have an impact on the quality of concrete it is used to produce the next day depending on the grade and type, although it should be generally suitable for lower grades.

Other waste material comes from concrete returned by the site. This is expensive in terms of both energy and money (a return charge of about £75 per m^3 commonly being made). At some plants, usually a central plant with other plants located near by, this material can be separated and reused, with attendant input energy cost, but in most cases disposal is simply by dumping the wet concrete with subsequent breaking up and removal to a tipping site. If is possible the hardened concrete may be broken up and reused as hardcore or aggregate.

Most concrete batching plants have some problems with dust (mainly cement), noise and visual pollution. Dust is the major problem with newer plants having measures such as water sprays and sealed hoppers installed to limit the leakage.

Older plants tend to be of the tall variety with modern sites limited by environmental limits on height - although, as noted above, taller plants tend to be slightly more energy efficient.

7.2.4.5 Energy Figures

As noted in the preceding sections, there is a very wide range of batching plant permutations. In addition each permanent plant will have associated office requirements which can range from a simple cabin for two people, up to a regional office containing sales and technical staff. Since an estimate can be made separately for the office equipment, a mobile batching plant series was selected to perform the energy calculations on. As noted in the previous section, the energy requirements for a mobile plant operation is expected to be similar to a permanent plant of similar capacity and design (low profile). These plants are wet batch and so allow a totally separate consideration of the truckmixer transport energy component. In addition it is simpler to make an assessment of additional equipment, such as testing, quality control or water heating, that may be run along side the plant as they are designed to be modular.

Table 7-39 contains data for a range of batching plants. These are mobile batching plants and so using these figures will allow for comparison to be made between on site against dedicated batching plant in energy terms. The total power (the maximum rated loading) available increases approximately linearly with the increase in output capacity. These motors are designed to handle the peak load condition which occurs at start-up, from where the power draw will fall to around 33% of the maximum. The 120 KVA maximum power for the smallest plant is only double the hoist capacity for the larger tower crane detailed previously.

Table 7-39: Batching Plant Power and Output (8)

Model	Output (m^3/hr)	Aggregate (t)	Total Power KVA
CRM 20	20	10	120
CRM 30	30	15	150
CRM 40	40	15	180
CRM 60	60	25	220
CRM 80	80	30	300
CRM 120	120	50	350

The transportation energy involved in moving a mobile plant has also been considered when it is situated on site. Where the mobile plant energy measurement has been used as a substitute for a permanent plant, the transport energy has been ignored as insignificant over the life of the plant.

Each of the batching plants comes in containers - larger plants will require more containers. For example, the CRM 60 batching plant will require, in the basic configuration, delivery in four containers - two for the main plant (including mixer and aggregate silos), one for ancillary equipment and one for the cement silo. Additional silos will each require one container. These are standard containers and require no special transportation permission.

Table 7-40 has been calculated from the data in Table 7-39. The average power consumption has been assumed to be 33% of the maximum, divided by the output per hour. This was averaged for the whole range of plant which gave an energy consumption of 1.42 kWh/m^3. This includes the energy for the batching plant control booth. An addition for one extra person who is assumed to be controlling quality and supervising production and this has been added at the basic site accommodation rate. The transportation component has been calculated for the CRM 60 model, based on a six month stay on site. The energy for delivery of cement has been calculated separately. The output per half year (15000m^3) has been calculated assuming 50m^3 output per hour for eight hours over two and a half days. This has been used in distribution of the office and transportation cost. The transportation cost is for the plant and equipment rather than for moving concrete.

Table 7-40: Environmental Impacts: Batching (Mobile Configuration)

Batching	Embodied Energy (GJ/m^3)	Embodied CO_2 (kg/m^3)	Transportation Distance (miles/m^3)	Transportation Time (hours/m^3)
Batching Plant	0.014	0.75		
Loading Shovel	0.003	0.22		
Basic Accommodation	0.000	0.01	0.00	0.000
Equipment	0.001	0.06	0.04	0.001
Total	0.018	1.03	0.04	0.001

Table 7-41 details the energy contributions for a static batching plant. The transportation energy is assumed to be distributed over such a large quantity of produced material that it is insignificant. The energy for batching and the loading shovel are assumed to be the same as for the mobile configuration, however the office energy has been increased to take account of the sales and technical staff that would be found on a static site. The total quantity produced per half year has been assumed to be twice that for the mobile plant.

Table 7-41: Environmental Impacts: Batching (Static Configuration)

Batching Primary	Embodied Energy (GJ/m^3)	Embodied CO_2 (kg/m^3)	Transportation Distance (miles/m^3)	Transportation Time (hours/m^3)
Batching Plant	0.014	0.75		
Loading Shovel	0.003	0.22		
Basic Accommodation	0.000	0.03		
Office	0.000	0.02		
Total	0.018	1.01		

The requirements for a static batching are higher than for a mobile plant in spite of the lack of transportation for the plant. This is incurred because of the extra staff required for sales. This analysis takes no account of the on site space requirements needed for a batching plant.

7.2.5 Energy Figures For Materials Other Than Aggregate

The energy figures for aggregates have already been discussed, but other materials are used in production of concrete. The most important of these is cement.

7.2.5.1 Cement

The calculation of an embodied energy value for cement was beyond the scope of this thesis, so data from the BRE (9), which is currently unpublished, has been used and shown in Table 7-42. These values are national figures for both wet and dry cement production processes. The dry process tends to produce cement with a lower embodied energy. The figures ranged from 5.1 - 6.7 GJ/t (primary) which indicates that there has been a considerable improvement in accuracy from the 1994 figures detailed in Table 4-7 which indicated a range of 3.0 - 7.5 GJ/t. This information includes an element for transportation, but the actual breakdown was unavailable, therefore a separate calculation has been made.

Bulk cement transportation occurs in sealed silos which can be linked directly to batching plants and which minimise the handling requirement. The transportation data has been provided by Rugby Cement based on the output for their Barrington works. The total output was around 250000 tonnes of cement and the distribution mileage was 828000. The cement silos contain 25 tonnes maximum and these would normally be transported full. This means a total of 10000 trips made at an average of 82.8 miles (return trip). The average fuel consumption for the lorries involved in this distribution was 7.5 MPG. The values calculated for embodied energy and CO_2 have not been incorporated into the BRE data, but are shown (in brackets) for comparison purposes. These are values calculated for this model and may not be the same as those calculated by the BRE. The transportation time and distance have been included because these elements were not part of the BRE calculation but exclude the raw materials procurement.

Table 7-42: Environmental Impacts: Cement

Cement	Embodied Energy (GJ/t)	Embodied CO_2 (kg/t)	Transportation Distance (miles/t)	Transportation Time (hours/t)
Cement Production	5.800	1193.00		
Transportation	(0.087)	(5.70)	3.29	0.088
Total	5.800	1193.00	3.29	0.088

7.2.5.2 GGBS

GGBS is made from the slag produced during the iron making process. Slag made from steel is not used in this way because of the quantity of heavy metals present. There are a number of uses for this product, but in terms of this thesis the calculation has been made for use as a cement replacement material.

The values shown in Table 7-43 were provided by Civil and Marine Slag Cement Limited, based on production from four plants. Only the average value for these plants has been provided for reasons of confidentiality. These figures were provided as primary rather than delivered energy and it is not known what conversion factors were used. No allowance has been made for partitioning (that is reduction of the pig iron energy and increasing the GGBS energy). These values are for work at the plant. The plants are all situated next to steel works[5] reducing the transportation requirement. The values here compare favourably to those for cement and using GGBS as a cement replacement is likely to reduce concrete embodied energy.

The transportation energy has been calculated at an average of 105 miles, and transportation occurs in the same manner as concrete.

Table 7-43: Environmental Impacts: GGBS

GGBS	Embodied Energy (GJ/t)	Embodied CO_2 (kg/t)	Transportation Distance (miles/t)	Transportation Time (hours/t)
GGBS Production	1.228	63.53		
Transportation	0.222	14.56	8.40	0.224
Total	1.450	78.09	8.40	0.224

7.2.5.3 PFA

PFA is a waste product from coal fired power stations. As such the supply is reducing with the reduction in numbers of coal power stations outlined in Chapter 2. The information about PFA was provided by Ash Resources and gives the delivered energy required in the basic processing. This figure also includes an element for associated office energy.

The basic waste source material is taken straight from the power station, on which site the plant is located. This material is air classified (sorted) into different categories for different uses, of which only use as a cementitious material is considered. The ash material has a residual calorific value after being burnt by the power station. No allowance has been made for this for two reasons, firstly the British Standard for PFA as

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[5] Only steelworks producing iron provide useable GGBS. There is therefore no production from electric arc furnaces which only use recycled materials.

a cementitious material limits the carbon content of the material to 7% (material with values higher than this can not be used) and second, all the useful energy for power generation has already been extracted.

It is possible to make a case to reduce the environmental impacts for PFA because previously, when used considered a waste product, it required transportation and disposal as landfill. This requirement has been now been eliminated but is not considered due to a lack of data.

Table 7-44: Environmental Impacts: PFA

PFA	Embodied Energy (GJ/t)	Embodied CO_2 (kg/t)	Transportation Distance (miles/t)	Transportation Time (hours/t)
PFA Production	0.118	6.30		
Transportation	0.222	14.56	8.40	0.224
Total	0.339	20.86	8.40	0.224

7.2.5.4 Light Weight Aggregates

There are a number of lightweight aggregates which can be used in concrete both naturally occurring and man made. There are no natural sources in the UK, so supply is limited to man made types. Lytag is one of the most widely used and this is the material which has been studied. The information used has been provided by Lytag[6]. Lightweight aggregates have a number of uses, but in terms of construction use it is mainly used in concrete. This is done from a number of possible reasons -

- Lower density. Concrete made from Lytag weighs less than concrete made using standard weight aggregates (typically 1800 against 2400 kg/m^3). This could allow longer spans, thinner sections and smaller foundations.

- Lower thermal expansion coefficient allows fewer construction joints

- Better fire resistance than concrete made with normal aggregates

To benefit from these features the design must be optimised - a simple substitution of normal for lightweight concrete will incur little benefit and cost significantly more. Typically in the UK, lightweight concrete made with Lytag has been used in steel structures as a topping for metal decking to maximise clear span distance.

In terms of low impact structures, some of the features which make Lytag advantageous in normal construction may be drawbacks. Lightweight aggregates may require less materials in total, have a lower density and are better insulators than standard concrete.

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[6] Lytag is both the name of the product and the company producing the product.

Standard values for both standard and Lytag concrete are included in Table 7-45. In simple terms, the lower density means that less heat can be stored for any given quantity of material and the lower conductivity slows the heat movement through the concrete. The possible effects of these factors should be fully examined before lightweight concrete is exploited for the thermal mass.

Table 7-45: Properties of Concrete

	Density kg/m^3	Thermal Conductivity w/m K	Specific Heat Capacity J/kg K
Standard Concrete	2400	1.13	1000
Lytag Concrete	1800	0.85	1000

The production of Lytag is similar to PFA in so far as the plant takes the raw PFA directly from the Power station. The processing makes use of two fuels - electricity and oil which consume 30 kWh and 8 litres per tonne respectively. The electrical energy includes the office running cost. The office is relatively small with a maximum of ten people in occupation. The oil used in processing has an calorific value which has been taken as 47.9 GJ/t.

Transportation has been assumed to be similar to that for normal aggregates, except over the same distances as PFA.

Table 7-46: Environmental Impacts: Lytag

Lytag	Embodied Energy (GJ/t)	Embodied CO_2 (kg/t)	Transportation Distance (miles/t)	Transportation Time (hours/t)
Lytag Production	0.648	40.43		
Transportation	0.272	17.84	12.35	0.329
Total	0.920	58.27	12.35	0.329

The total energy for Lytag, as shown in Table 7-46 is just under 1 GJ/t and this is an order of magnitude greater than the energy for basic aggregates. This will clearly have an impact on any concrete containing this material. Where aggregate impacts approach the BRE upper figure, the difference would be less pronounced.

7.2.5.5 Admixtures

A calculation has been made for additives, based on information supplied by Grace Chemicals. The production of admixtures is relatively small scale, with one factory supplying the whole UK. Annual production is around 16000 tonnes per annum. The production energy inputs come from two fuels - gas and electricity - at a ratio of around 10:1. Most of the additive products manufactured by Grace make use of water as the carrier agent (that is water will make up the major proportion of the finished material), however in two cases a gas oil variant is used in this role and an estimate for the feedstock energy has been made in these cases. The variants that use gas oil are used as mould release agents, rather than in batched concrete, but are included here because they are produced in the same location and using the same processes as concrete admixtures.

For these calculations admixtures has been taken to include all plasticisers, superplasticisers, accelerators, etc. It was practically impossible to allocate energy individually given that 79 varieties are produced on one site.

The calculation for transportation energy was made relatively simple because of the accounting methods used on site. Distribution of materials is via bulk container, each of which will carry 6 different varieties on each trip. These are taken from site to site topping up containers which are permanently located at the batching site. The lorries continue distribution until all the tanks are empty. In other circumstances this could make calculation difficult, however in this case a simple average figure of distance per tonne had already been calculated - 35 miles per tonne.

The results of this analysis are shown in Table 7-47 and Table 7-48. For admixtures the transportation energy forms the vast majority of the total energy.

Table 7-47: Environmental Impacts: Admixtures

Admixtures	Embodied Energy (GJ/t)	Embodied CO_2 (kg/t)	Transportation Distance (miles/t)	Transportation Time (hours/t)
Additive Production	0.085	4.40		
Transportation	0.770	50.56	35.000	0.933
Total	0.855	54.95	35.00	0.933

Table 7-48: Environmental Impacts: Release Agent

MRA1	Embodied Energy (GJ/t)	Embodied CO_2 (kg/t)	Transportation Distance (miles/t)	Transportation Time (hours/t)
Additive Production	0.085	4.40		
Transportation	0.770	50.56	35.000	0.933
Feedstock	46.991			
Total	47.845	54.95	35.00	0.933

The analysis in Table 7-48 includes an addition for feedstock energy based on 95% of the total being gas oil, the other 5% comprising the active ingredients. No addition has been made for the associated CO_2 which is considered to be sequestered. Clearly adding in the energy for gas oil increases the energy enormously - the energy per tonne approaching double that of steel! There are 1172 litres per tonne, so the energy per litre is 0.041 GJ and each litre could be expected to cover 5 - 5.5 m^2 of formwork. For the other items, which are made up mostly of water there are 1000 litres per tonne.

7.2.5.6 Water

No allowance has been made for water for normal use in concrete. However, in some cold whether heated water might be used to increase the concrete temperature. Generally the aim would be to increase the temperature of the concrete to between 7-10°C, but the starting point for the materials will depend on the prevailing conditions. In a situation where the temperature has been 0°C, the water would need to be raised to around 27°C to get a resultant concrete temperature of around 10°C. The calculations are based on a specific heat capacity for water of 4.187 kJ/kg.k, which translates to 1.16 kWh per 1°C temperature increase (delivered energy) and assume a ratio of water to other materials of 11:1 by weight. The water is assumed to be heated by electricity, so appropriate conversion factors have been used.

Table 7-49: Environmental Impacts: Water

Heated Water +27°	Embodied Energy (GJ/t)	Embodied CO_2 (kg/t)	Transportation Distance (units)	Transportation Time (units)
Water Heating	0.312	16.71		
Total	0.312	16.71		

7.2.6 Concrete Transportation

Work carried out by Anson and Cooke (**10**) and calculated using 108 trips in a regional study of the ready mixed concrete industry, shows the average speeds achieved by truckmixers. These figures can be compared with the ETSU data for standard light and heavy goods vehicles. This comparison shows that truckmixers have lower average speeds in rural areas than both HGV and LGV and that the urban values are similar to HGV's. The figures in Table 7-50 are calculated using kilometres radial (straight line point to point) rather than kilometres travelled. This will tend to reduce the figure quoted for the distance covered, but the extent of the underestimation is not stated.

Table 7-50: Average Distances Travelled For Concrete Delivery (10)

Vehicle Category		Average Radial MPH
Truckmixer	Urban Peak	12.5
	Urban	16.9
	Rural	20.6

There is currently no data available on the fuel economy of Truckmixers, but given the low average speeds and time spent on site, it is expected that these will be worse than for similar vehicles doing other work. The time spend on site is crucial to the calculation of the transportation element of embodied energy since, as calculated by Anson and Cooke (**10**) and shown in Table 7-51, it can consume as much as 56% of the time for a return trip. During this time the engine must be kept running to provide power to the mixing drum.

Table 7-51: Truckmixer Round Trip Times (10)

Radial Distance	2 Miles		4 Miles		8 Miles	
	Min.	%	Min.	%	Min.	%
Travelling To Site	9.4	23%	15.3	34%	23.2	38%
Time On Site	23.0	56%	16.2	36%	17.1	28%
Returning From Site	8.6	21%	13.5	30%	20.7	34%
	41		45		61	

Interestingly, the time on site in real terms is higher on shorter trips (23 minutes) than on longer ones (16.2 and 17.1 minutes for 4 and 8 miles respectively). The report provides no explanation for this fact. The time on site includes an element for washing out, which took up, on average, 4 minutes. Using the data in this table, an average speed can be estimated. The total travel time has been found and used in conjunction with the radial distance. The radial distance has been increased by 50%, based on discussion with truckmixer drivers, to approximate the actual distance travelled. This gives average speeds of 10, 12.5 and 16.4 MPH for 2, 4 and 8 radial miles respectively. In this case the selection of the site to batching plant distance has been calculated using the mode rather than mean average because this best represents the 'average' site. The average distance to site has been taken as 3 miles.

The average fuel consumption of 7 MPG is significantly worst than an average HGV. This is because of the time spent with the engine running on site and at the batching plant. Therefore the road miles travelled include all the energy required by the truckmixer. The time on site has thus been rated as requiring zero energy, since it has already been included elsewhere.

The data presented in Table 7-52 has been tabulated for a range of average load sizes. Obviously a lorry carrying 1 m^3 will incur more energy per metre than one carrying 6 m^3. The average load is simply the total material carried per pour divided by the number of deliveries. This calculation is based on a maximum six cubic metre capacity truckmixer. Any pour where all the deliveries are full will obviously have an average of 6 m^3. All medium and large pours (20 m^3 or more) should be above 5 m^3. For the purposes of this work all slab pours are assumed to be 5.75 m^3 average while column and beam pours are assumed to be 5m^3 average. A figure has also been assumed for on site batching, for which an average load has been taken as 5.5 m^3. This assumes use of truckmixers rather than dumpers and that this unloads in the same way as truckmixers coming from off site. The time and distance for this transportation is zero, because it occurs off the public roads.

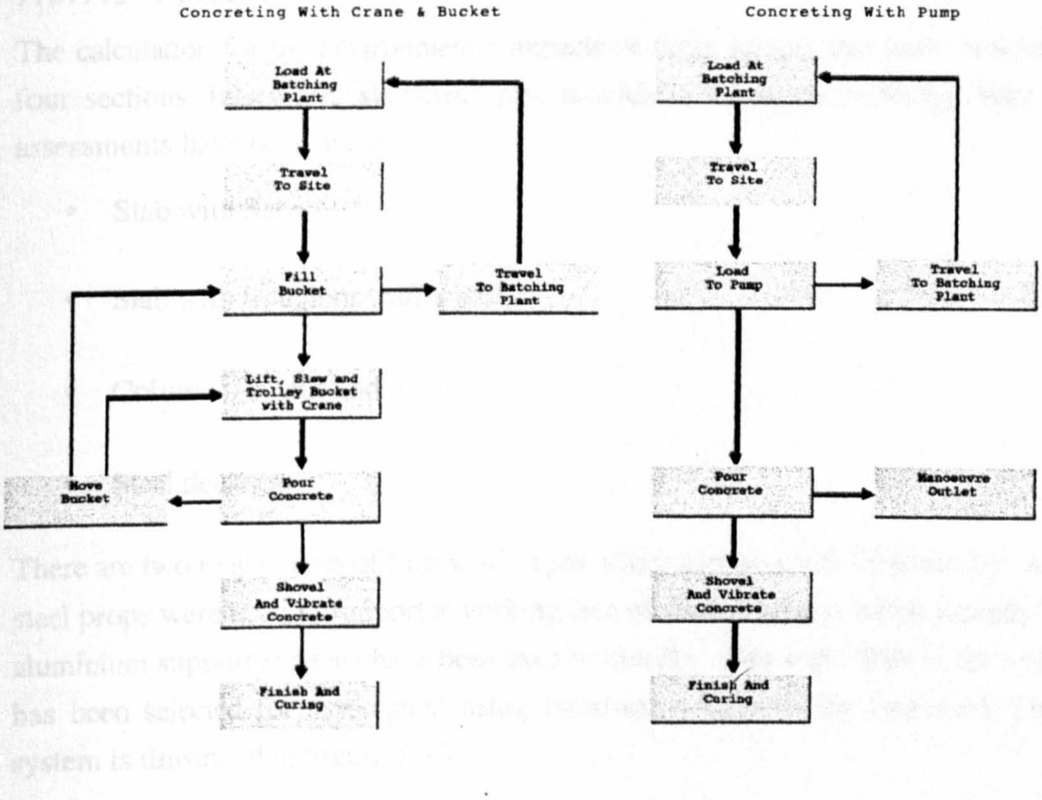
Table 7-52: Environmental Impacts: Concrete Transportation

Concrete Transportation Average Load (m³)	Embodied Energy (GJ/m³)	Embodied CO_2 (kg/m³)	Transportation Distance (miles/m³)	Transportation Time (hours/m³)
1	0.170	11.10	6.00	0.600
2	0.085	5.60	3.00	0.300
3	0.057	3.70	2.00	0.200
4	0.042	2.80	1.50	0.150
5	0.034	2.20	1.20	0.120
5.5 (Column & Beam)	0.031	2.00	1.09	0.109
5.75 (Slab)	0.030	1.94	1.04	0.10
6	0.028	1.90	1.00	0.100
On Site	0.006	0.37	0.00	0.000

7.2.7 Concrete Movement On Site

The active phase for concrete construction involves the movement from the batching plant onto site and within the site to the place of use. Figure 7-12 shows the steps that must be considered in pumping and skipping concrete. The calculation for crane energy has already been made, so only the pumping energy is discussed here.

Figure 7-12: Concreting Activities



Once the concrete has been delivered to site the main requirement is to place it in the shortest time. There are two main methods for the placement of concrete in any quantity - using a pump and using a crane. Other methods can be used for ground floor or basements placing, for example by tipper truck, or ideally in energy terms simply via the truckmixer chute.

Placing via a pump is the best solution for any large quantity of pour, for example, floor slabs, however cranes will be better in areas where small precise amounts are called for, such as columns and walls. The use of a crane will depend on the time required for other jobs and the scheduling. Where the frame material is concrete, the tower crane will usually be given over to this task as a priority. Incorrect scheduling of a concrete pour can lead to extreme waste of materials due to time limits being exceeded.

To prepare for the concrete pour, there is a requirement for reinforcement, formwork, falsework and forms to be prepared. These will all incur an energy cost, both through embodied energy and transport costs. In addition, where items have been stored on site for long periods of time, waste may occur.

During the pour, a small number of plant items will be required for placing including poker vibrators and possibly power floats. These may be running for long periods of time during the pour. After the pour, there may be a requirement for use of curing agents, covers or some special finish, however the small quantities involved mean that these have not been considered. In the longer term, the formwork can be struck and moved to a new position or disposed of. In this analysis no allowance has been made for curing because these factors will vary depending on the system used.

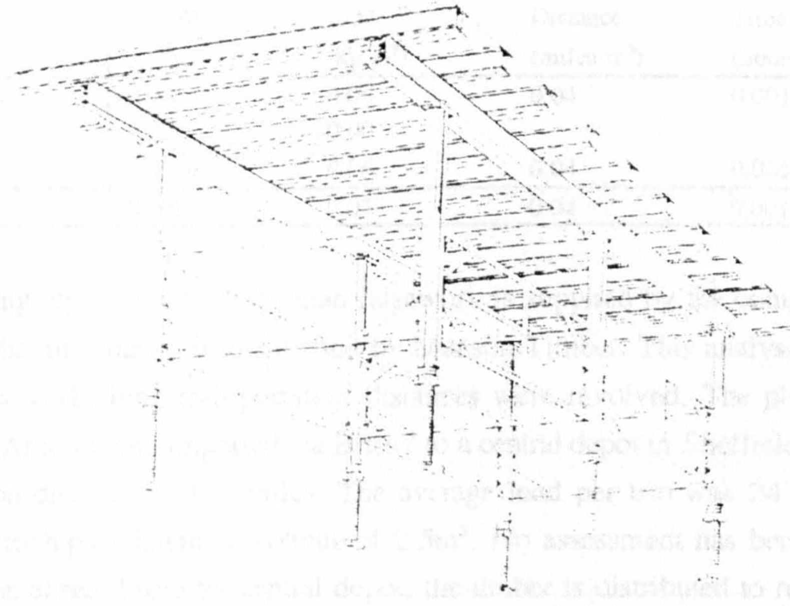
7.2.7.1 Formwork

The calculation for the environmental impacts of these factors has been broken up into four sections: falsework, shuttering ply, moulds and concrete working. Four separate assessments have been made:

- Slab with flat soffit.
- Slab with trough or waffle soffit.
- Columns, beams and walls.
- Steel decking.

There are two major types of falsework types which can be used. Historically, adjustable steel props were used to support a working area of shuttering ply. More recently modular aluminium support systems have been used with a ply 'table top'. This is the system that has been selected for assessment using information supplied by Ischebeck Titan. The system is illustrated in Figure 7-13.

Figure 7-13: Titan Falsework System



The system comprises four aluminium elements, the legs, tie struts, beams and top supports. The legs can be configured at centres ranging up to 3m x 3m, however in this case a grid of 2.4m x 2.4m has been selected as being generally representative. The legs, which have been taken as weighing 17 kg each, are tied together with struts weighing 13.5 kg each. The main support beam run along the top of the legs and weigh 8.9 kg/m run. Running over the main beams are the top supports at 500 mm centres and weighing 5.6 kg/m run. Shuttering ply is laid over the top supports and forms the 'table top' upon which the concrete is placed. The ply is supplied by the concrete contractor and is recommended at 18 mm. The number of reuses will depend on the grade of ply and the care with which it is handled. Ply used in this manner will tend to last longer than using an old steel prop system due to the gentler striking required. Once this system has been erected once, it can be moved as a whole unit rather than having to be disassembled.

Assuming that all the supports run in one direction and legs at 2.5m square, this provides a total of 11.5m^2 of formwork and weighs 304 kg. The weight per square metre is 26.4 and this is the figure which has been used in calculation of transportation and waste.

Titan have one depot, located in Burton Upon Trent, which supplies the whole country, which results in relatively high transportation impacts. The average delivery distance was calculated at around 125 miles with an average load of 15 tonnes. The waste per job (the elements damaged beyond repair) was estimated at 2-3%, but will fluctuate with the contract. This waste element provides the majority of the energy due to the high embodied energy of aluminium. The environmental impacts for falsework are shown in Table 7-53.

Table 7-53: Environmental Impacts: Falsework

Falsework	Embodied Energy (GJ/m²)	Embodied CO_2 (kg/m²)	Transportation Distance (miles/m²)	Transportation Time (hours/m²)
Transportation	0.001	0.06	0.04	0.001
Waste Energy	0.008	0.00		
Transportation	0.001	0.06	0.04	0.001
Total	0.009	0.07	0.04	0.001

The shuttering ply for use with the titan falsework is supplied by the contractor. For this calculation the information was supplied by Manson Timber. This analysis showed that, as with falsework, long transportation distances were involved. The ply was sourced from North America and imported via Bristol to a central depot in Sheffield, giving a UK transportation distance of 166 miles. The average load per trip was 24 tonnes and 20 packs, with each pack having a volume of 2.5m³. No assessment has been made for the transportation at sea. From the central depot, the timber is distributed to regional outlets, the pattern varying with time. For this assessment shuttering ply with a thickness of 18 mm was assumed, giving an area per pack of 140m². The ply has been assumed to last for the full duration of the job and then been disposed of. No value has been assigned for possible use of the timber as fuel or methane in landfill.

A value has also been added to the ply for release agent. This provides nearly half of the energy due to the use of gas oil as a carrier for the active agents. The environmental impacts are shown in Table 7-54.

Table 7-54: Environmental Impacts: Shuttering Ply

Shuttering Ply	Embodied Energy (GJ/m²)	Embodied CO_2 (kg/m²)	Transportation Distance (miles/m²)	Transportation Time (hours/m²)
Travel To Yard	0.000	0.02	0.02	0.000
Travel To Site	0.000	0.01	0.01	0.001
Embodied Energy	0.009	0.83	0.00	0.000
Release Agent	0.008	0.01	0.01	0.000
Disposal	0.000	0.01	0.01	0.000
Total	0.018	0.87	0.04	0.002

Two version of the shuttering impacts have been calculated: one for flat slabs which includes shuttering ply and falsework and one which includes an allowance for soffit mould (for waffle and trough decks) in addition to the other elements. The environmental impacts for these forms are high due to the high embodied energy of the materials from which they are manufactured (GRP) and the high waste that occurs. For this assessment the forms, are assumed to be reused 50 times (although these reuses need not occur on the same site) and cover 60% of the slab. After 50 uses the mould would require refurbishment and could then be used for a further 50 times, but this element has been excluded from the calculation. On sites where the moulds are not treated well, the number of reuses might be lower. The transportation element is relatively unimportant as shown in Table 7-55.

Table 7-55: Environmental Impacts: Moulds

Moulds	Embodied Energy (GJ/m^2)	Embodied CO_2 (kg/m^2)	Transportation Distance (miles/m^2)	Transportation Time (hours/m^2)
Transportation	0.000	0.01	0.01	0.001
Waste	0.087	6.98		
Removal	0.000	0.01	0.01	0.001
Total	0.087	7.00	0.02	0.001

The final element which has been added is for the plant required to enable the pour. Two items have been included - a compressor which is used to clean out the formwork prior to the pour and a poker vibrator for compaction. No transportation element has been added for these items due to the difficulty of assessing the way the energy should be split and the magnitude of impacts involved. The impacts are also thought to be too minor to be measured. The plant impacts are shown in Table 7-56.

Table 7-56: Environmental Impacts: Plant

Moulds	Embodied Energy (GJ/m^2)	Embodied CO_2 (kg/m^2)	Transportation Distance (miles/m^2)	Transportation Time (hours/m^2)
Compressor	0.002	0.11		
Poker Vibrator	0.001	0.07		
Total	0.003	0.17	0.00	0.000

The items out lined have been added and together provide a unit rate for impacts and are presented under the broad heading of formwork. These values are shown in Table 7-57 (for shaped soffits) and Table 7-58 (for flat soffits).

Table 7-57: Environmental Impacts: Formwork (Shaped Soffits)

Formwork (Shaped Soffits)	Embodied Energy (GJ/m^2)	Embodied CO_2 (kg/m^2)	Transportation Distance (miles/m^2)	Transportation Time (hours/m^2)
Falsework	0.009	0.07	0.04	0.001
Shuttering Ply	0.018	0.87	0.04	0.002
Moulds	0.087	7.00	0.02	0.001
Off Loading	0.005	0.33		
Craneage	0.009	0.51	0.18	0.004
Plant	0.003	0.17		
Total	0.130	8.94	0.28	0.008

Table 7-58: Environmental Impacts: Formwork (Flat Soffits)

Formwork (Flat Soffits)	Embodied Energy (GJ/m^2)	Embodied CO_2 (kg/m^2)	Transportation Distance (miles/m^2)	Transportation Time (hours/m^2)
Falsework	0.009	0.07	0.04	0.001
Shuttering Ply	0.018	0.87	0.04	0.002
Off Loading	0.005	0.33		
Craneage	0.009	0.51	0.18	0.004
Plant	0.003	0.17		
Total	0.043	1.95	0.26	0.007

All the formwork values calculated up to this point are for slabs, either flat or trough, however a significant proportion of on site work involves columns, beams and walls. The values shown in Table 7-59 are derived from the values for slabs. The value for shuttering ply has been doubled because roughly twice the ply is required for the same volume of concrete (exactly so in the case of walls which form a concrete 'sandwich').. The exact ratio will depend of the relevant dimensions. For example a column 500 x 500 mm by 3.6 m tall requires 7.2 m^2 of ply and 0.9m^3 of concrete (neglecting the effect of reinforcement and ply overlaps) which equals 0.125m^3 of concrete per m^2 of ply. A slab of depth 250 mm equals 0.25 m^3 of concrete per m^2 of ply, which is double that for the column. The values for off loading and crane time are the same as for slabs, but no value has been added for the compressor because there would be no need on a well run site. Poker vibrator energy has been doubled, reflecting the lower rates of placing and the increased difficulty of correctly compacting the concrete. No value has been added for forms or moulds although in some cases these may be present, usually to act as ties for cladding. The value for propping has been taken as zero because the requirements are negligible (a high level of reuse and only 2 steel props per column) next to that for slabs.

Table 7-59: Environmental Impacts: Formwork For Columns, Beams and Walls

Formwork (Columns, Beams, Walls)	Embodied Energy (GJ/m^2)	Embodied CO_2 (kg/m^2)	Transportation Distance (miles/m^2)	Transportation Time (hours/m^2)
Shuttering Ply	0.035	1.747	0.077	0.003
Off Loading	0.005	0.33		
Craneage	0.009	0.51	0.18	0.004
Poker Vibrator	0.003	0.20		
Total	0.052	2.78	0.26	0.008

These figures represent one possible scenario for provision of formwork, albeit a popular one. Other methods include using expanded polystyrene formers, coated ply or steel shuttering and other falsework systems.

The calculation for steel decking has been carried out in a similar way, however the formwork is permanent and must be calculated for a single use rather than 10 uses for ply. The transportation distances are assumed to be the same as for structural steel, but the energy value is for sheet rather than structural steel and is thus higher (33.7 GJ/t). A value for propping has been take equal to 10% of the value for the concrete system as suggested by the Titan design office. Although it is possible to use no support at all, it was felt to be unrealistic in 'real world' conditions. This value includes the falsework but not shuttering ply and mould elements. The off loading, craneage and plant elements have all been taken as being the same. This evaluation is show in Table 7-60. Clearly, the decking requires the majority of the energy, although the transportation element might well be higher in other scenarios.

Table 7-60: Environmental Impacts: Steel Decking

Steel Decking	Embodied Energy (GJ/m^2)	Embodied CO_2 (kg/m^2)	Transportation Distance (miles/m^2)	Transportation Time (hours/m^2)
Transportation	0.002	0.14	0.10	0.003
Energy	0.352	27.91		
Off Loading	0.005	0.33		
Craneage	0.009	0.51	0.18	0.004
Propping	0.001	0.01	0.00	0.000
Plant	0.003	0.17		
Total	0.375	29.35	0.28	0.007

7.2.7.2 Concrete Placing

The method selected for placing of concrete will depend on a number of factors which will include where in the building the concrete is to be placed, the quantity of concrete, the availability of a crane and the relative costs involved. This data should be considered in conjunction with the section on Concrete Batching and transportation and specifically the work by Anson (10). This data, which looks at the operation and capacity of ready mixed plants, while looking in some depth at transportation and discharging times, unfortunately contains no information about the method of discharge in each case. This makes it impossible to separate out times for crane and pump discharge.

7.2.7.3 Concrete Placing By Pump

Attitudes towards the placing of concrete, specifically with regards to pumping, have been studied by Anson and Cooke (**11, 12**) who provide some data which will be applicable in calculation of embodied energy. These two articles examine the attitudes of concrete pump users, the nature and extent of delays and the rates achieved in pumping concrete. The work, carried out in 1997, was originally set out to contrast the differences in attitude between the UK and West Germany. For the purposes of this work the UK information has been considered primarily, although in some cases the German information has been used to supplement this. The information can be used in a number of ways when calculating energy requirements.

Table 7-61 shows the answers to the question of whether a concrete pump would be the placing method of choice in the event that a crane was available on site. The large majority was clearly in favour of assessing the situation for each individual pour. The report suggested that this was due to pumping being considered uneconomic. Although the factors upon which the choice would rest are not given, it is reasonable to assume that they might include the cost of pump hire, the size of the concrete pour and the availability of the tower crane.

These results indicate that the assessment of placing energy should be made on the basis that larger pours will be carried out by pump, while smaller pours will be carried out by tower crane. The exact level of this split would be determined by the level.

Table 7-61: Attitudes Towards The Choice Of A Pump (11)

Would you use a concrete pump if a crane is already on site?	% Answering
Yes	4
Depends On Many Factors	80
No	16

Table 7-62 details the average placing speeds achieved using concrete pumps. This data was calculated excluding any initial delays (that is factors with might delay the expected start time of the pour, but not the pour duration). The paper does not specify to what extent the size of the concrete pump played a part in the rate of placing achieved, although it does acknowledge that this was a factor. However, assessing trade literature for a range of pumps revealed that even small 'trailer' type pumps can achieve throughputs far higher than the minimum shown here. It is notable that the average throughputs achieved on comparable sites in West Germany were significantly higher than those on UK sites. The report also notes that there are examples of much higher placing rates being recorded, up to 48m^3 per hour. This suggests that factors other than pump size are at work in slowing placing rates in the majority of cases. In almost all cases the rates achieved by concrete pumps are lower than would be expected, given the rated throughputs of the pumps. This will increase the energy requirement involved.

Table 7-62: Average Placing Speed (11)

Pour Size	Placing Speed (m^3/h)	
m^3	UK	Germany
0-20	9.9	13.7
20-50	12.7	20.8
50-100	16.0	24.0
>100	25-30	-

The actual placing rate will be affected by a range of factors which will include the number of men in the placing gang, the mix design and poor access. However the major causes of delay on smaller pours was found to be discontinuity of concrete supply. Where a pump is used in conjunction with a ready mix supplier, in ideal conditions the supply of concrete would be continuous, with one truckmixer starting to discharge concrete just another is finishing and moving away. This will only happen in a small number of cases on small pours due to problems between the site and batching plant - provisional order times, addition of 'plus' loads and limitations on truckmixer numbers.

No data has been found for rates of placing where the concrete is supplied by an on site mobile batching plant.

Of all the problems outlined only one has major implications for energy requirement - the time delay on site for truckmixers. This type of delay causes waste mainly because the truckmixer must continue to agitate the concrete until it is fully discharged, thus even when on site it is not possible to switch off the engine. This type of delay has been incorporated into the data via the transportation times detailed by Anson (10) who found that the longest delay before initial discharge was limited to 30 minutes in any case. As already noted, this has been incorporated in the fuel consumption in transportation.

For pumping to achieve maximum efficiency and to minimise wear on the machine it may be necessary to alter the mix design - termed a pump mix - this will often have a higher slump and be more cohesive that a normal mix. This may alter the relative proportions of materials, especially the cement and water contents. A selection of mix designs has been used when assessing the energy requirements for placing.

To use the data on pumping rates a figure for a mobile pump fuel consumption is required. A machine was selected which could provide a maximum throughput above the 30m^3 per hour suggested by the data and with sufficient power to provide the distribution potential to supply the buildings used in the model. In some cases, where a larger pump is used, it may be possible to discharge two truckmixers side by side at once. This arrangement should ensure continuity of concrete supply to the pump, but will only be possible if there is adequate room on site and a large enough fleet of truckmixers available.

When calculating the energy requirement for pumping two major factors need to be considered - the pumping and the transportation elements. The distances travelled moving pumps to site follow a similar pattern to mobile cranes, so the larger capacity pumps are fewer in number and travel further. For trailer mounted pumps the same engine is used for both travel and pumping. The information use in this analysis came from two sources - technical data from Putzmeister and operation data from Utranazz.

The only in use energy data was for a medium sized truck mounted pump capable of an output of 60m^3 per hour and using 1.3 G/hr. The transportation fuel consumption was rated at 12 MPG. The fuel used during pumping provides an energy consumption figure of 0.0043 GJ/m^3 and CO$_2$ emissions of 0.282 kg/m^3. Given that only one source of data was available, a check was made using the technical specifications provided by Putzmeister the results for which are shown in Table 7-63. These results are of the same order as the real world figure which has thus been used in Table 7-64. It is notable that the larger truck mounted pump actually has a greater energy consumption than the smaller. This can be tied to the greater pumping distances (both vertical and horizontal) required of larger pumps. Larger pumps will be able to pump higher, further and faster but at a cost in energy.

When truck mounted pumps are used they will often only be in operation for a proportion of the day. For example, even the relatively small CP40M would be able to place 200m^3 in 5 hours, if used to maximum effect and many pours are smaller in size than that. However the transportation energy is the same whether the pump is used on site for 1 or 10 hours so an output figure is needed to spread the energy per cubic metre. Truck mounted pumps would not generally stay on site over night because after a large pour there will almost always be a gap before the next can be made ready. This is reflected in the different environmental impacts for each of the daily pumped quantities. In Table 7-64 the value of 5000m^3 pumped is to simulate a static trailer mounted pump located on site for the duration of the pour.

Table 7-63: Energy Per Metre By Pump Type

	Trailer Mounted		Truck Mounted		Real Value
	BSA 1002	BSA 1400	CP 40M	BRF 32.13	
Max. Throughput m^3	20	90	40	116	60
Engine Power (kW)	26	78	48	207	
Max. Throughput Per Day			320	928	
Primary Energy (kWh)	28	84	52	224	
Primary Energy (GJ)	0.101	0.303	0.187	0.805	0.257
Energy Per Metre (GJ/m^3)	0.005	0.003	0.005	0.007	0.004
CO$_2$ per Metre (kg/m^3)	0.33	0.22	0.31	0.46	0.28
Daily throughput based on an eight hour day					

Table 7-64: Environmental Impacts: Concrete Pumping

Concrete Pumping	Embodied Energy (GJ/m^3)	Embodied CO$_2$ (kg/m^3)	Transportation Distance (miles/m^3)	Transportation Time (hours/m^3)
Pumping Energy	0.004	0.28		
Transportation (50m^3)	0.033	2.17	2.00	0.080
Transportation (100m^3)	0.016	1.08	1.00	0.040
Transportation (150m^3)	0.011	0.72	0.67	0.027
Transportation (200m^3)	0.008	0.54	0.50	0.020
Transportation (300m^3)	0.005	0.36	0.33	0.013
Transportation (5000m^3)	0.000	0.02	0.02	0.001

7.2.7.4 Concrete Placing By Crane

Placing concrete using a crane and skip has been observed to be slower than when using a pump. This can be attributed to a number of factors - the time taken to fill the skip, the time for movement to place of use and the time for placing. Generally the increased time for placing is a function of the complexity of the placing where cranes tend to be used - for example in columns with high quantities of closely spaced reinforcement.

Following the work on pumping detailed above Anson provided more information on placing rates, specifically 'pours averaging 19m^3'. Although it is not possible to specify the method of placing in each case, Anson suggests that 'many were in fact direct tips into footings or slabs'. This data is shown in Table 7-65. As with pumped concrete pours, the rates of placing are surprisingly low with 75% of rates falling at or below 8 m^3/hr. This compares extremely unfavourably with the maximum rate of discharge possible when simply using the truckmixer chute - around 6m^3 in 5 minutes, which equates to 72m^3/hr! When assessing this data it should be remembered that the rates achieved include time the truckmixer is on site but not discharging and washing out, if these were excluded the figures would be higher, but unrepresentative.

Table 7-65: Placing Rates For Smaller Pours (10)

Placing Rate m^3/hr	Percentage Of Pours %
4	19%
6	35%
8	21%
10	12%
12	9%
15	3%
>15	1%

Unlike for pumping, there will probably not be much of an improvement in the rates achieved in larger pours, although some gains may be made if truckmixers can be arranged for regular arrival. Unlike for pumped concrete, there is no possibility of discharging two truckmixers at the same time, unless two cranes are available, which is considered unlikely given the demands made on crane time.

7.2.7.5 Other Methods of Placing

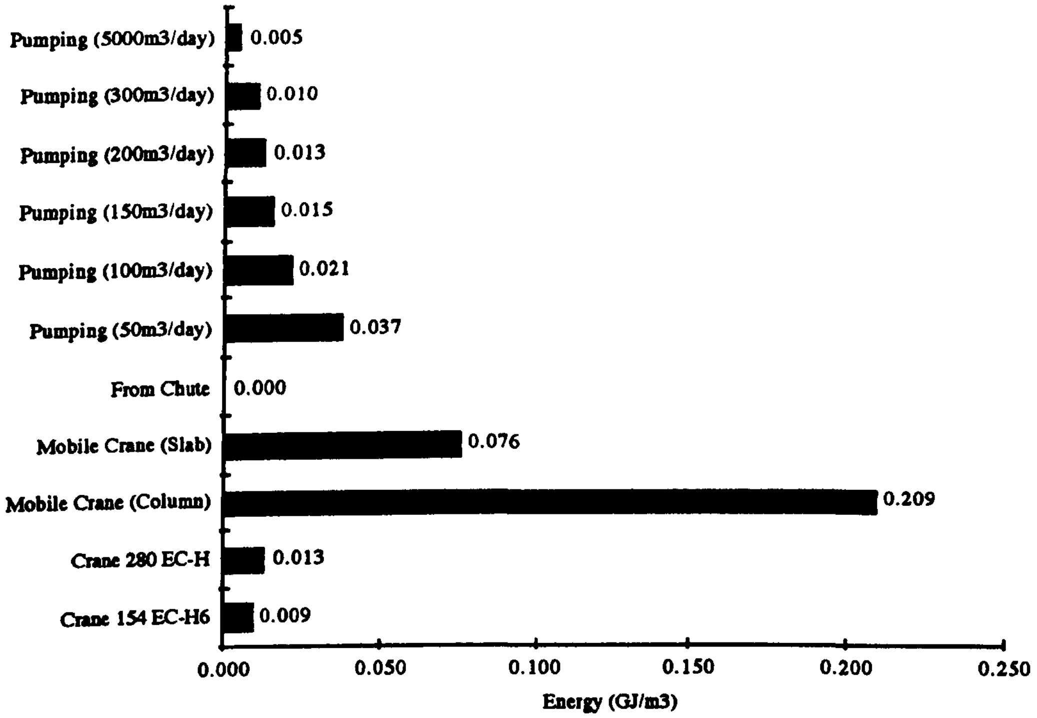
As suggested in the previous section, simply placing concrete directly using the truckmixer chute has a very high theoretical maximum rate, however this is usually not achieved in practice. Although concrete discharge is generally desirable due to the lower energy cost, in many situations it is not possible to do this due to access limitations - the truckmixer can usually only travel to the edge of the construction then discharge up to a maximum of 3m from the rear wheels.

Where direct discharge is not possible other methods are possible, usually making use of plant available on site generally tipper trucks, although there are other possibilities including excavation equipment (in one case Anson observed placing using an excavator which only achieved a placement rate of 1.7 m^3/hr).

7.2.7.6 Values for all placing rates

Figure 7-14 show all the possible energy values for placing concrete developed for this thesis. All these values will depend, to a greater or lesser degree, on the transportation values used. The values using a mobile crane are clearly much higher than the others especially for columns and beams, however, it should be remembered that the crane used in the analysis has a very high transport component and would be much lower if the crane came from a local depot. Based on this analysis using a mobile crane for placing would represent an unacceptably high energy use. The value for discharging from the chute has been taken as zero because, as noted previously the energy for discharging on site is already included in the fuel consumption figure used for transportation. Use of a pump or crane are the two major methods of placing. This analysis shows that using a pump for relatively small volumes of concrete is more energy expensive than either of the crane options. For pours of 200m^3 and over the energy is roughly similar. Using a static pump on site represents the most energy effective method of placement.

Figure 7-14: Energy For Concrete Placing



7.2.7.7 Batched and Placed Concrete

The factors outlined in this section for concrete batching and placing have been brought together to provide the environmental impacts for concrete batched and placed on site. The wide range of parameters mean that simply working through all the permutations would be extremely complicated and would serve to obfuscate the wider picture. With this in mind two combinations of data have been carried out. The first combination assesses all the different mixes using one set of parameters which, except for factors where this would clearly be inconsistent with the design purpose, are held constant. This should reveal the gross variations between mixes. The values used in this analysis are shown in Table 7-66. Where the concrete has been specified as a pump mix, pumping has been used as the method of placement, all other mixes are assumed to use the skip, taking the value for the smaller tower crane. Two values have been used for the average delivered load 5.75 m^3 for pump mixes and $5m^3$ for other mixes. Generally pumped concrete will de required in larger quantities with only the final load not being full. The list of mix designs, including the waste allowances, are shown in Table 7-37.

Table 7-66: Values Fixed For Mix Analysis

Cement	5.800	GJ/t
GGBS	1.450	GJ/t
PFA	0.339	GJ/t
Lytag	0.920	GJ/t
Aggregate	0.093	GJ/t
Water	0.000	GJ/t
Admixtures	0.001	GJ/lt.
Batching	0.018	GJ/m^3
Average Delivery $5.5m^3$	0.034	GJ/m^3
Average Delivery $5.75m^3$	0.030	GJ/m^3
Pumping (200m3 pumped)	0.013	GJ/m^3
Crane (154 EC-H6)	0.009	GJ/m^3

The second method is to use one mix design and vary the other parameters. This will show the relative contributions for each of the factors. The mix chosen for this analysis was the C30 PFA mix. This was used primarily because of the lower overall quantity of cement which made the contributions of other factors relatively greater, illustrating changes better. While each of the factors shown in Table 7-66 could be varied, GGBS is not required for this mix and the value for PFA calculated in this thesis is the only one available. While this mix does not call for admixtures, a value has been added for illustration purposes.

7.2.7.8 Concrete Impacts With Set Parameters

Using the set parameters, each of the mix designs was evaluated for each of the four impacts and the results shown in Table 7-67. Clearly there is a wide range of figures with embodied energy values ranging from 1.153 to 3.899 GJ/m^3, so the largest value is 3.4 times the lowest! The energy does not directly correlate with the characteristic strength due to the moderating effect of the lower energy PFA and GGBS. Although PFA has a lower embodied energy than GGBS, the GGBS mixes have a lower overall energy requirement because a higher proportion can be substituted for cement. As expected the Lytag mixes are the most energy intensive, with the C30 Lytag normal mix having a higher energy than the C60 OPC only mix. This is both because of the higher energy for the lightweight aggregate itself and higher amounts of cement used. This effect can be moderated somewhat by using PFA or GGBS with the Lytag. The lowest 'structural' (C30) grade concrete mix used GGBS and has an embodied energy of 1.349 GJ/m^3. The pump mixes all have consistently higher energy requirements than the skip versions, the difference depending on the mix.

In terms of embodied CO_2 the trend is similar to energy, although the range is greater. The lowest CO_2 is 174.54 and the highest 705.66 GJ/m^3 meaning that the highest value is 410% of the lowest. GGBS performs better than PFA in terms of CO_2 reduction, simply due to the higher levels of substitution for cement.

The values for distance travelled range from 6.72 to 18.47, so the highest value is 2.8 times the lowest. In this case the high cement mixes come out better, because of the higher local availability of OPC compared with GGBS, PFA and Lytag. The Lytag mixes require the most transportation, with Lytag/PFA or GGBS mixes incurring the highest values. The travel times reflect the same values as the distances although the differences are not as great because the longer distances travelled by GGBS, PFA and Lytag tend to be on fast roads at speeds higher than for OPC and aggregates.

A full listing of the values for all mixes, calculated using the stated design parameters is contained in Appendix B.

The range of values for this data is such that it will have a serious impact on any environmental evaluation of structures using concrete. The individual factors are assessed in next and this will reveal the impacts of individual items of the whole mix. Both PFA and GGBS are highly desirable in terms of energy and CO_2 reduction, although this is at a cost in increased transportation. While PFA has a lower energy, GGBS can replace more cement which means that overall it produces the mixes with the lowest energy requirements. A PFA and GGBS mix design would probably lower the overall energy requirement still further and the possibility deserves attention.

While Lytag is a good material when used correctly, in environmental terms there are clearly problems., It should be remembered that this is simply a measure of energy per m^3 and no allowance is made for the work done by each mix. So while all the standard weight mixes of a given grade are directly comparable, the same is not true of the lightweight mixes. In spite of this, at a basic level the lowest energy requirement for a C40 pump mix is less than half the lowest energy C40 Lytag pump mix and it is difficult to imagine a situation where the weight saving by using Lytag enables a steel and foundation reduction by half. If values at the higher end for aggregate energy requirement were used then the Lytag would represent a relatively lower impact. Some further calculations have been carried out to see the effect on the whole frame and these are discussed in Chapter 9.

Cement has by far the highest impact of all the materials and, while it is required at certain levels to enable the reactions in replacement materials or to give early strength, in environment terms lower quantities are preferable.

The wide range of material values is one significant area where steel and concrete differ as structural materials - there are limited options available for such massive reductions in energy in steel as concrete can make simply by altering the mix design, even when the difference between new and recycled values is considered.

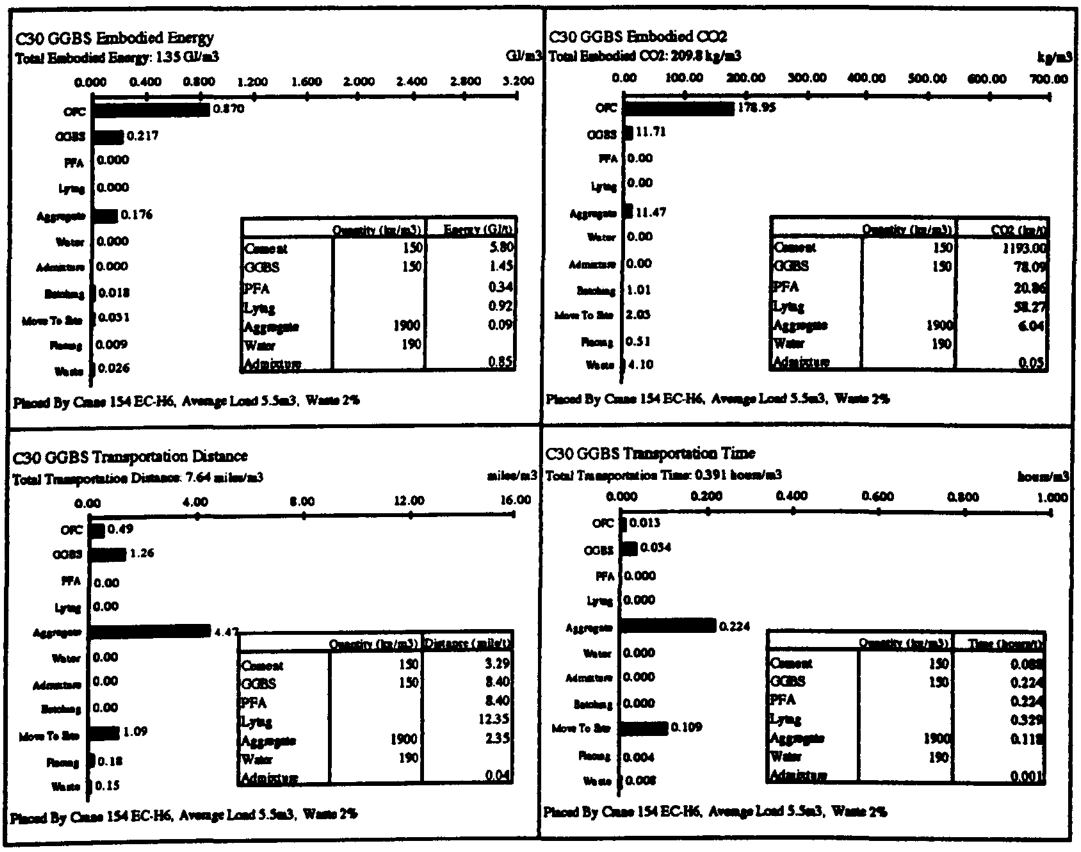
Table 7-67: Environmental Impacts: Concrete Mix Design

Mix	Energy GJ/m^3	CO_2 kg/m^3	Distance mile/m^3	Time hours/m^3
C20	1.695	313.64	6.89	0.377
C20 PFA	1.244	216.31	7.39	0.391
C20 GGBS	1.153	174.54	7.54	0.395
C30	1.982	374.16	6.79	0.368
C30 GGBS	1.348	209.78	7.64	0.391
C30 GGBS Pump	1.409	221.46	7.94	0.402
C30 Lytag	2.999	493.23	14.34	0.504
C30 Lytag Fines	3.368	514.92	18.47	0.573
C30 Lytag GGBS Pump	2.264	312.46	14.17	0.503
C30 Lytag PFA	2.564	398.09	14.77	0.506
C30 Lytag PFA Pump	2.475	401.01	13.30	0.481
C30 Lytag Pump	3.104	540.30	12.23	0.451
C30 PFA	1.509	271.64	7.38	0.383
C30 PFA Pump	1.571	264.99	7.64	0.393
C30 Pump	2.112	400.84	7.08	0.377
C40	2.220	424.30	6.72	0.360
C40 GGBS	1.620	258.56	7.84	0.390
C40 GGBS Pump	1.697	271.72	8.26	0.406
C40 Lytag	3.544	608.01	13.99	0.481
C40 Lytag Fines	3.844	627.00	17.47	0.546
C40 Lytag GGBS Pump	2.728	398.35	14.29	0.500
C40 Lytag PFA	3.006	490.49	14.86	0.501
C40 Lytag PFA Pump	3.054	518.62	13.71	0.482
C40 Lytag Pump	3.899	705.66	12.38	0.448
C40 PFA	1.675	306.32	7.40	0.378
C40 PFA Pump	1.808	313.34	7.72	0.392
C40 Pump	2.338	448.50	7.01	0.370
C60	2.979	580.75	7.07	0.368

7.2.7.9 Concrete Impacts with Variable Parameters

The C30 GGBS mix chosen as the benchmark for assessing the mix design parameters is represented in Figure 7-15, which shows how each factor contributes to the four measured impacts.

Figure 7-15: C30 GGBS Environmental Impacts



C30 GGBS Embodied Energy

Total Embodied Energy: 1.35 GJ/m3

	Quantity (kg/m3)	Energy (GJ/t)
Cement	150	5.80
GGBS	150	1.45
PFA		0.34
Lytag		0.92
Aggregate	1900	0.09
Water	190	
Admixture		0.85

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 2%

C30 GGBS Embodied CO2

Total Embodied CO2: 209.8 kg/m3

	Quantity (kg/m3)	CO2 (kg/t
Cement	150	1193.00
GGBS	150	78.09
PFA		20.8
Lytag		58.27
Aggregate	1900	6.04
Water	190	
Admixture		0.05

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 2%

C30 GGBS Transportation Distance

Total Transportation Distance: 7.64 miles/m3

	Quantity (kg/m3)	Distance (mile/t)
Cement	150	3.29
GGBS	150	8.40
PFA		8.40
Lytag		12.35
Aggregate	1900	2.35
Water	190	
Admixture		0.04

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 2%

C30 GGBS Transportation Time

Total Transportation Time: 0.391 hours/m3

	Quantity (kg/m3)	Time (hours/t)
Cement	150	0.08
GGBS	150	0.224
PFA		0.224
Lytag		0.329
Aggregate	1900	0.11
Water	190	
Admixture		0.001

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 2%

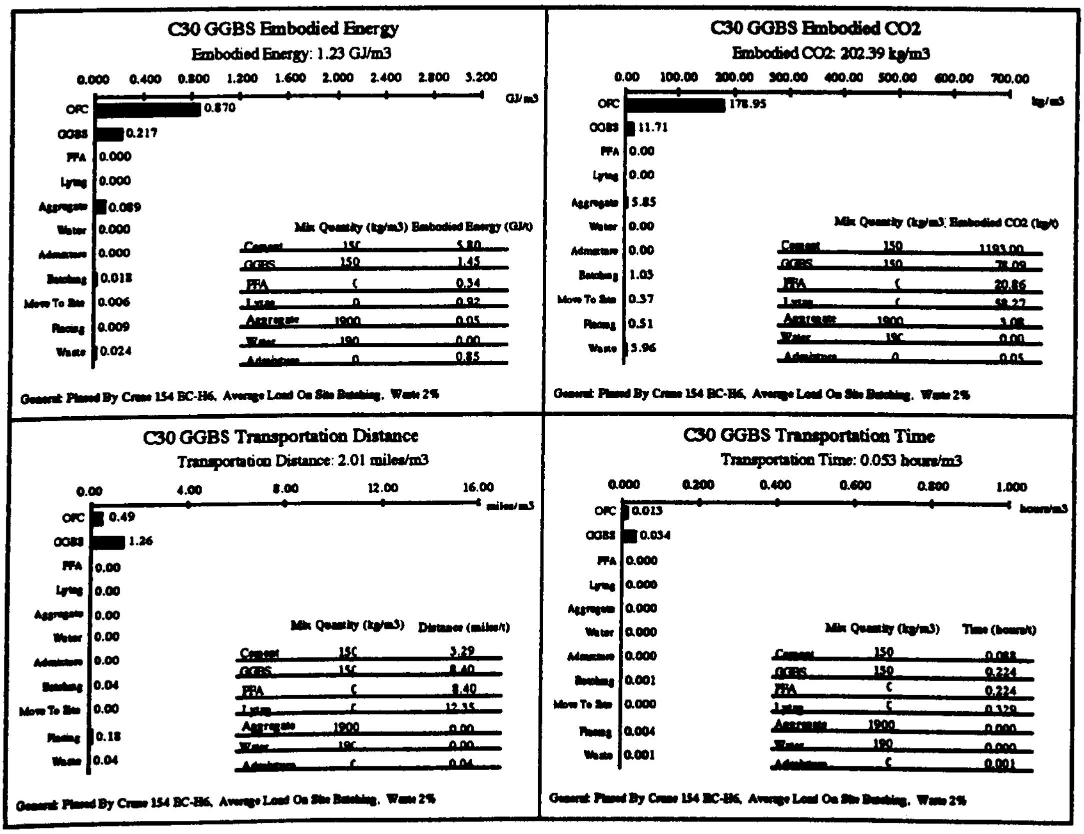
Even for this relatively low cement mix, the embodied energy is dominated by the value for cement, at 64% of the total. The GGBS and aggregates both contribute similar levels to each other at about 15%, while other values are less significant in this standard configuration. The value for water is zero because no heating is used. The batching, movement and placing items all contribute small quantities to the total energy at around 4% for all three. The waste has been taken as 2% but could be more significant on badly run sites. The embodied CO_2 follows the same pattern as energy, with the cement forming the major item at around 85% of the total. This percentage is higher than for energy because of the disproportionally large CO_2 for cement.

The transportation impacts reveal a different pattern, with the aggregates being the major facotr at around three times the value for GGBS. The transportation to site is also a major item in this analysis, being just less than for GGBS. The distances for cement are nine times less than for aggregates. The transportation times follow the same basic pattern, but with the transportation to site becoming more important than the delivery of GGBS, due to the relatively low speed of truckmixer travel.

The first set of parameters which was altered allowed for on site batching and the use of site recycled aggregates (figure 7-16). This data set should provide the lowest possible value over the range of impacts. There are not many sites where the would be room for both an on site batching plant and recycling of aggregates, so the values should not be used in any standard evaluation.

The energy requirement in this evaluation has been lowered by around 9% while the CO_2 has been reduced around 4%. The reductions have been limited because the quantity of cement is the same in both scenarios. However the transportation elements have been massively reduced with the two single largest elements (aggregate and concrete movements) being reduced to practically zero. Transportation distance has been reduced form 7.64 to 2.01 miles/m^3, a reduction of 75%. The transportation time is even further reduced from 0.391 to 0.053 hours/m^3, a reduction of 86%.

Figure 7-16: Environmental Impacts C30 GGBS On Site Batching and Recycled Aggregates



When using on site batching, but no recycling the reductions are much less dramatic. The embodied energy falls by 2% and the CO_2 by 1%. The falls in transportation requirement are 14% for the distance with a 28% reduction in time. The time reduction is the most significant because it cuts out the relatively slow truckmixer movement.

The single parameter which has the most significant effect is cement and the BRE provided high and low values of 5.1 and 6.7 GJ/t. The transportation elements have been assumed to remain the same. For this mix using the high value results in a mix energy of 1.49, while using the low value gives 1.24 GJ/m^3. This represents a spread of +10 to -8%. While these differentials are significant, it is difficult to foresee a situation in which values for individual plants would be given and without this the data is of limited use. Generally, the plants which are less energy efficient will tend to cost more to run and, in the longer term, be the first to be replaced by more efficient plants.

Of the other items, one which might be of particular importance is admixtures. As already noted, it is desirable to reduce the cement in a mix and admixtures (specifically water reducing admixtures) can achieve this but incur even lower energy additions than PFA or GGBS. The strength of concrete is dependant mainly on the ratio of cementitious materials to water (although many other factors come into play). Plasticisers and superplasticiers allow the lowering of the water content for a given cementitious content with no loss of workability. Conversely, this means that the cement can be reduced without loss of strength. One litre of admixture has an energy of around 0.001 GJ while one kilogram of cement has an energy of 0.005 GJ. While the limits in the reduction of cement in this way is finite and will depend on other design factors, admixtures can clearly be used to reduce impacts.

Aggregates can have a significant effect on the total energy. The high and low values suggested by the BRE were 1 and 0.02 GJ/t respectively. These values could result in an increase of 2.3 times the total energy to 3.11 GJ/m^3 or a reduction to 1.21 GJ/m^3. Clearly, the possible increase is of much more significance than the possible reduction. The high value is actually higher than the value for Lytag. In a situation where the energy requirement was that high, the monetary cost could also be expected to increase so it is likely that recycled aggregates will be used where possible. The standard value, calculated for the thesis, has been used for the basic calculations, but the high value has been used for illustrative purposed in the total frame results.

The effect of heating water, given the increase described earlier, would be around 0.059 GJ/m^3. This is significant for individual mixes, but should not be required for all concrete produced. A significant factor is that lowering cement content reduces the concrete heat gain and makes the requirement for heating more likely. However the increase due to heating is much less than the saving by cement reduction.

The values for placing concrete are similar for tower crane and pump, with the pump being less efficient for lower quantities. Only the placing using a mobile crane would increase the total energy significantly (for C30 GGBS mix the increase from tower to mobile crane, while placing to columns is around 15%, which is more than the increase for the high value of cement). These values are highly dependant on the pattern of crane use and the distances involved.

The final factor which would have a significant effect is the waste allowance. Different waste have been allowed for each of the mixes, based on the placing and the grade (more expensive concrete is less likely to be wasted). For this report a relatively low values have been assumed (around 2%), but on badly run sites, this many be higher.

These figures are for a mix with a relatively low cement content. For mixes with more cement the effect of changing other parameters would be relatively less.

7.2.7.10 Maintenance and Repair

Where concrete has been correctly placed, there should be little need for repairs and maintenance, although in some cases drastic repairs may be required, for example the application of cathodic protection. These may be considered as major works in their own right and is beyond the scope of this thesis.

7.2.7.11 Demolition

The equipment required for demolition can be considered as a subset of that required during construction. These items will incur similar energy costs in day to day use, but over a much shorter time span than during the initial construction. Some specialised items of plant may be required, for example evacuators with longer than normal reach, however these operate using the same basic engine configuration as the standard models and will use the same quantities of fuel.

For larger buildings demolition may occur via explosives followed by movement of rubble. On the smaller office buildings considered in this report, the standard method of demolition will involve long reach excavators or cranes equipped with wrecking balls.

Prior to the structural demolition the structure should be stripped out, removing all materials with potential to be recycled. Although this process is not directly related to the structure, it can have a beneficial effect, removing all the materials which might contaminate the concrete waste and reduce the possibility of reuse as aggregate. All contaminants should be avoided, but special care should be taken to remove reinforcement because it has a recycling value in its own right and it may clog crushing machinery slowing the recycling process. The need to separate contaminants is especially true when the material is to be recycled at a fixed off site plant which may take waste from several sources - contaminants could reduce the usefulness of these as well.

The energy calculations for demolition are made in the Steel section. The example building was steel framed, but with concrete fire protection.

7.2.7.12 Recycling

Demolished brick stone and concrete structures can be crushed either for use as fill materials or reuse as aggregates for concrete. As noted in section 7.2.4.3, concrete can be produced at strengths well above 40 N/mm^2, however recycled materials would not normally be considered for use in these due to the inherent variability of the material. Given good quality control for recycled material, there is no reason why the majority of concrete should not make use of recycled aggregates, however most recovered materials are currently used as fill.

Table 7-68 shows the energy calculation for recycled materials at the BFI quarry both for uncontaminated and contaminated waste. The estimate for contaminated waste will vary more than for uncontaminated waste, depending on the degree of adulteration. The recycled materials have a higher fuel requirement than new materials due to the need for greater care when screening which causes a lower average daily throughput. The material crushed in this example is not screened and would therefore only be used as fill material. This table excludes the energy required for transportation to the quarry site which is accounted for in the waste disposal section. Transportation away from the quarry would occur in the same manner as for new aggregates. The BFI site handled a relatively small quantity of recycled material and these figures are included for comparison with the more comprehensive analysis carried out for the demolished building. The average environmental impacts for these processes are shown in Table 7-69. Additions should be made to these values for handing and transportation.

Table 7-68: Plant Fuel Requirements - Recycled Material

Operation (Daily Average)	Plant Required	Average Material (t)	Average Diesel (lt.)	Fuel /Tonne (lt./t)
Good Material				
Moved To Crusher	Wheel Loading Shovel	1200	100	0.08
Crushed & Graded	Crusher & 3 Screens	1200	375	0.31
Moved To Stock	Wheel Loading Shovel	1200	100	0.08
				0.48
Adulterated Material				
Moved To Crusher	Wheel Loading Shovel	800	100	0.13
Crushed & Graded	Crusher & 3 Screens	800	375	0.47
Moved To Stock	Wheel Loading Shovel	800	100	0.13
				0.72

Table 7-69: Environmental Impacts: Brick And Concrete Recycling

Aggregates (Recycled)	Embodied Energy (GJ/t)	Embodied CO_2 (kg/t)	Distance (miles/t)	Time (hours/t)
Clean	0.026	1.69		
Contaminated	0.038	2.53		
Average	0.032	2.11		

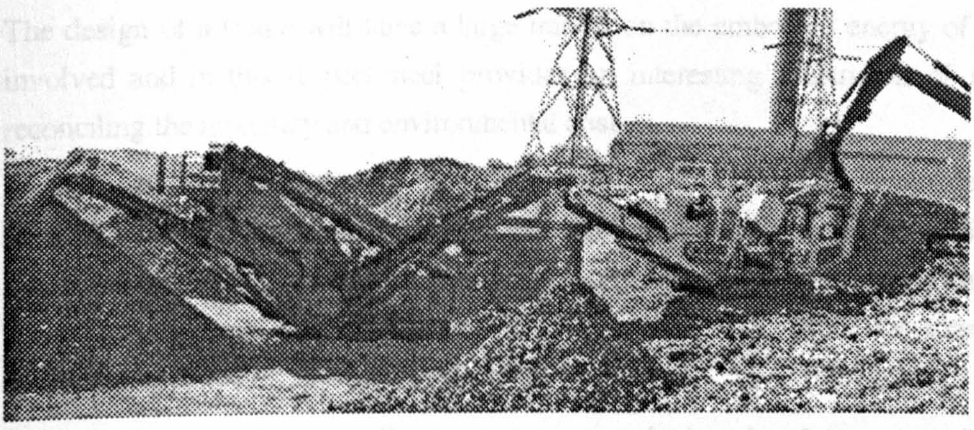
Table 7-70: Environmental Impacts: Off Site Recycling and Transportation

Aggregates (Recycled) Inc. Transportation	Embodied Energy (GJ/t)	Embodied CO_2 (kg/t)	Distance (miles/t)	Time (hours/t)
Move To Site	0.036	2.36	1.72	0.069
Crush and Screen	0.032	2.11		
Move From Site	0.028	1.87	1.29	0.052
Total	0.097	6.34	3.01	0.121

Table 7-70 shows the recycled aggregates including a factor for transportation from a demolition site and returned to the same site. The difference in energy requirements arises from the different bulk of crushed and uncrushed materials. The site was assumed to be 11 miles distant. Given that the calculated energy for new aggregates was 0.094 GJ/t, but with a distance to site of 20 miles, it is clear that the energy efficiency of off site recycled aggregates is dependant on the distances involved. The transportation distances are greater for the off site recycled materials, reflecting the fact that two journeys are made rather than one. It is possible that an arrangement could be made where the lorry is full for both legs of the trip, bringing rubble from site and returning with crushed materials. This would roughly half the transportation impacts, giving an energy of 0.064 GJ/t.

Figure 7-17 shows a crusher and screens working on site, fed by a tracked excavator. This type of arrangement can be used either at a quarry or on a building site. If it is used on a site, space may become a limiting factor and should be given serious consideration, especially with regard the stockpiled materials. At the BFI quarry site, the crusher for fill materials is fed by a wheeled loader from a store rather than directly by tracked crane as depicted and has no screens.

Figure 7-17: Waste Crushing And Screening[7]



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[7] This picture is for illustration purposes and was taken from promotional literature rather than on the BFI site.

7.3 Steel Design And Construction

Much of the steel data on which this report is based, prior to the on site phase, comes directly from the companies involved. Overall, the number of processes involved are fewer than for concrete and the most complex operations occur during steel manufacturing and fabrication stages. This is expected to result in a lower environmental impact in areas such as transportation (depending on the relative location of the plants involved, the site and methods of transportation). However, because the initial energy cost of steel is higher than for concrete, this may not result in a lower overall structural embodied energy. It should also be noted that a 'steel' frame uses significant amounts of concrete - for foundations, ground and floor slabs and sometimes for fire protection. This means that there is significant linkage between the steel and concrete process diagrams.

The calculations contained in this section evaluate the processes after the steel works and must therefore use a secondary value for the basic steel. The values used have been taken from the Oxford Brookes model, previously discussed in Chapter 5.

7.3.1 General Principles

The same principles that are applied for concrete are applied in steel construction, so the design and construction are assumed to have been carried out to a high standard using sensible methods. During the design and planning stages, allowance has been made for a good construction sequence including adequate crane facilities and storage space with work carried out in a logical manner.

There are an almost unlimited range of possible permutations during the construction phase, such as the plant used and the preferences of the main contractor and related subcontractors with respect to methods. The major items of variance will be the speed of construction and the crane type and use.

7.3.2 Design

The design of a frame will have a large impact on the embodied energy of the materials involved and in this respect steel provides an interesting illustration of the problems reconciling the monetary and environmental cost.

As with concrete there is more than one possible solution for any given design and for steel the trade off is between the quantity of steel used and the complexity of the solution and hence the cost of fabrication. Greater complexity will generally lengthen the both the fabrication time and the erection period required, but will reduce the tonnage of steel required. As stated in "Design For Steel" (**13**)

> *"Minimum weight usually equates to complexity, involving extensive local stiffening and stiffeners have a large influence on the cost of fabrication and erection. As a rule of thumb, for every fabrication hour saved 100 kg of steel could be added to the frame without any cost increase........ In a design and*

> *build situation the steel work contractor may well take advantage of commercial benefits of rationalising and simplifying the steel design"*

Clearly there is may be a possible monetary advantage in producing a frame that uses more than the minimum possible quantity of steel in any given structure. However, because of the large amount of embodied energy in steel, and the relatively small amount of energy in fabrication and erection, adopting this design method could be expected to significantly increase the total building environmental cost.

7.3.3 Steel Works

The production of steel involves the use of large amounts of energy, specifically in the smelting process, but also in other processes including moving materials around the sites which are often large. There are two major types of steel making process - electric arc and oxygen furnace.

7.3.3.1 Oxygen Furnace

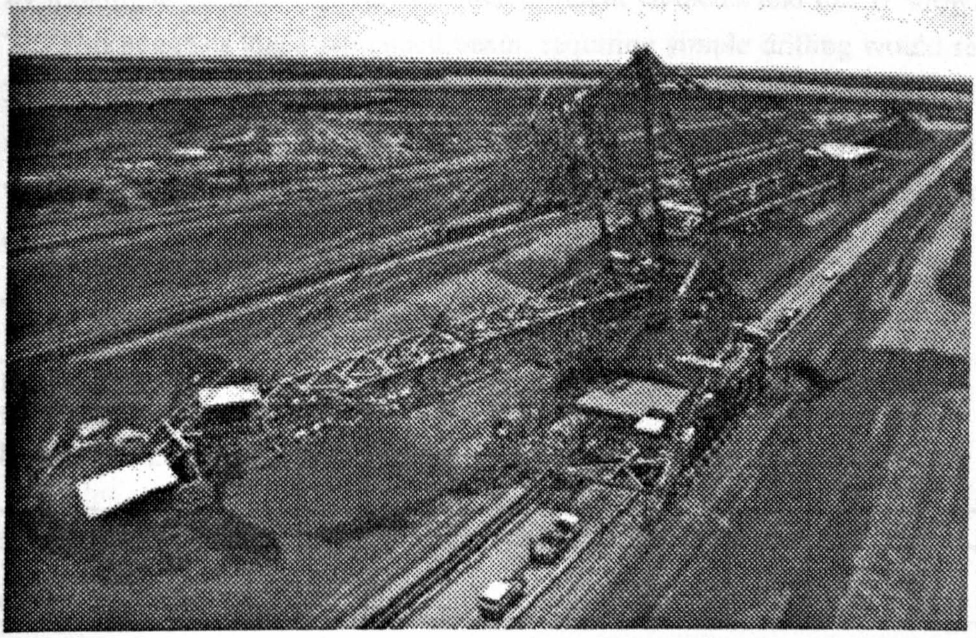
This process is used mainly for production of new steel and thus will require large inputs of raw materials. Iron ore and coke, the two main inputs for new steel, are often mined in geographically remote areas and transportation of raw materials into the site will often be by sea and rail rather than the road transportation used for concrete. Figure 7-18 shows the materials handling for an oxygen furnace works - clearly the scale materials handling in this set up is larger than that at concrete batching plants, although there are many more concrete batching plants than steel works. A comparison can be made with the batching plant in Figure 7-10 on page 156 - this plant stockpiles materials from an on site quarry which is used for both concrete batching and simply as aggregate, and is thus larger than many examples, but is dwarfed by the steel works.

7.3.3.2 Electric Arc Furnace

While the basic oxygen furnace produces new steel, the electric arc is used to recycle scrap materials. Metals generally have a high recycling potential - they can relatively easily be separated out, using magnets, are relatively compact and are more easily reused than concrete materials.

One problem in calculation of the energy requirement for Electric Arc furnace is that, as implied by the name, it makes use of electricity rather than gas for the energy needed to melt the scrap. This means that a correction is needed to change from delivered energy to primary energy.

Figure 7-18: Steel Works Materials Handling



Because this type of plant uses scrap, there is an increased need for transportation some of which will be by rail and some by road. It should also be remembered that recycled steel is usually gathered up in relatively small quantities from individual users and then moved to larger waste management centres. At the management centre decisions about whether to reuse or recycle can be made and materials moved as appropriate. These factors are discussed in more detail in the following sections.

7.3.4 Structural Steel Fabrication

The value for structural steel fabrication and transportation was provided by Barrett Steel. The steel is brought in from two sources - 1/3 directly from steel mills and 2/3 from stockholders. The steel directly from mills requires an average of around 50 miles in 24 tonne loads, the steel from stockholders tends to be more locally sourced, but brought in smaller loads, averaging 4-5 tonnes. The value chosen for the calculation of environmental impacts is based on the distance from the mill, because even when steel comes from a stockholder it will have to have been moved from the works. Therefore an average distance of 50 miles has been assumed at an average loading of 24 tonnes. Using a single distance rather than two legs may cause a slight underestimate of the energy, but this simplification is reasonable given the wide range of possible permutations.

The fabrication energy was provided as an averaged figure (that it is calculated by dividing the whole electric energy bill by the quantity of steel processed over that period) and this data is shown in Table 7-71. If a value for steel production of 25 GJ/t was used, the fabrication energy would be around 4% of the total. It should also be remembered that this value is the average fabrication value. Less complex designs might be expected to require less energy than more complex ones. While the depth of information to accurately differentiate these levels of complexity was not available, a basic assessment was made by looking at the time required for three different elements and this is shown in Table 7-71. This suggests that a pin ended beam, requiring simple drilling would require around 38% of the energy per tonne of a more complex portal rafter. A complex column would require more than twice the energy of the portal rafter. These values should be treated with caution and are for illustration only. The average value has been used for the overall calculations.

Table 7-71: Steel Fabrication Energy

Electricity/Quarter	Total
Drilling & Welding (per tonne)	101 kWh
Primary Energy	275 kWh
	0.99 GJ
Assumed Production	1 t
Total Energy	0.989 GJ/t
CO_2	52.91 kg/t

Table 7-72: Fabrication Energy Split For Different Elements

Element		Pin Ended Beam	Portal Rafter	Complex Column
Information Provided				
Length	(m)	6	15	6
Weight	(t)	0.45	1.10	0.45
Weld Time	(min.)	26	134	105
Other Activities Time	(min.)	99	200	315
For 1 Tonne Elements				
Length	(m)	13.3	13.6	13.3
Weight	(t)	1.00	1.00	1.00
Increase	(m)	7.3	-1.4	7.3
%age time for each extra m	(%)	5%	10%	17%
%age Change	(%)	137%	86%	222%
New Weld Time	(min.)	35.5	115.7	233.3
New Other Activities Time	(min.)	108.5	181.7	443.3
Weighting				
%age Weld Time	(%)	80%	80%	80%
%age Other Activities	(%)	20%	20%	20%
Weighted Power Required		50	129	275
As %age		39%	100%	213%
Weighted Average	(GJ/t)	0.38	0.99	2.11

This table, along with the basic steel energy, allows examination of the proposition in "Design for Steel" that, in monetary terms, one hour of fabrication is equal to 100 kg of steel. This statement suggests that more complex, but lighter weight, elements could be replaced by simpler, but heavier, elements at no extra financial cost. This analysis, while not questioning the validity of that statement in monetary terms, examines it from an energy perspective.

To perform the calculations, use has been made of the most complex example calculated in the table. For this element the weld time for a 1 tonne section is expected to be 233 minutes and this is where the majority of the energy is used. This equates to 0.26t/hour, taking the weighted average of 2.11 GJ/t gives an energy of 0.55 GJ/hour. The increase in steel for this saving in fabrication is 100 kg at an energy cost of 26.8 GJ/t which is equal to 2.68 GJ. Therefore, for a saving in fabrication energy of 0.55 GJ an increase of 2.68 GJ is incurred in steel (around 5 times the saving). This analysis takes no account of the effects on transportation energy or time on site. Clearly, even though the figures are approximate, decreasing fabrication time at the expense of increasing the total steel makes much less sense in environmental terms. Following this analysis through to calculate the break even point in energy terms, a 1 hour saving in fabrication time is only offset by 20 kg of steel.

The transportation from facbricator to site occurs in two major ways with smaller loads travelling shorter distances (suggested averages being 15 tonnes up to 50 miles) and larger loads over longer distances (average 23 tonnes over 100 miles). The total for steel fabrication are shown in Table 7-73 (shorter transportation distance) and Table 7-74 (longer route). The waste allowance at the fabrication plant has been set at 1%, while the waste on site has been taken as 0%.

While it should be remembered that the majority of structural steel will be made from new materials, it is possible that it could be made from recycled materials. A figure has thus been calculated on the basis that the structural steel is produced from recycled sources, so the basic energy is the same as for reinforcement. All the other factors are the same as Table 7-73. This modification is shown in Table 7-75. This energy figure alters the balance, discussed above, between steel energy and fabrication time. With a input figure of 17 GJ/t the energy breakeven point becomes 32 kg.

Table 7-73: Environmental Impacts: Steel Fabrication (Shorter Route)

Structural Steel Fabrication (Shorter)	Embodied Energy (GJ/t)	Embodied CO_2 (kg/t)	Transportation Distance (miles/t)	Transportation Time (hours/t)
Basic Steel Energy	26.624	2016.97		
Travel To Fabricator	0.101	6.63	4.59	0.184
Fabrication	0.989	52.91		
Transport To Site	0.088	5.78	5.33	0.213
Off Loading	0.005	0.33		
Craneage	0.009	0.509	0.179	0.004
Total	27.816	2083.12	10.10	0.401

Table 7-74: Environmental Impacts: Steel Fabrication (Longer Route)

Structural Steel Fabrication (Longer)	Embodied Energy (GJ/t)	Embodied CO_2 (kg/t)	Transportation Distance (miles/t)	Transportation Time (hours/t)
Basic Steel Energy	26.624	1997.00		
Travel To Fabricator	0.101	6.57	4.55	0.182
Fabrication	0.989	52.91		
Transport To Site	0.200	13.13	9.09	0.242
Off Loading	0.005	0.33		
Craneage	0.009	0.51	0.18	0.004
Total	27.927	2070.44	13.82	0.429

Table 7-75: Environmental Impacts: Steel Fabrication (Recycled Steel)

Structural Steel Fabrication (Shorter)	Embodied Energy (GJ/t)	Embodied CO_2 (kg/t)	Transportation Distance (miles/t)	Transportation Time (hours/t)
Basic Steel Energy	17.029	1290.07		
Travel To Fabricator	0.101	6.63	4.59	0.184
Fabrication	0.989	52.91		
Transport To Site	0.088	5.78	5.33	0.213
Off Loading	0.005	0.33		
Craneage	0.009	0.51	0.18	0.004
Total	18.221	1356.22	10.10	0.401

7.3.5 Reinforcement Cutting And Bending

The fabrication of reinforcement from basic steel products can be carried out either on or off site. This section assesses off site production and then makes calculations for on site production using same basic figures except where noted and excluding the extra transportation costs.

The information for production of steel reinforcement was gathered from ROM Ltd and Derim Steels Ltd. ROM are a national firm with depots all over the UK, while Derim have one plant near Sheffield, although they operate nationally.

The number of steel plants manufacturing steel for reinforcement in the UK is limited to three plants located in Cardiff, Newport and Sheerness (Kent). In some instances materials are sourced from overseas, in which case it arrives at various ports including Shoreham (south coast), Liverpool or Grove Wharf (Humber estuary) amongst others. These calculations have been based on reinforcement produced in the UK. Due to agreements between the steel plants, the cost to the fabricator for delivery is the same for steel from each plant, so there is no incentive to reduce transportation distances. The distances involved are large in both these cases but generally, the further north the site, the higher the transportation energy cost for reinforcement will be (excluding possible use of steel brought in via sea). The transportation distances from the steel plants to Derim and The ROM plants are shown in Table 7-76 and are clearly going to involve significant environmental costs. The transportation distances to Whitburn have not been included in the overall analysis because ROM use outside hauliers and it is likely that loads would be carried both ways. The movement to the fabricators has been done assuming equal supply from all plants with 24 tonne loads.

Table 7-76: Reinforcement Road Transportation Distances

To From	Derim	Cannock	Whitburn
Shearness	250	150	420
Newport/Cardiff	190	110	367

Steel bar up to 12 mm diameter can be delivered in two forms, either as straight bar lengths, or as a coil. Larger diameter bars are delivered as straight lengths. This distinction is important in terms of waste calculation because the coils are much longer and thus there are fewer unusable 'bar ends' of a few 100 mm in length. However this must be set against the energy requirement for decoiling the steel which is significant in energy terms (although in financial terms coil is cheaper). Derim Steels have one plant for decoiling and one for cutting and bending and the ratio of energy use between the two was 2.8:1. In this case it was not possible to separate out the quantity of steel arriving as coil and as straight lengths. For this calculation a simple 'all in' estimate has been made. Electricity is the only energy used in fabrication of reinforcement, including loading and off loading (which is carried out by gantry crane). The basic energy calculations for Derim are shown in Table 7-77.

Table 7-77: Derim Reinforcement Production

Electricity/Quarter	Office	Production	Total
Cutting & Bending	750	3340	4090 kWh
Decoiling	1000	10480	11480 kWh
Delivered Energy			15570 kWh
Primary Energy			42350 kWh 152 GJ
Production/Quarter			1218 t
Total Energy			0.125 GJ/t
CO_2			6.70 kg/t

The energy calculations for ROM ltd are based on figures from two plants, based in Cannock (near Birmingham) and Whitburn (near Glasgow) and these figures are shown in Table 7-78. Clearly the figures are much higher than those for Derim and this is thought to be due to the higher quantities of coiled rather than straight steel used by the larger company. The difference between the two ROM plants is thought to be due to the

Cannock site performing reinforcement prefabrication, in addition to simply shipping cut and bent lengths. The Whitburn site does no prefabrication, but also handles around double the quantity of materials per quarter.

Table 7-78: ROM Reinforcement Production

Cannock Plant	
Electricity/Quarter	Total
Decoiling, Cutting & Bending	250000 kWh
Primary Energy	680000 kWh
	2448 GJ
Production/Quarter	7000 t
Total Energy	0.350 GJ/t
CO_2	18.71 kg/t
Whitburn Plant	
Electricity/Quarter	Total
Cutting & Bending	400712 kWh
Primary Energy	1089935 kWh
	3923.77 GJ
Production/Quarter	14496 t
Total Energy	0.271 GJ/t
CO_2	14.48 kg/t

These figures suggest that, for reinforcement at least, energy economies of scale may not apply. For production of the energy calculations, a weighted average for the three plants was used.

Transportation away from the fabrication site occurred in two basic ways, either larger quantities moved large distances or smaller quantities moved locally (often collected from the plant rather than delivered). Two values have been calculated which reflect this split. Notably, Derim reported instances of cut and bent steel being sent to sites in the same city as the steel works which originally produced the bar!

The on site movement has been assumed to be via forklift and tower crane. The off loading occurs using a forklift which moves materials to a place of storage from where the tower crane lifts it to the slab, to allow the operatives access. In some cases the steel can be assembled on the ground and moved into place 'whole', however the actual weight moved will be similar in each case. The energy requirement for the forklift is relatively low because of the large quantities of material which can be moved quickly (estimated at 20 tonnes in 50 minutes). The reinforcement will be delivered to site grouped by bar mark, and these bundle sizes determines the quantity of material in each off loading cycle. However because the forklift energy is allocated by time this factor has been ignored in this analysis. Observation on site leads to the conclusion that the quantity of material moved by tower crane varies massively each cycle from literally a few bars to whole cage assemblies and this makes an accurate assessment very difficult to make. Bearing these factors in mind, a value of 0.5 tonne has been assumed per bundle, so two crane cycles are required for each tonne of material.

There are a number of possible base values which could be used for the input steel energy value. As shown in Chapter 5, in the Oxford Brookes study, Amato has noted that reinforcement is produced mainly from scrap, while structural steel used raw materials and thus has a higher energy. However Table 5-6 shows structural and reinforcement steel as having exactly the same values. While it is known that a parametric study of structural steel values was carried out, the higher value was used in major calculations. It is not clear what value was used for reinforcement in the overall calculations. For the purposes of this thesis both values have been used for comparison purposes, however the lower (scrap use) values has been used in the main calculations because this represents more truly the actual production. Where values from the Oxford Brookes study have been used, the transportation element (calculated as 0.44 GJ/t for both structural and reinforcing steel) has been stripped out and replaced by the new values. This may well result in some factors being excluded because they have not been calculated for this these (for example the shipping energy of raw materials) and could result in a slightly low figure being assumed. It is not possible to accurately assess this effect because the Amato work does not give the transportation parameters. The new values for CO_2 have been calculated on a pro rata basis from the energy figures.

The quantity of steel delivered to the fabrication plant will be larger than the amount output and this waste factor will differ depending on the site and use. Both Derim and ROM estimate a waste factor of 1-2%. This would be expected to be higher for on site fabrication for a number of reasons, including the less controlled conditions, the use of straight rather than coil steel and an inability to 'save' unsuitable lengths for other jobs. The value for on site fabrication has been taken as 5%. The use of straight rather than coil should reduce the basic steel energy, but not enough data was available to make that distinction. Waste for steel on site after fabrication should be minimal so a figure of 0.5% has been assumed.

These factors are brought together and the various environmental impacts shown in Table 7-79 and Table 7-80. The basic steel figures make up most of the total of the total impact for both the high (98%) and low (96%) basic figures. This figure decreases by around 1% in each case where the longer transportation to site element is used. Where steel is cut and bent on site there is actually an increase in the energy by around 2.5%, while the travel element decreases by 1/3! The increase in energy is due simply to the higher waste expected on site. Clearly, if a decision about where to cut and bend steel was to be made on environmental grounds there would be a conflict in possible strategies between energy and transportation.

Table 7-79: Environmental Impacts: Reinforcement, Low Steel Value

Reinforcement	Embodied Energy (GJ/t)	Embodied CO_2 (kg/t)	Transportation Distance (miles/t)	Transportation Time (hours/t)
Basic Steel Energy	17.113	1296.45		
Travel To Fabricator	0.228	14.95	11.50	0.307
Fabrication	0.287	15.37		
Travel To Site (Short)	0.133	8.71	10.71	0.306
Off Loading	0.005	0.33		
Craneage	0.018	1.02	0.36	0.009
Total	17.872	1343.50	22.69	0.625

Table 7-80: Environmental Impacts: Reinforcement Permutations

Reinforcement	Embodied Energy (GJ/t)	Embodied CO_2 (kg/t)	Transportation Distance (miles/t)	Transportation Time (hours/t)
High Steel Value	27.563	2077.66	22.69	0.625
Low Steel Value with on site fabrication	18.340	1380.22	12.32	0.328
Low Steel Value with long transport leg	18.065	1334.31	28.23	0.752

7.3.6 Mesh Fabrication

The production of mesh is similar in many ways to reinforcement fabrication. The basic steel is sourced from the same plants as reinforcement, however, there are few plants operating which transform bars to mesh. ROM have one central plant, at Cannock, which deals with all mesh fabrication, while all the other depot act only as handling stations. This means that, on average, the transportation distances will be further for mesh than for reinforcement, with an associated increase in energy use. For ROM the raw steel is transported to Cannock, the mesh fabricated and then rehandled to other depots, from where it is transferred to site. In some cases the mesh will be sent directly from Cannock to site. Derim steel do not manufacture mesh, but do act as a handling centre for mesh made elsewhere.

It was found that the actual fabrication energy for mesh was found to be higher than reinforcement due to the welds required at each intersection. The fabrication energy for the Cannock plant is shown in Table 7-81 and is around 170% of the reinforcement energy. The off loading and on site movement requirements are assumed to be the same as for reinforcement. The total figure for steel mesh is shown in Table 7-82.

Table 7-81: ROM Mesh Fabrication Energy

Electricity/Quarter	Total
Decoiling, Welding	396154 kWh
Primary Energy	1077538 kWh
	3879.14 GJ
Production/Quarter	8000 t
Total Energy	0.485 GJ/t
CO_2	25.94 kg/t

Table 7-82: Environmental Impacts: Mesh

Mesh	Embodied Energy (GJ/t)	Embodied CO_2 (kg/t)	Transportation Distance (miles/t)	Transportation Time (hours/t)
Basic Steel Energy	17.113	1296.45		
Travel To Fabricator	0.228	14.73	11.33	0.302
Fabrication	0.485	25.94		
Travel To Depot	0.082	5.417	4.167	0.111
Travel To Site	0.133	8.71	10.71	0.306
Craneage	0.018	1.02	0.36	0.009
Total	18.149	1359.03	26.71	0.732

The energy and carbon dioxide figures for mesh are around 1.6 and 1.1% greater than for reinforcement, however the transportation elements are 17% greater due to the double handling involved. In all cases where transportation distances have been assumed actual values for real sites could be significantly different.

7.3.7 Site Construction

Site construction of structural steel members calls for a limited range of specialist machines, notably a crane capable of lifting each member into place. This is preferably done straight off the lorry, but some double handling many well be required. As with concrete, to reduced the number of stages in the calculation, the on site processes of off loading and materials handling have been included in the previous section. Some welding and cutting might be required, but usually only if problems occur so, in line with the good practice assumed in the rest of the thesis, no allowance has been made.

The item which will be of most importance in terms of environmental impacts is the need for fire protection on steel elements. For this analysis a board system (Vicuclad) which has an embodied energy value of 69.86 GJ/t (Oxford Brookes figure) has been used. The most significant aspect for fire protection, after the material energy itself, is the required protection time. For any given thickness of Vicuclad there will be a different protection time depending on the location in the structure and size of element, but there are two basic configurations - 18 and 30mm. 18mm of board will provide 1 - 1.5 hours of protection, 30mm provides around 2 hours. For the purposes of assessment, values have been calculated for both 18 and 30mm. The material density has been taken as 405 kg/m3 and the on site waste around 5%, both figures being provided by the manufacture, Eternit UK ltd.

Table 7-83: Environmental Impacts: Vicuclad 30mm

Fire Protection (30mm Vicuclad)	Embodied Energy (GJ/m^2)	Embodied CO_2 (kg/ m^2)	Transportation Distance (miles/ m^2)	Transportation Time (hours/ m^2)
Transportation	0.004	0.237	0.292	0.008
Energy	0.849	2.430		
Off Loading	0.005	0.325		
Craneage	0.009	0.509	0.179	0.004
Total	0.910	3.68	0.49	0.013

Table 7-84: Environmental Impacts: Vicuclad 18mm

Fire Protection (18mm Vicuclad)	Embodied Energy (GJ/ m^2)	Embodied CO_2 (kg/ m^2)	Transportation Distance (miles/ m^2)	Transportation Time (hours/ m^2)
Transportation	0.004	0.24	0.29	0.008
Energy	0.509	1.46		
Off Loading	0.005	0.33		
Craneage	0.009	0.51	0.18	0.004
Total	0.553	2.66	0.49	0.013

When calculations have been made for the whole building, the 18mm values have been used giving an assumed fire protection value of 1 - 1.5 hours. This is a very significant value - for comparison, the energy calculation for steel decking is only 0.375 GJ/m^2!

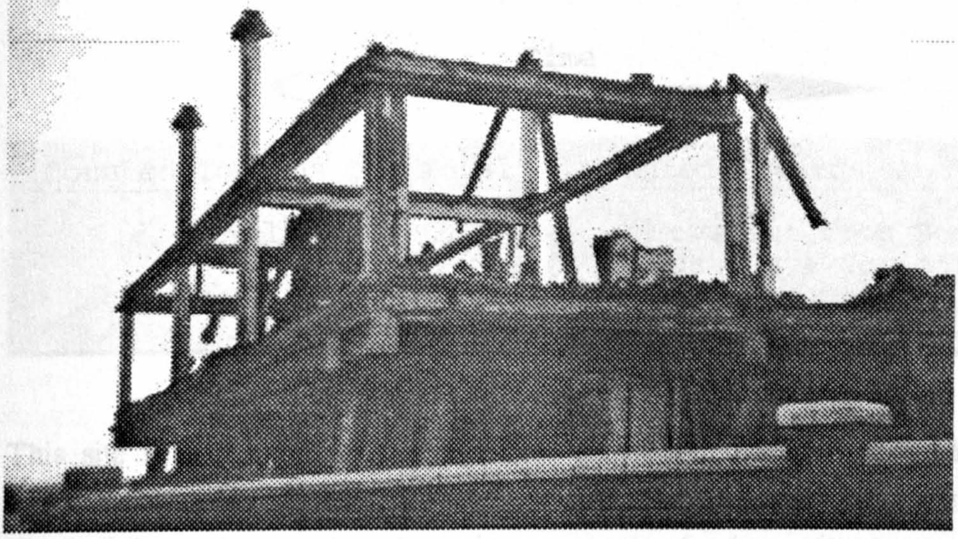
7.3.8 Repair and Maintenance

Where the steel frame is hidden beneath the building cladding, very little maintenance should be required, however external structural members will require periodic repainting. If the steel has been badly designed, some serious decay may occur. These factors are not evaluated in this thesis.

7.3.9 Demolition and Recycling

The demolition phase requires similar equipment to construction. In some cases, it may be possible to remove and reuse structural members, albeit in non critical situations. The reports studied in chapter 5 suggest that steel requires less energy to demolish than concrete however the building studied here was built in the 60's and had a steel frame (gross area of 8100m^2) clad in concrete for fire protection which behaved similarly to a concrete structure for demolition purposes. The structure is shown, during the demolition, in Figure 7-19.

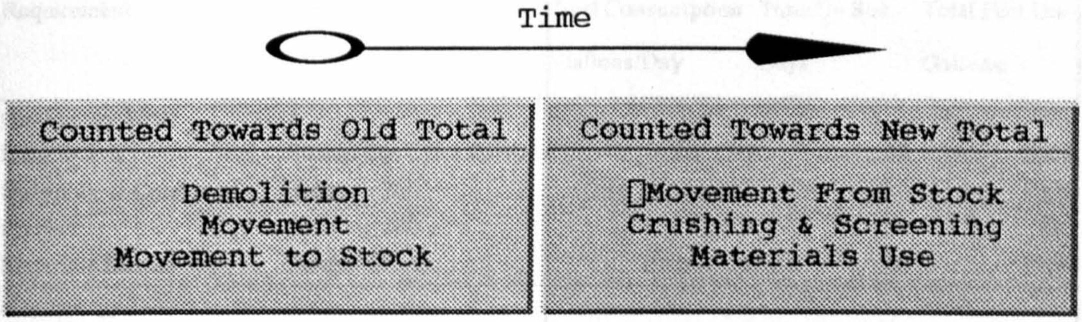
Figure 7-19: Steel Frame Building Demolition



Determination of the demolition and recycling parameters is slightly problematical. To recycle reinforcement and concrete covered structural steel requires that the concrete to be crushed and the materials separated. This step is not necessary if the material is to be sent straight to landfill, which means recycling increases the energy requirement. This factor is linked to the cut off point between old and new environmental impacts. The question arise about exactly where the energy added to the tally of the old building stops and starts being added to the new. If recycling requires a higher energy than simple disposal, should the impacts be added to the new materials or counted for old materials? This split will vary depending on the site and the practices used. As with other factors in the thesis, an approach has been taken which will maximise recycling, thus all impacts are added to the old materials until it is moved to stockpile. From this point a 'clean slate' is assumed. In terms of demolition, this means that recycled aggregates have lower environmental impacts than might otherwise have been the case which encourages use.

These factors are shown graphically in Figure 7-20. These factors could occur over a long period of time or happen on the same site contiguously. In some cased a value judgement may be called for about where the stockpile occurs because it may be a theoretical point. On the site studied, the 'stockpile' occurred just before the excavator placed the materials in the crusher and should not be confused with the actual physical stockpile of crushed materials.

Figure 7-20: Distribution Of Impacts



This site used a range of equipment for demolition including a crawler crane with wrecking ball, three crawler excavators, several rear tipper trucks and a wheeled loader. The building to be demolished was in one corner of a large site upon which, in other areas, work was commencing on construction of a new structure. This was advantageous for a number of reasons - the work on demolition could continue in parallel with the ground work for the new structure, the demolished material could be used in the new structure and plant could be used on a non continuous basis. These factors would not apply on all sites. The plant and fuel used are shown in Table 7-85. Splitting the data as per Figure 7-20, all the energy up to supplying the crusher are added to the old building, while the energy after that is added to the new building. The set up in this example will reduce the energy for both the old and new building. The demolition of the old building requires much less transportation than would otherwise be the case and incurs no landfill costs while the new building gains a ready supply of material. As well as the rubble material, included within the structure, were a mass of steel, mesh and reinforcement. The structural steel was separated by one of the excavators equipped with crushing jaws and then sent to a depot for sorting. It is interesting to note that this is one area where extra energy was used because the steel was taken to the yard of the demolition company while a steel yard existed less than 200m from the site exit. The mesh and reinforcement was separated out during, rather than before crushing, which presents a problem in terms of how to allocate the energy. This has been dealt with by allocating the crushing energy totally to the rubble while adding the transportation for the steel to the old building. This slightly over estimates the energy for the new materials, but it was not possible to make a more accurate assessment with the data available.

Table 7-85: Demolition and On Site Recycling

Requirement	Machine	Fuel Consumption Gallons/Day	Time On Site Days	Total Fuel Use Gallons
Old Energy Total				
Demolition	Ruston Bue Cyrus 25RB	50	40	2000
Stripping & Crushing	Samsung 280	39	28	1092
Breaker	Samsung 280	39	20	780
Materials Movement	Dumper Trucks	30	40	1200
New Energy Total				
Supply Crusher	Samsung 210	30	20	600
Breaking Down Materials	Crusher	32	20	640
Materials To Stock	Komatsu 400	37	20	740

Table 7-86: Environmental Impacts: Demolition

Demolition	Embodied Energy (GJ/m^2)	Embodied CO$_2$ (kg/m^2)	Transportation Distance (miles/m^2)	Transportation Time (hours/m^2)
Plant Transportation	0.000	0.03	0.02	0.002
Ruston Bue Cyrus	0.049	3.21		
Strip And Crush	0.023	1.50		
Beaker	0.019	1.25		
Tipper	0.030	1.99		
Steel Removal	0.001	0.04	0.03	0.001
Rebar Removal	0.001	0.04	0.04	0.002
Total	0.121	7.978	0.022	0.002

Table 7-87: Environmental Impacts: Fill Materials (On Site Recycled)

Fill (Recycled)	Embodied Energy (GJ/t)	Embodied CO$_2$ (kg/t)	Transportation Distance (miles/t)	Transportation Time (hours/t)
Plant Transportation	0.000	0.03	0.02	0.001
Supply Crusher	0.006	0.42		
Crushing	0.022	1.47		
Materials To Stock	0.008	0.52		
Total	0.037	2.43	0.02	0.001

The demolition impacts as actually occurred are shown in Table 7-86 and the energy values for the crushed rubble fill material in Table 7-87. The value calculated for new aggregates, which would often be used as fill, was 0.093, which is more than double the value for recycled. In addition there is a negligible transportation element.

To get the most from the data, these values have been combined with other known values, for example from the BFI, to cover scenarios other than actually occurred. The first example of this is using the on site materials and assuming that the crushing had been accompanied by screens to provide aggregates for concrete and is shown in Table 7-87. An element has been added in for moving the materials from stock to the batcher silo, but no allowance has been made for cleaning the aggregates. The energy for aggregate rather than simple fill materials increases by around 27%. This value will be used in conjunction with an on site batching scenario to assess how the energy value for concrete changes.

Table 7-88: Environmental Impacts: Aggregates (On Site Recycled)

Aggregates (Recycled)	Embodied Energy (GJ/t)	Embodied CO_2 (kg/t)	Transportation Distance (miles/t)	Transportation Time (hours/t)
Plant Transportation	0.000	0.03	0.02	0.001
Supply Crusher	0.006	0.42		
Crushing	0.027	1.79		
Materials To Stock	0.008	7.72		
Materials To Silo	0.005	0.36		
Total	0.047	10.29	0.02	0.001

The second example of recombining values is for moving the demolished material to a processing centre rather than crushing on site. This value has been calculated because discussion with the demolition contractor revealed that handling centres are being set up to act process and hold these bulk materials, rather than simply metals. This is shown in Table 7-89. This option requires increases in energy and transportation compared to the on site option, but not massively so, but has the advantage of making recycled materials open to a wider range of users because, as noted previously, many sites would not have the option of on site recycling due to time and/or space requirements. In this case the processing station was 6 miles away for steel and 11 miles for concrete. The transportation element is greater than would be the case if the materials had been crushed, due to the extra bulk for a given mass of uncrushed materials and it is calculated that, had the distance to the processing station been 22 miles or more, crushing on site prior to movement would lower the energy requirement.

Table 7-89: Environmental Impacts: Demolition and Off Site Processing

Demolition & Off Site Processing	Embodied Energy (GJ/m²)	Embodied CO_2 (kg/m²)	Transportation Distance (miles/m²)	Transportation Time (hours/m²)
Plant Transportation	0.000	0.03	0.02	0.002
Demolition	0.049	3.21		
Strip And Crush	0.023	1.50		
Beaker	0.019	1.25		
Tipper	0.036	2.36	1.72	0.069
Steel Removal	0.001	0.04	0.03	0.001
Handling At Yard	0.006	0.41		
Total	0.134	8.81	1.77	0.072

The suggestion that a steel frame can be dismantled using less energy than a concrete frame has been found not to be the case with concrete clad steel frames. A comparison with demolition energy given in other reports is shown in Table 7-90. The energy calculated for this thesis is similar to the Forintek results for concrete, but significantly higher than the Chalmers figures.

Table 7-90: Demolition Energy

Report	Forintek (GJ/m²)	Chalmers (GJ/m²)	SEEAM (GJ/m²)
Concrete	0.119 - 0.176	0.052	
Steel	0.071 - 0.105	0.018	0.121

Discussions with the demolition contractor suggest that even where there is no concrete fire cladding demolition, rather than dismantling, may be the preferred option because of the increased speed. With this factor in mind for the purposes of calculation in the SEEAM model, a slight modification of the data has been used. Given that the model uses actual values for quantity of steel and concrete, these can be used in the estimation of demolition impacts. Therefore the demolition value used in the model is not the same as found on site, but has been altered to take advantage of the greater information available as demolition has been separated from the transportation elements which gives greater flexibility. The values for demolition of concrete and steel are shown in Table 7-91 and Table 7-92. The values for movement of uncrushed materials on and off site are shown in Table 7-93 and the value for structural steel transportation shown in Table 7-94. The values in Table 7-93 assume that the weight of mesh and reinforcement is also being transported, therefore if the on site value is used, the reinforcement, once separated, must also be transported and this value is shown in Table 7-95. It the rubble is moved off site, then the value for rubble should be used for reinforcement because the two materials are not separated. The environmental impacts for reinforcement transportation are greater than that for structural steel (even though the distances are assumed to be the same and the fuel consumption is lower) because, even when separated from rubble, the material is not very compact.

Table 7-91: Environmental Impacts: Demolition Concrete Frame

Demolition (Concrete)	Embodied Energy (GJ/m²)	Embodied CO_2 (kg/m²)	Transportation Distance (miles/m²)	Transportation Time (hours/m²)
Plant Transportation	0.000	0.03	0.02	0.002
Demolition	0.049	3.21		
Stripping & Crushing	0.023	1.50		
Breaker	0.019	1.25		
Total	0.091	5.99	0.02	0.002

Table 7-92: Environmental Impacts, Demolition Steel Frame

Demolition (Concrete)	Embodied Energy (GJ/m²)	Embodied CO_2 (kg/m²)	Transportation Distance (miles/m²)	Transportation Time (hours/m²)
Plant Transportation	0.000	0.013	0.010	0.001
Demolition	0.049	3.21		
Breaker	0.019	1.25		
Total	0.068	4.47	0.01	0.001

Table 7-93: Environmental Impacts: Rubble Transportation

Demolition	Embodied Energy (GJ/t)	Embodied CO_2 (kg/t)	Transportation Distance (miles/t)	Transportation Time (hours/t)
On Site (Uncrushed)	0.013	0.841		
Off Site (Uncrushed)	0.036	2.364	1.72	0.069

Table 7-94: Environmental Impacts: Steel Transportation

Demolition	Embodied Energy (GJ/t)	Embodied CO_2 (kg/t)	Transportation Distance (miles/t)	Transportation Time (hours/t)
Structural Steel Trans	0.012	0.79	0.55	0.022

Table 7-95: Environmental Impacts: Reinforcement Transportation

Demolition	Embodied Energy (GJ/t)	Embodied CO_2 (kg/t)	Transportation Distance (miles/t)	Transportation Time (hours/t)
Reinforcement Trans	0.040	2.60	2.40	0.096

It should also be remembered that, in real terms, a structure is erected, used for many years, then demolished but for this model the structure is assumed to be knocked down as soon as it is erected. Current techniques are therefore used to assess the environmental impacts. It is beyond the scope of this work to try and evaluate how a building might be demolished 50 years in the future.

7.4 Conclusions

This section contains a wide range of information on construction methods and materials and from this data a number of conclusions can be drawn.

7.4.1 Generic Items

- The location of the tower crane is relatively unimportant at this level of the analysis. The hoisting energy is by far the most important element.

- Items of plant work in teams which in some cases are better matched than in others. It is also the case that a plant team which functions well in one situation may not function as well in others. In many cases the plant applied to jobs is based on the selection available in the yard, rather than by an assessment of which items would work well together.

- The low price of plant fuel means that there is little incentive for accurate measurement and the general level of information was lower than had been hoped.

- On site transportation is more energy expensive for a given distance than road haulage. This means that on site recycling is not as advantageous in energy terms as might have been expected. The reason for this factor is not known, but is probably due to both the design of site plant (heavier, more durable and lower geared for the rough ground),plant may work in inefficient teams and on site plant tends to stand with the motor running more than road traffic.

7.4.2 Concrete Items

- The environmental impacts for concrete are spread over a wide number of items. While some of these are relatively more important than others (primarily cement and aggregates), many other items require consideration.

- Mobile pumps are much more efficient when larger quantities are moved. It is recognised that in some cases pumps provide a much more satisfactory answer to placing concrete than a tower crane. Use of a static pump should be much more energy efficient and, where site factors make this a viable option, it is recommended. Mobile cranes should not be used for moving concrete, given the parameters used in this thesis, except when they are on site for other business already.

- There are a wide range of possible values for concrete. Any environmental assessment should take account of this by allowing individual mix designs to be assigned.

- Any site which uses one 'pump' mix will have higher environmental impacts than would be the case if different mixes were used.

- A reduction in cement use is desirable and this can be achieved by using other cementitious materials or by using admixtures. Both of these courses are strongly recommended.

- Reinforcement should not be cut and bent on site due to the higher levels of waste expected which will outweigh any benefits which might accrue from reduced transportation.

- On site batching can reduce the transportation element for concrete impacts significantly, especially when supplied by on site recycled aggregates. This is also desirable in terms of waste reduction.

- Lightweight concrete is less environmentally sound than standard concrete per cubic meter for two reasons - firstly, it is less efficient for thermal mass purposes and secondly the embodied environmental impacts tend to be higher both because of the energy needed in creation and the higher cements contents generally used. It should be remembered that the positive factors for light weight concrete (less structure weight, thermal insulation, use of a waste material, etc.) have not been directly assessed in this thesis. The use of lightweight concrete in place of standard concrete is assessed in chapter 9.

- The environmental impacts for concrete are not all positively linked. For example, while energy and CO_2 contribution can be made to fall by using PFA instead of cement, the transportation elements will rise with the same substitution.

7.4.3 Steel Items

- The impact for steel construction is concentrated in fewer items than concrete. These items are fabricated off site and will, through the process of financial imperatives and increased control, already tend to be efficient. Overall there is less scope for significant reductions in the associated impacts than for concrete.

- The design of steel element for simplicity rather than minimum weight will tend to increase the environmental impact of a frame.

- The concentration of energy in a few items makes it imperative that these are correctly assessed if the calculations are to be accurate.

- The fire protection element represents a more significant energy cost than was anticipated and this is expected to be reflected in the overall frame results.

- The fabrication element for steel (structural, mesh and reinforcement) is not insignificant, although more work is required to assess the cost of different elements. While it was not possible to get energy figures for steel decking, the indications are that this item will be similar to the others in terms of environmental impact.

7.4.4 Overall Conclusions

- The calculations are all based on average data and any individual site could have different values.

- There is a trend to distribute equipment from central depots which increases the environmental impacts of construction, especially for concrete.

- There is a degree of uncertainty in the results and some factors can 'swamp' the smaller values. This is compounded by the choice of units - GJ or MJ. In this work GJ have been used which makes some values look disproportionately small.

- Demolition and recycling of a concrete clad steel frame requires more energy than a simple concrete frame. The extent to which the figure for recycled steel takes into account this extra energy for transportation and demolition is unknown. Use of on site crushers will be desirable in most cases where fill is required on site due to the reduction in transportation. If the materials are required off site, crushing will be advantageous if the distances are great or the materials are to be crushed at the destination anyway.

- Assessing the environmental impacts of construction processes is difficult even in the present. Accurate assessment of methods which might be employed in the future is virtually impossible. Values should not be modified in this way unless they are clearly marked as being conditional.

- There is insufficient data currently available to do a full evaluation of environmental impacts, with factors such as plant embodied energy not yet available. Using the calculations carried out for tower cranes and aggregate, it is possible to say that these while these values might not be expected to change the overall values significantly, there will be an impact which should not be neglected if the information can be gathered.

- The data presented can help to optimise construction and limit environmental impacts. While it may not be possible to possible to make large improvements, the cumulative effect of many smaller improvements should not be ignored. In addition many of the items which produce small gains (where materials are sourced for example) can be controlled by Architects, Engineers and Contractors, while major items (for example the energy of a cement manufacturing plant) can not.

7.5 References

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8. STRUCTURAL EMBODIED ENERGY ASSESSMENT MODEL

The data detailed in the preceding chapters has been gathered together in the Structural Embodied Energy Assessment Model. The majority of the tables shown in this thesis are lifted directly from the model (subject to alterations in formatting to fit in the thesis). The model has been designed to be primarily useful at the design stage of a project to compare different design options. Over time the values could be checked against actual data and the range of data calculations built up.

Facilities are included in the model for retaining basic design parameters and results to aid side by side comparisons of different concepts. The model can be used as a design tool to provide numerical assessment of environmental impact for individual designs. However to gain maximum value comparisons should be made with different designs. The cases could be selected to carry out a parametric study, representing the range of current and future design options under consideration in each case. The model can take a wide range of data and this variation has been used to show how calculations can be manipulated to alter the results to favour one or other material. For the levels of data to be strictly compatible any imported data should use primary energy data and process the four elements used in this thesis (embodied energy, embodied CO_2 and transportation time and distance). Where imported values are used and the full spread of data is not available, the best solution would be to cover these gaps with equivalent information from this model.

The model was created as a book of spreadsheets in Microsoft Excel 5.0, to allow for maximum access and compatibility over computer platforms. The workbooks contain all of the data needed to perform an assessment of the frame energy, although outside supporting programs would be needed to analyse aspects such as thermal modelling.

A spreadsheet was used rather than creating a standalone application for a number of reasons

- The model can be moved with relative ease across computer platforms. The core work was done on a Macintosh but transfer to IBM PC causes no problems with the calculations. Basically any computer which can run Excel can use the model.

- The basic data and calculations made to provide the results are easily accessible and can be examined. The model is fully transparent.

- The model can be tailored to suit each company or site much more easily than would be possible in a dedicated application.

8.1 Structural Embodied Energy Assessment Model Workbook

The model is split into a number of worksheets which interact in relatively complex ways. Care is needed when using the model not to break any of these connections. The calculations have been split over a number of sheets into general groups to make it easier to understand.

8.1.1 Summary Worksheet

There are two duplicates summary worksheets (Summary 1 and Summary 2) which allow the comparison of two sets of data side by side. This would take the form either of assessing one building with two difference parameter sets (for example different rates for structural steel), or comparing different designs for the same building using the same parameters (for example a concrete and steel comparison) or even to assess to different buildings using different parameters. The values which can be selected in this comparison are shown in the 'Data' worksheet. The values in these sheets have been kept simple but are based on more complex calculations, which allows a simple, quick and relatively accurate assessment to be made without having to configure all the data. One of the problems that has been seen in other models is a possible 'overload' of data, due to the complexity of the area, which makes comparisons difficult to make. If more control over the operation and values used in the calculations is required, it is available from other sheets.

The data is presented in a standard format and the input items required are shown in Table 8-1. Space has been left in the worksheet to add a limited number of further items if required. The items have been split to reflect the bill of quantities, although in some cases the units have been changed to make the operation simpler. As noted in the previous section, concrete mix has a massive effect of environmental impact and so a high degree of configuration has been retained.

Table 8-1: Input Data

Substructure	Units	Superstructure	Units
Excavate and Backfill	m^3	Concrete Walls	m^3
Excavate and Dispose	m^3	Concrete Columns	m^3
Level & Compact	m^2	Concrete Beams	m^3
Granular beds	t	Concrete Slab	m^3
Sand Blinding	t	Lightweight Concrete	m^3
Concrete Blinding	m^3	Reinforcement	t
Concrete Foundations	m^3	Mesh	t
Concrete Columns	m^3	Column Formwork	m^2
Concrete Walls	m^3	Slab Formwork	m^2
Concrete Ground Slab	m^3	Steel Decking	m^2
Reinforcement	t	Steelwork	t
Mesh	t	Fire Protection	m^2
Column Formwork	m^2		
Slab Formwork	m^2		

Each sheet is split into five areas. The headings area contains the overall results for each sheet including the name, gross floor area, results for each section and average figures per area of floor. There is also a section to allow notes to be added for each data set (primarily for use when printing copies), which should be updated for each set of data parameters. The worksheet is configured with a frozen top pane, so these values will be in view whichever part of the sheet is being worked on. This area contains a dropdown menu to allow the selection of the input building data.

The second section contains the data for substructure. For each of the items shown in Table 8-1 a data value can be assigned. For some items there are several choices, while for others (mesh for example) there is only one real option. Due to the way the spreadsheet works, any value can be selected for any item. This means that inappropriate items could be matched (for example Concrete blinding in m^3 could be matched with reinforcement in tonnes). In this case the calculations are carried out, but the worksheets will present a warning that this has occurred and when printed a warning will show for which items this has occurred. This has been allowed to increase the flexibility and ease of addition for new data. For each item the unit rates, for all the measured parameters, which have been selected are displayed. The total values, where the units rates are multiplied with the material quantities, are also displayed.

The third section contains data for the building superstructure, presented in the same way as the previous section. The items for substructure tend to be similar for all types of structure, but the items for superstructure will vary more according the materials used. A separate item has been included for lightweight concrete to simplify the calculations and changeover between different structures.

The fourth section is for demolition data. No data input is required for this section because the values used in construction are 'reversed' to calculated demolition (that is, all the concrete and steel materials that have been used construction are assumed to be demolished).

The final section contains some of the basic data which has been used to build up other rates. While all the data directly used (for example for structural steel) is directly displayed in association with the relevant items, the values for concrete are derived from other data (for example cement) which would not otherwise be directly displayed. These values are therefore shown to allow the user to keep track of which modifications have been made. It should be noted that this base data must be the same for each summary steel, so it is not possible to do side by side evaluations using different values for, for example, aggregate. If this type of evaluation is required the easiest method is simply to create a duplicate of the model, which is then configured with the altered base values. Many example summary sheets are shown in Appendix C.

8.1.2 Printout Worksheet

This sheet contains combined data from the summary sheets. A single graphic is contained which can be configured to display any of the parameters simply by using a dropdown menu. This table shows the total building figures for the selected parameter for data from summary worksheets 1 and 2 as well as a selection of the data figures used in the calculations. Many examples of the graphic output from the model are shown in Appendix C.

8.1.3 Data Worksheet

This is the storage area for building data used. The worksheet is configured to accept 30 separate building data sets each of which can be accessed from either of the summary sheets. When new data is entered, it should be placed in this worksheet rather than using the summary sheets.

8.1.4 Built Up Rates Worksheet

In the model this sheet is labelled 'Rates'. This sheet contains all the built up rates which can be plugged into the structure data for the overall calculations. These figures are gathered from the other data sheets and if a simple record of the values used at any given point is required then this is the table which should be printed. The format has been set to allow printing to occur with the data taking up one sheet in width printed in landscape. Some of the values in this table have been used in the calculation of other process values so, for example, the values for tower cranes are used in most other calculations. Each line in this sheet is a copy of the final summary line in other sheets, so no actual calculation occurs. A sample of this data in shown as Table 8-2. Each item includes in the title the data source. In most cases this is 'SEEAM' showing that the data has been gathered exclusively for this thesis. Where two sources have been shown but SEEAM is listed first the calculation uses data from another source as part of the overall calculation, usually a unit rate for steel or cement, but this data is supplementary. Where SEEAM is listed second the result has been modified only slightly for this work. In reading data from the table care is required to ensure that the units are correct in each case because they differ from item to item.

Table 8-2: Built Up Rates Table Example

Name Of Process	Units	Energy GJ/unit	CO_2 kg/Unit	Transport Miles/Unit	Hours/Unit
Large Mobile Crane (SEEAM)	Day	10.450	686.44	100.00	3.333
Medium Mobile Crane (SEEAM)	Day	9.216	605.43	100.00	2.857
154 EC-H6 (One Cycle) (SEEAM)	Cycle	0.009	0.51	0.18	0.004
280 EC-H (One Cycle) (SEEAM)	Cycle	0.013	0.78	0.38	0.009
Basic Site Hut Per Person (SEEAM)	Week	0.153	8.72	2.00	0.053
Site Office Per Person (SEEAM)	Week	0.381	21.47	4.00	0.107

8.1.5 Imported Data Worksheet

In the model this sheet is labelled 'Imported' and contains the few values which could not be gather at first hand. Where values from the Oxford Brookes work have been used, the data has had the transportation element removed and replaced by a value calculated for this report only the basic value is shown on this sheet, while the total figure is listed with the built up rates. The table is set up in the same way as other examples with the data source listed last. Although a column has been provided for the transportation distance and time, no external data was available which provided this information, so the columns are not used. Table 8-3 shows an example of the imported data table.

Table 8-3: Imported Data Example

Name Of Process	Units	Energy GJ/unit	CO_2 kg/unit	Transport miles/unit	hours/unit	Source
Explosive	t	0.001	0.00			MacSporran
Cement	t	5.800	1193.00			BRE
Steel (Structural)	t	26.360	1997.00			OB
Steel (Reinforcement)	t	16.860	1277.29			OB

8.1.6 Plant Energy Worksheet

In the model this sheet is labelled 'Plant'. This worksheet contains data for specific machines performing specific actions. A sample of the data is shown in Table 8-4. The actual table also includes a notes column which has been excluded in this case to allow the table to fit on the page.

Table 8-4: Plant Energy Data Example

Use	Plant Type	Material (units/day)	Units	Fuel (g/day)	Energy GJ/unit	CO_2 kg/unit
Earth Excavation	Tracked Excavator	392.0	m3	40.0	0.020	1.33
BFI Move Materials (New)	Tipper	1200	t	44.0	0.007	0.48
BFI Supply Crusher (New)	Wheel Loading Shovel	1200	t	22.0	0.004	0.24
BFI Crushing (New)	Crusher & 3 Screens	1200	t	110.0	0.018	1.19
PO Demolition	Ruston Bue Cyrus 25RB	203	m2	50.0	0.049	3.21
PO Strip and Crushing	Samsung 280	290	m2	39.0	0.027	1.75
PO Breaker	Samsung 280	405	m2	39.0	0.019	1.25

8.1.7 Transportation Impacts Worksheet

In the model this sheet is labelled 'Travel' and shows all the routes which have been used in building up total environmental impacts. The data in this table is called upon mainly when building up new rates and alterations to the values for distance, speed and fuel consumption are linked to these figures. Table 8-5 shows sample data from this worksheet. In the model the route name is supplemented by columns showing origin and destination, but these have been omitted to allow the table to fit on the page. The column showing the 'split' indicates how the environmental impacts for the route should be allocated between the different units. In the case of, for example, aggregate this is simply the load per lorry (17t). Where the route is, for example, transportation of plant, the split will be 1, indicating that all the impacts are allocated to the machine being moved. Where one load forms part of a machine, for example with a tower crane, the route impacts are multiplied out as the rate is built up. The calculations for energy, CO_2 and travel are controlled by equations which should not be altered.

Table 8-5: Travel Data Example

Route Name	One Way	Speed	Fuel	Split	Energy	CO_2	Travel	
	(miles)	(MPH)	(MPG)		GJ/unit	kg/unit	miles/unit	hours/unit
Aggregates 1	20.0	20.0	9.0	17.0 t	0.052	3.40	2.35	0.118
Aggregates 2	25.0	20.0	9.0	17.0 t	0.065	4.25	2.94	0.147
Cement 1	41.1	37.5	7.5	25.0 t	0.087	5.70	3.29	0.088
Cement Additives 1	17.5	37.5	9.0	1.0 t	0.770	50.56	35.00	0.933

8.1.8 Rate Build Up Worksheet

This sheet contains the data used in the rates as they were built up, and these tables have been used in the thesis under the heading Table X.Y: Environmental Impacts, Material/Process. In addition to the data transferred into the thesis, there are a number of other parameters which can be altered and which affect the calculated results, for example the waste values used. The build up of these rates calls on data from all of the other data sheets. The data has been presented as a single column rather than using the width of the sheet (that is the tables are placed above and below each other rather than side by side) which allows all the data to be printed out more easily.

Table 8-6 shows a sample data table. It should be noted that this information has extra information from that presented in the thesis, which was needed in data configuration. For example the column 'items' shows that the plant rate for a wheeled loader should be multiplied by four because that is the number of items employed in that process, while there is only one tipper and one set of crusher and screens. The actual tables also include a column for notes which has been excluded in this example. The headings and use of these modifier columns change depending on the process being analysed.

Table 8-6: Data Build Up Example

Aggregates (New)	Embodied Energy (GJ/t)	Embodied CO_2 (kg/t)	Distance (miles/t)	Time (hours/t)	Materials Week	People	Items
Explosive	0.001	0.00					
Wheeled Loader (x4)	0.015	0.95					4
Tipper	0.007	0.48					1
Crusher And Screens	0.018	1.19					1
Basic (Landfill)	0.000	0.00			9888	4	
Office (Landfill)	0.000	0.02			9888	10	
Transportation	0.052	3.40	2.35	0.118			
Total	0.093	6.04	2.35	0.118			

8.1.9 Calculations Worksheet

This worksheet contains the constituent data, for example, the calculations of tower crane slewing, office energy and all of the information gathered from companies (except where this was confidential). A number of these tables appear in the thesis document.

While this worksheet contains the information built up for concrete constituent materials, the calculations for concrete are carried out on another sheet, due to the special requirements which become apparent when the data is viewed.

8.1.10 Concrete Worksheet

This worksheet contains the calculations used in building up rates for each concrete mix assessed. This information was placed on a separate sheet because the calculations required a very 'wide' table.

The range of mixes assessed can easily be extended downward as can the parametric data. The parameters which can be changed come in two groups which apply to all mixes and which apply to each mix. The parameters which apply to all mixes include the environmental impacts for concrete constituents (cement, aggregates, etc.) while the details which apply to each mix are the method of placing, the waste allowance and the expected number of loads per trip.

A printout is available for these concrete mixes (the mix being selected using a dropdown menu) showing each of the measured parameters. This feature has been used in creation of the data shown in Appendix B.

8.1.11 Base Data Worksheet

The table includes the fundamental building blocks for all the figures including the energy for diesel, the conversion factors from delivered to primary and CO_2 values. These values are linked to all the calculations made elsewhere so altering, for example, the conversion factor for electricity will affect all processes where electricity is used. Care is therefore required to ensure that this data is correct.

8.1.12 Graphics Worksheet

This sheet contains graphics other than those already noted for concrete and summary results. These are linked to the calculation data and will change to reflect changes in the data. Only those graphics considered most important have been included, because there are simply too many possible combinations for every parameter to be shown. The majority of these have been created for use in the thesis.

8.2 Conclusions

A model has been created which allows calculation of frame environmental impacts in a form where the basic data is clearly shown. It allows a wide range of parameter to be varied, while remaining reasonably easy to understand. It is also possible to substitute alternative values where there are variables which require exploration, for example the embodied energy value for steel. The basic data used in this model allows an evaluation of the frame materials, however a similar architecture could be used to extend the model and cover other areas, for example the cladding. A proportion of the data would common to all construction activities.

The model also allows customisation to suit specific situations, for example an individual company operation. The presentation of results is such that is reasonably clear which 'headline' figures have been used, although to extract more detailed figures requires a more detailed examination of the model set up.

This model has been used in conjunction with the gathered data to calculated the results presented in the next chapter.

9. RESULTS

The model discussed in the previous chapter has been used to make an environmental assessment of a range of buildings frames. This has been done both to assess where the environmental impacts occur for different frame types and to make comparisons between frame materials, specifically concrete and steel. The structures examined represent only a few out of the many possible designs and there many be marked differences between buildings.

9.1 The Designs

These types were taken from a cost model produced by the Reinforced Concrete Council. This model included enough detailed design information to allow a reasonable depth of environmental analysis of four building types - 3 and 7 storey buildings located along both the M4 and M62 corridors. All four of these buildings were designed in steel and concrete. The basic plan and elevation for the 3 storey buildings are shown in Figure 9-1 and Figure 9-2. The 7 storey buildings are similar to the 3 storey buildings in plan, simply having a greater number of floors. This affects the column but not the floor design.

The quantities for these buildings were published along with the cost information and these have been used, with some simple modifications to make the calculation. The modifications made involved some reorganisation of the data into groups which could be assessed using the SEEAM. For example the quantity for concrete blinding was given as x m^2 at 50 mm depth and this was changed to m^3 for calculation purposes. The data input into the model is shown in Table 9-1. As noted in Chapter 7, the demolition data is calculated using the building floor area and the materials quantities, so no data input is required for this section.

The values for the steel buildings used in the Oxford Brookes report would have been used for comparison purposes but because they have not been published they are not available. It might have been possible to calculate the quantities using the dimensions provided in the relevant references, but problems of accuracy would apply.

Figure 9-1: M3 Corridor Plan & Elevation

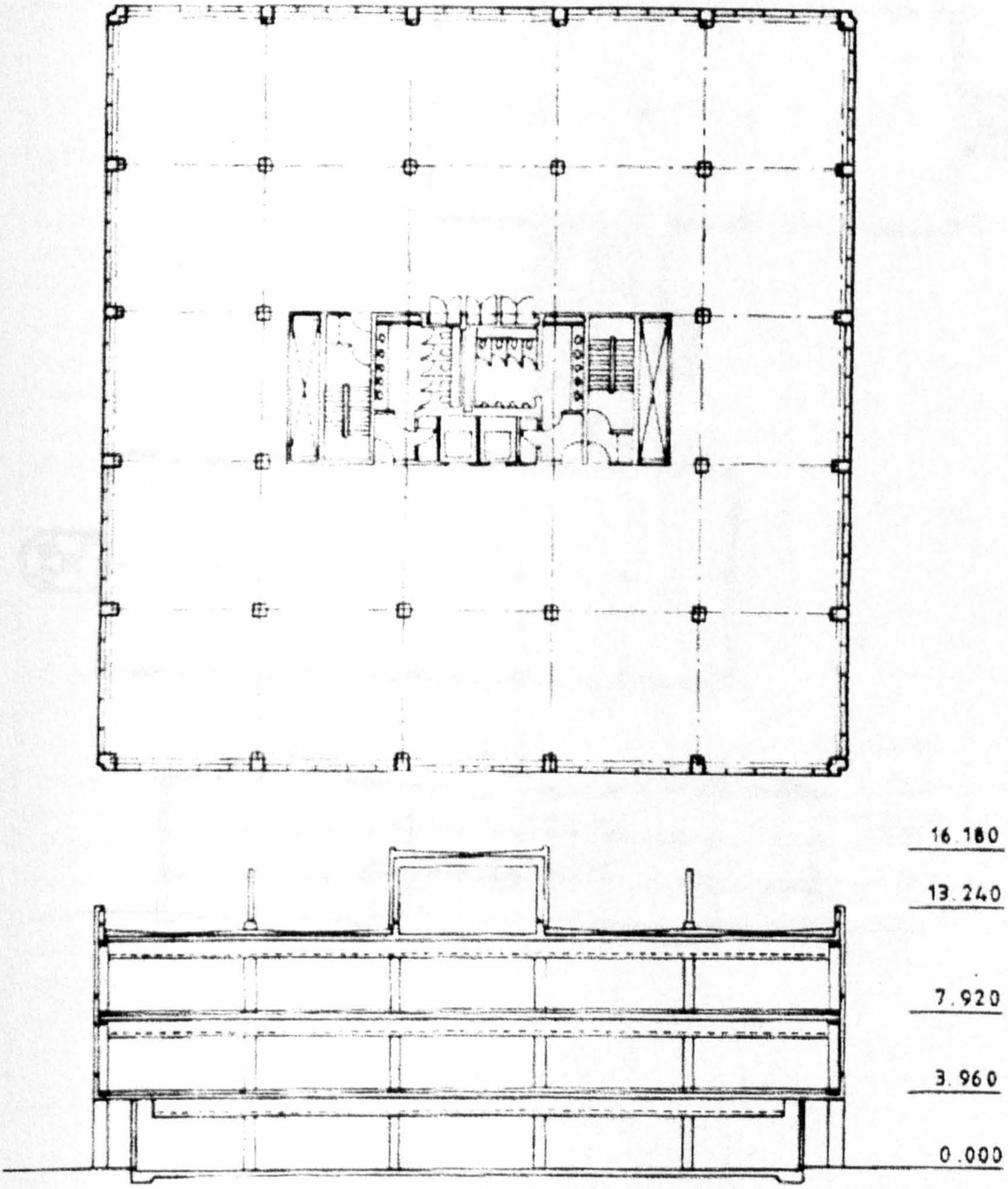


Figure 9-2: M62 Corridor Plan & Elevation

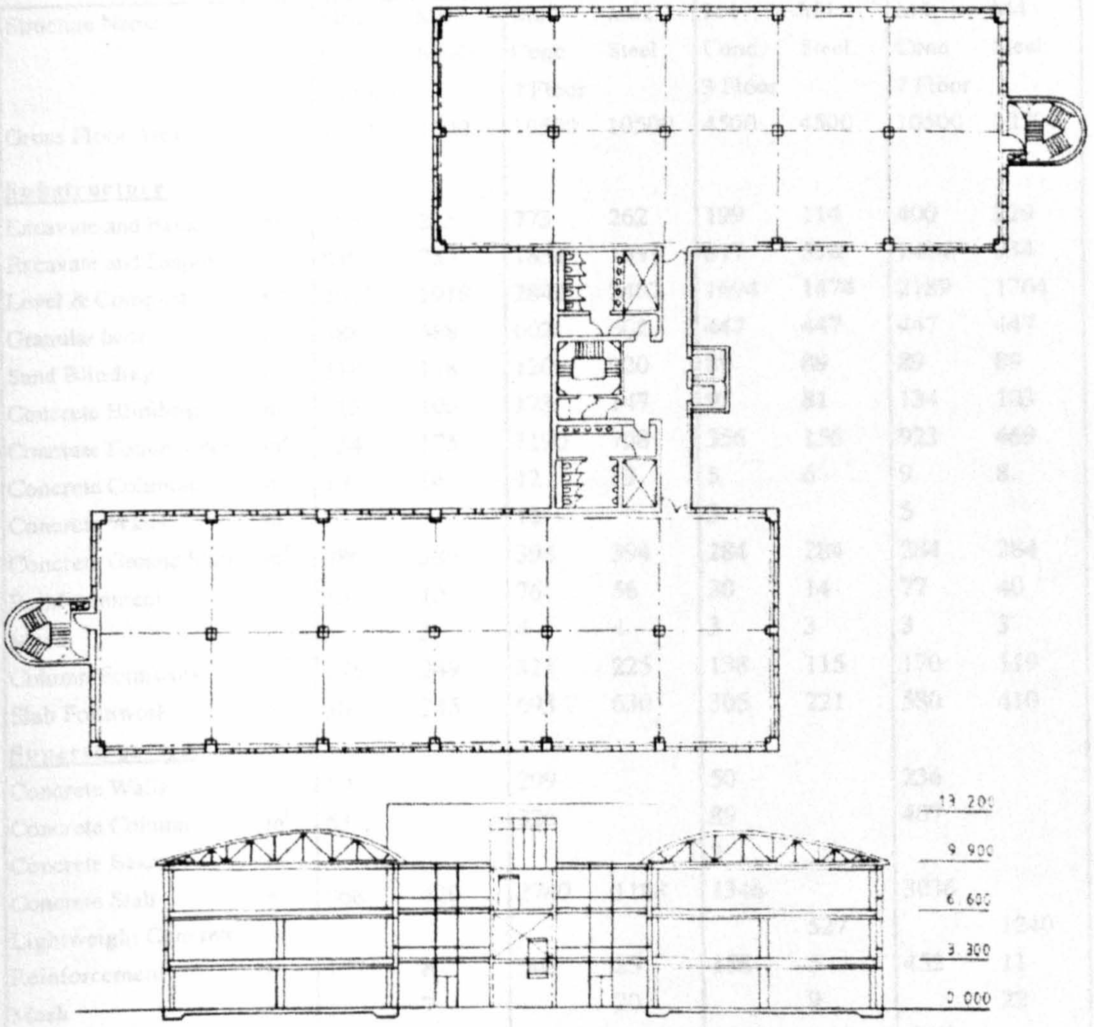


Table 9-1: Standard Building Quantities

Structure Name		M62 Conc 3 Floor	M62 Steel	M62 Conc 7 Floor	M62 Steel	M4 Conc 3 Floor	M4 Steel	M4 Conc 7 Floor	M4 Steel
Gross Floor Area		4500	4500	10500	10500	4500	4500	10500	10500
Substructure									
Excavate and Backfill	m^3	255	225	273	262	199	114	400	229
Excavate and Dispose	m^3	839	753	1851	1391	817	596	1434	934
Level & Compact	m^2	2013	1918	2842	2492	1694	1474	2189	1764
Granular beds	t	588	588	602	602	447	447	447	447
Sand Blinding	t	118	118	120	120	89	89	89	89
Concrete Blinding	m^3	112	105	173	147	97	81	134	103
Concrete Foundations	m^3	254	175	1190	758	356	156	923	469
Concrete Columns	m^3	10	16	12	13	5	6	9	8
Concrete Walls	m^3	7		12		3		5	
Concrete Ground Slab	m^3	386	386	394	394	284	284	284	284
Reinforcement	t	19	15	76	56	30	14	77	40
Mesh	t	3	3	4	4	3	3	3	3
Column Formwork	m^2	275	249	321	225	138	115	170	119
Slab Formwork	m^2	301	245	693	630	305	221	580	410
Superstructure									
Concrete Walls	m^3	60		299		50		236	
Concrete Columns	m^3	53		326		89		407	
Concrete Beams	m^3					2			
Concrete Slab	m^3	968	420	2740	1188	1346		3036	
Lightweight Concrete	m^3						527		1240
Reinforcement	t	157	8	508	25	158	5	452	11
Mesh	t		7		20		9		22
Column Formwork	m^2	1262		5434		1599		5362	
Slab Formwork	m^2	3227		9133		4214		9920	
Steel Decking	m^2		3230		9138		4214		9920
Steelwork	t	53	230	54	600		208		534
Fire Protection	m^2	431	3525	511	10319		3480		8355

Calculation of the results for this data has been approached in the same way as the calculations for concrete, with a standard data set used to assess all the buildings then other parameters for two selected buildings. To make the structural differences more apparent the M4 7 floor building was used for this purpose because the M64 building contains more materials cross over. It is also worth noting that the M4 steel buildings were designed to use lightweight concrete and this will make the examination of the associated energy effects more valid than if a design where lightweight concrete has simply been substituted for standard concrete.

9.2 The Standard Data Set

The values contained in the standard data set are particularly important when the spread of results noted in Chapter 7 is taken into account, in particular for concrete. For the initial analysis the concrete has been assumed to be 'standard' OPC mixes, C30 pump mix for slabs and C40 skip mixes for columns, walls and beams. The lightweight concrete calculation uses the C30 lytag pump mix. This will tend to slightly overestimate the impacts, because a significant proportion of current mixes make use of other cementitious materials. The values selected as standard data are shown in Table 9-2.

Table 9-2: Standard Unit Rates

Item	Unit	Energy GJ/unit	CO_2 kg/unit	Transport miles/unit	hours/unit
Excavation and disposal (SEEAM)	m^3	0.075	4.93	1.80	0.120
Excavation and Backfill (SEEAM)	m^3	0.058	1.16	0.02	0.001
Aggregates (New) (SEEAM)	t	0.093	6.04	2.35	0.118
Static Batching (SEEAM)	m^3	0.018	1.01		
Cement (BRE/SEEAM)	t	5.800	1193.00	3.29	0.088
Lytag (SEEAM)	t	0.920	58.27	12.35	0.329
Admixtures (SEEAM)	lt.	0.001	0.05	0.04	0.001
Release Agent (SEEAM)	lt.	0.041	0.05	0.03	0.001
Reinforcement (Standard) (SEEAM/OB)	t	17.872	1343.50	22.69	0.625
C20 (SEEAM)	m^3	1.548	392.37	5.18	0.261
C30 Pump (SEEAM)	m^3	1.973	474.82	5.48	0.268
C30 Lytag Pump (SEEAM)	m^3	3.104	540.30	12.23	0.451
C40 (SEEAM)	m^3	2.087	495.60	5.17	0.255
Mesh (SEEAM/OB)	t	18.149	1359.03	26.71	0.732
Structural Steel (Standard) (SEEAM/OB)	t	27.816	2083.12	10.10	0.401
Pumping (200m^3 pumped)	m^3	0.013	0.82	0.50	0.020
Formwork (Shaped Soffit) (SEEAM/OB)	m^2	0.130	8.94	0.28	0.008
Formwork (Flat Slab) (SEEAM/OB)	m^2	0.043	1.95	0.26	0.007
Formwork (Non Slab) (SEEAM/OB)	m^2	0.052	2.78	0.26	0.008
Steel Decking (SEEAM/OB)	m^2	0.375	29.35	0.28	0.007
Fire Protection (18 mm Vicuclad) (SEEAM/OB)	m^2	0.553	2.66	0.49	0.013
Level & Compact (SEEAM)	m^2	0.018	1.20	0.02	0.002
Demolition (Concrete)	m^2	0.091	5.98	0.015	0.001
Demolition (Steel)	m^2	0.068	4.47	0.010	0.001
Rubble Off Site Transportation (Uncrushed)	t	0.036	2.36	1.719	0.069
Steel Transportation (Demolition)	t	0.012	0.79	0.545	0.022
Reinforcement Transportation (Demolition)	t	0.040	2.60	2.400	0.096

9.3 The Parametric Data

There is a wide range of parameters which could be adjusted altering the results produced by the Structural Embodied Energy Assessment Model. The majority of these are associated with concrete production and use because, as noted in Chapter 7, the production and use of steel is carried out under much more controlled conditions than concrete and has smaller range of activities associated.

No consideration has been given to factors which have been assessed in chapter 7 and one 'reasonable value' has been identified. For example the value for reinforcement has been based on a value for recycled steel of 16.86 GJ/t. It is possible to assess reinforcement energy using the much higher steel figure of 26.36 GJ/t for structural steel. This has not been done for the simple reason that the mills producing this type of steel require the lower and not the upper energy and to simply change these values would be incorrect, however the possibility of structural steel production at a lower cost has been addressed, using the value calculated in Chapter 7.

There is such a wide range of parameters that simply altering values which, in reality, are fixed would simply serve to unnecessarily obscure the overall results. The factors identified for alteration therefore represent data which might reasonably be expected to vary on a site by site basis and have been used to provide a lowest and highest reasonable range of results. Five major factors have been identified which should be addressed in this parametric study, supplemented by one set of combined of factors, shown below.

- All the results will be altered by changing the basic transportation factors, for example increasing the distances involved. However, as shown in the results using the basic data set, concrete use incurs considerably greater impacts in this area than steel and changing the basic values would thus have more effect. The transportation values used in the model are considered representative of construction generally and while accurate use of the model for any specific design would require the values to be localised, there is little point in doing so in a general assessment. Two factors have been modified which will have a serious effect on the transportation elements, both of which might reasonably occur - on site batching and on site aggregate recycling. These are expected to provide environmental impact figures which are approaching the lowest possible for transportation. Where this option has been chosen, it is assumed that the quantities required for the new building match or are less than those from demolition. Any materials left over are assumed to be used on site for landscaping or other purposes. Where not enough materials are available on site and would need to be imported, no allowance is made and the environmental impacts will be underestimated. This factor will vary from site to site.

- The constituents of concrete can have a major effect on the calculated embodied energy and CO_2 for each mix. High and low values for aggregate and cement have been used to calculate the upper and lower bands for these environmental impacts.

- The other factor that was identified as having a major impact on concrete environmental impacts was the mix design and more specifically the use of cement replacement materials. The mix designs suggested in Chapter 7 are reasonably representative of the range which might be found on site therefore, where a substitution has been made, a similar mix type with the lowest embodied energy has been used. This applies to both standard and lightweight mixes.

- The two factors of mix design and on site batching and recycling have been combined to give an overall lowest value for concrete use.

- The standard data set provides fire protection using 18 mm board vicuclad. This will provide between 1 - 1.5 hours of protection depending on the use which would a adequate in most circumstances. The 30 mm option, providing 2 hours of protection, might be required in some circumstances and so this option has been used to assess the upper energy requirement for this factor. A value has also been provided for a structure with no fire protection for comparison purposes.

- The data rate calculated for structural steel produced using recycled steel has been used to see what effect a lower value has on the overall results

9.4 Structure Assessment

Each of the buildings has been considered, in the first instance, in conjunction with its pair (for example the M62 steel and concrete 3 floor structures) and then with all the other buildings for an overall analysis. The parametric study has been calculated for the M4 7 floor building, which is the last of the 4 pairs considered. For simplicity the full results have not been included in the thesis text, but are given in appendix C. Appendix C contains 2 tables and 4 figures for each of the building pairs assessed using the standard data. An additional 3 results sets have been provided for the altered concrete parameters (using GGBS, on site recycling and batching and on site recycling and batching with GGBS). The other parameter changes will not produce large differences in all the results so the graphics have not been shown. So, for example, altering the values for structural steel has no effect on any factors apart from one value for embodied energy and CO_2.

9.4.1 M62 3 Floor Steel and Concrete Buildings

The data for these structures are shown in appendix C, tables 1 and 2, with comparisons occurring in figures 1 to 4.

The concrete building incurs an embodied energy impact of 2.31 GJ/m^2 compared with the steel building value of 3.01 GJ/m^2. For this frame and data set the concrete frame is 77% of the steel total. The highest individual component in the steel frame is structural steel accounting for 49% of the total, while the fire protection is 15% and the decking 9%. Concrete makes up most of the rest at 18%. The pattern for the concrete frame is different with the major user of energy being concrete at 39% followed by reinforcement at 31% of the total. This structure also uses a significant quantity of structural steel which incurs 15% of the total. One other notable item is the formwork at around 5% of the total.

The pattern for CO_2 is different from energy, with the steel building having a lower total than the concrete - 268 compared with 275 kg/m^2. The difference is mainly due to the higher CO_2 generated by using cement compared with steel (cement generates around 2.7 times the CO_2 per GJ compared with steel). The steel and cement figures were not created for this thesis, so it is not possible to comment on how these rates were built up. For the steel structure the steel is the single largest item (41%), but the concrete used incurs almost as much (39%). The decking incurs 8% and the fire protection 5%. The concrete structure incurs the majority of CO_2 via the concrete (64%) and reinforcement (20%).

The transportation element reveals a different picture from energy and CO_2. The steel structure requires only 73% of that for concrete (4.6 against 6.3 miles/m^2). While the concrete structure incurs transportation for many items, the major occurrence is for concrete. Unlike for energy and CO_2 however there is also a large element for demolition rubble removal, which accounts for 17% of the total. The values for the steel frame are more evenly spread, but with demolition waste accounting for 16% of the total.

The transportation times show a similar pattern to the distances with the average time is 0.21 hours/m^2 for steel and 0.29 for concrete. The concrete traffic travels at an average of 21.7 MPH, which is very similar to steel traffic at 22.0 MPH, however there is simply more traffic generated by the concrete frame.

9.4.2 M62 7 Floor Steel and Concrete Buildings

The data for these structures are shown in appendix C, tables 3 and 4, with comparisons occurring in figures 5 to 8.

The results for the 7 floor structure are similar in nature to the results for the 3 floor version, except that the substructure is relatively less important. In energy terms the proportion for the concrete frame substructure has fallen from 22.8 to 21.4%, while for the steel structure the amount has fallen from 15.5 to 12.3%. This explains why the gap between the energy totals for the two materials has increased. The concrete requires 2.54 compared to 3.29 GJ/m^2, a reduction of 23%.

In terms of CO_2 the overall values are 282 and 309 kg/m^2 respectively for steel and concrete, a the difference of 10%.

In transportation terms the requirements have increased due simply to the higher quantities of concrete, aggregates and demolition materials that require moving. Demolition accounts for 18% of the total distance for concrete, while for steel the figure is

16%. The average transportation distance for concrete is 7.03 miles/m^2 while the value for steel is 4.40, representing a 37% reduction by using steel. The values for transportation follow a similar pattern but, due to the low speeds of bulk aggregate and concrete movement, the gap has widened to 0.13 hours/m^2 from 0.08 hours/m^2 for the smaller building. The steel traffic is now also travelling slightly faster than for concrete at 22.7 and 22.1 MPH respectively.

9.4.3 M4 3 Floor Steel and Concrete Buildings

The data for these structures are shown in Appendix C, tables 5 and 6, with comparisons occurring in figures 9 to 12.

There are significant differences between the M4 and the M62 building in terms of materials. While the M62 concrete buildings makes significant use of structural steel for the roof, the M4 has none. The figures for these buildings should therefore represent more extreme values for concrete and steel.

The overall energy values are 2.00 and 2.76 GJ/m^2 for concrete and steel respectively, with the concrete value being only 72% of the steel value. The superstructure represents 69% of the energy total for concrete and 85% for steel. The use of lightweight concrete in the steel structure means that a volume of 527m^3 is required for the suspended slabs against 1346 m^3 for the standard concrete structure. The energy required for the lightweight concrete is 1636 GJ against 2842 GJ. This means that while the quantity of concrete for the steel structure is 57% lower than in the concrete structure, the energy is 68%. This would suggest that the use of lytag concrete is justified in energy terms where normal OPC mixes are concerned, however when comparison is made with the M62 3 floor structure the picture is different. The steel structure requires a concrete volume of concrete of 420m^3 which is less than the lightweight concrete required in the M4 structure! There is however a 22 tonne saving in structural steel. Clearly the issue of treatment of lightweight concrete is a complex one and is thus discussed further in the summary section.

Even for this structure, where the concrete has a significant advantage in terms of embodied energy, the steel structure still has a lower CO_2. The embodied CO_2 for the steel structure is 251 while the concrete produces 264 kg/m^2, a reduction of 5%. The same pattern emerges with the transportation distances, with the steel structure incurring 29% less miles than the concrete option. The reduction in transportation time is even greater at 39%. The difference in overall traffic speed is the greatest observed so far, with the concrete structure traffic moving at an average of 21.5 MPH, compared with steel traffic at 24.4.

9.4.4 M4 7 Floor Steel and Concrete Buildings

The data for these structures are shown in Appendix C, tables 7 and 8, with comparisons occurring in figures 13 to 16.

The M4 7 floor building might be expected to exhibit the most pronounced differences between steel and concrete because of the larger totals of materials involved and the smaller balancing effect of the substructure.

The embodied energy show a similar difference to the 3 floor the structure, with a value of 2.08 for concrete and 2.78 for steel so the concrete structure represents a reduction in energy of 25%. The energy for the steel frame is provided mainly by the structural steelwork (47%), while the fire protection, steel decking, mesh and concrete all contribute between 11-15% The concrete structure energy is made up almost completely two items - concrete (46%) and reinforcement (41%), with formwork contributing 6.9%. The substructure is again a much larger item for concrete (20%) than steel (9%), due to the much lower overall weight for steel and the higher energy cost for the steel items. The concrete structure frame material weighs 12614t, while the equivalent figure for steel is 5142t, a reduction of 60%!

The concrete again contributes the majority of the CO_2 towards the total, which is again higher than for the steel frame. The steel frame produces an embodied CO_2 requirement of 243 kg/m^2 compared with 264 for the concrete frame, a reduction of 8%

The transportation total follow a similar pattern to the previous examples, with the steel frame incurring significantly lower loads than the concrete frame. The required transportation distance for steel is 3.93 miles compared with 6.03 for concrete, a reduction of 35%. The gap in transportation time is even wider with a requirement for the steel frame of 0.15 hours/m^2 compared with concrete which requires 0.27, a reduction of 41%. The overall traffic speeds are similar to the 3 floor structure at 22.0 MPH and 25.4 MPH for concrete and steel respectively.

9.4.5 M4 7 Floor Steel and Concrete Buildings Using GGBS Concrete

The data for these parameters are shown in Appendix C, tables 9 and 10, with comparisons occurring in figures 17 to 20.

As noted in chapter 7, the use of cement replacement materials reduces the energy requirement for concrete significantly. For this assessment, the mixes using GGBS have been used because these produced the lowest overall energy requirements. This may not be the case if the base values, such as for transportation are changed.

The picture for both embodied energy and CO_2 is changed considerably in this permutation. The energy for concrete is now 1.78 GJ/m2 compared with 2.64 for steel, a difference of 33%. This represents a saving in the total frame energy of 3335 GJ for the concrete frame (a 14% reduction) and 1565 for steel (a 5% reduction). To place this into perspective, the reduction would allow an extra 1.5 floors to be added to the concrete structure at no added energy cost (neglecting substructure requirements) compared with use of the standard OPC concrete.

The steel structure now also has a higher CO_2 requirement compared with the concrete (206 kg/m^2 compared with 186, a difference of 6%). This is simply due to the substitution of GGBS for cement which has a larger effect in the concrete than steel frame. The concrete frame CO_2 requirement has been reduced by a massive 30% simply by this single measure, while the steel requirement is reduced by 16%.

The opposite effect is observed in the transportation requirement due to the increased distances required in GGBS transportation. The concrete frame requirement increases by 7% to 6.46 miles/m^2 while the steel frame requirement increases by 8% to 4.22 miles/m^2. The increase is lightly higher in the steel frame because the concrete materials have a greater effect than the smaller quantities for steel.

9.4.6 M4 7 Floor Steel and Concrete Buildings Using On Site Recycling and Batching

The data for these parameters are shown in Appendix C, tables 11 and 12, with comparisons occurring in figures 21 to 24.

The effect of altering this parameter has had limited effects on the embodied energy and CO_2, but massive effect on the transportation elements. There is a slight reduction in the energy for the concrete frame by 2% and 1% for the steel frame and the reductions in CO_2 are even lower (around 1%). However the transportation distance has fallen by 42% for the concrete frame and 21% for the steel. Even greater reductions in travel time are observed, by 55% for concrete and 35% for steel. Overall traffic speed is increased by 30% for concrete and 18% for steel. These massive increases can be attributed to the virtual elimination of the high volumes of slow moving traffic generated from batching plants and quarries.

Even using this set of parameters to massively reduce the concrete transportation requirements, the steel frame still incurs lower transportation distances (3.10 to 3.49 miles/m^2) and transportation times (0.10 to 0.12 hours/m^2). The transportation requirements for lightweight concrete are much more significant due to the requirement to bring the Lytag over long distances, because they can not be created on site. In this option the demolition transportation requirement represents the largest single factor at 34%.

It should be noted that the on site recycling of aggregates refers to those required at the start of the building life where it is assumed that a building has been demolished and these materials are used. The demolition at the end of the building life is a parameter which has not been changed.

9.4.7 M4 7 Floor Steel and Concrete Buildings Using Lowest Reasonable Values

The data for these parameters are shown in Appendix C, tables 13 and 14, with comparisons occurring in figures 25 to 28.

This data set adds the effects from both changes to the concrete mix designs and on site batching and recycling. This represents close to the minimum environmental impact values that could be applied in the majority of situations. Other reductions could be made, either by refining minor items or by reduction of the transportation element, but these should be assessed on a case by case basis.

This combination provides a reduction in the embodied energy of the concrete structure of around 17% and 5% for steel. The difference between the two structures has increased from 25% to 34% (steel 2.63, concrete 1.73 GJ/m^2). The total savings are only slightly better than when simply using GGBS mixes.

For this combination, the CO_2 requirements for the concrete frame requires only 94% of that for the steel frame. This set of parameters assumes that GGBS concrete is used and thus the transportation requirements increase slightly due to greater distances involved.

9.4.8 M4 7 Floor Steel and Concrete Buildings Using 30 mm Vicuclad

The data for this parameter is shown in Appendix C, tables 15 and 16.

Due to the high embodied energy for fire protection, increasing the thickness of the board from 18 to 30 mm (broadly this will increase fire protection from 1 - 2 hours) will significantly increase the environmental impact. The impact on the travel elements is negligible when compared to the movement of bulk materials such as concrete. This simple measure will increase the energy for the steel structure from 2.78 to 3.06 GJ/m^2 (an increase of 10%), which compares to the standard figure for the concrete structure of 2.08 GJ/m^2. With this option the concrete frame requires 68% of the energy for the steel structure.

There is also an increase in the overall CO_2 requirement from 250.1 to 251.5 kg/m^2, which represents a change of less than 1%.

9.4.9 M4 7 Floor Steel and Concrete Buildings Using Recycled Structural Steel

The data for this parameter is shown in Appendix C, tables 17 and 18.

The value for steel has been reduced from 27.8 to 18.2 GJ/t, a reduction of 35% and this lowers the frame embodied energy from 2.78 to 2.33 GJ/m^2, which compares to a concrete value of 2.08 GJ/m^2. The steel structure is therefore still 12% more energy intensive than the concrete.

The embodied CO_2 has also been reduced to 209 kg/m^2 compared with the value of 264 for the concrete, a reduction of 63%.

9.4.10 M4 7 Floor Steel and Concrete Buildings Using Low Cement and Aggregate Values

The data for these parameters are shown in Appendix C, tables 19 and 20.

The reduction of energy in aggregates and cement has a greater effect for the concrete frame than the steel, exacerbated by the use of Lytag, for which the energy value is unaffected. The new aggregate value is 0.02 compared with the standard value of 0.09, a reduction of 78%, The cement value is reduced by 12%. For these parameters, the concrete frame energy is 1.91 (reduced from 2.08) while the steel energy is 2.72 (reduced from 2.78). The gap between the two frames is therefore increased to 30%.

The CO_2 values for the low energy figures have not been assessed because of lack of source data, but this change would be expected to decrease the difference between the two materials.

9.4.11 M4 7 Floor Steel and Concrete Buildings Using High Cement and Aggregate Values

The data for these parameters are shown in Appendix C, tables 21 and 22.

In a similar way to the reduction of energy values, an increase has a disproportionally large effect on the concrete frame. In this case the increase in Aggregate energy to 1 GJ/t (from 0.09, an increase of 11 times) has given it a slightly higher energy requirement than Lytag. The cement value is increased by 16%. This means that overall the Lytag and standard concrete mix have almost identical energy values (4.151 GJ/m^3 for Lytag pump and 4.125 GJ/m^3 for the OPC pump). The higher value for aggregate is slightly offset by the Lytag requirement for more cement than the standard mix. These values mean that the steel structure has an energy of 3.05 GJ/m^2 compared with the concrete value of 2.97, a difference of less than 3%! It is considered unlikely that an aggregate with an energy requirement this high would ever be used in standard structure because, apart from other considerations, the financial cost would be large.

9.5 Overall Comparisons For All Data

The results for all the structures have been collected to show the energy, CO_2 and transportation elements for all the frames in two tables, one for the buildings using the standard data set and one for the parametric study. The tabulated data has been presented in overall rank order, from lowest (best) to highest (worst) and thus the buildings and options may occur in a different order for each of the measured impacts.

9.5.1 Embodied Energy

The embodied energy results for the standard data set is shown in Table 9-3 while the parametric data is shown in Table 9-4.

Table 9-3: Breakdown of Frame Embodied Energy (Rank Order)

	Total GJ/m^2	Substructure GJ/m^2		Superstructure GJ/m^2		Demolition GJ/m^2	
M4 Concrete 3 Floor	2.00	0.50	25.1%	1.39	69.2%	0.12	5.8%
M4 Concrete 7 Floor	2.08	0.41	19.9%	1.55	74.6%	0.11	5.5%
M62 Concrete 3 Floor	2.32	0.53	22.8%	1.68	72.2%	0.12	5.0%
M62 Concrete 7 Floor	2.54	0.54	21.4%	1.88	73.9%	0.12	4.7%
M4 Steel 3 Floor	2.76	0.34	12.2%	2.35	84.9%	0.08	2.9%
M4 Steel 7 Floor	2.78	0.25	9.1%	2.45	88.1%	0.08	2.8%
M62 Steel 3 Floor	3.01	0.47	15.5%	2.46	81.7%	0.08	2.8%
M62 Steel 7 Floor	3.29	0.41	12.3%	2.80	85.1%	0.08	2.5%

The substructure represents a higher proportion of the total energy in the concrete frames. The substructure represents between 20 - 25% for the concrete frame and between 9 - 16% for the steel frames. In energy terms, on a pair by pair basis the steel options are between 0.06 - 0.17 GJ/m^2 lower. In all cases the substructure represents a lower proportion of the total for the taller buildings with a reduction in the proportion of around 2 - 5% for an increase from 3 - 7 floors. The steel frames all incur lower materials weights, especially where lightweight concrete is used. The M62 steel structures require only 52 and 63% of the weight of materials of the concrete version, while for the M4 structure the figures are 46 and 41% respectively.

The superstructure requires more energy in the superstructure both in terms of the proportion and in absolute terms. On a pair by pair basis the increase in energy is between 0.79 - 0.96 GJ/m^2. Thus in energy terms, where the substructure is a higher proportion of the total there is less difference in the overall energy between steel and concrete, due to the averaging effect it exerts because of the similarity of materials and quantities involved.

The demolition energy is higher for concrete structures due to the greater quantity of materials involved. On a pair by pair basis the reduction is around half in proportion terms and 66% in energy terms.

The effect of using lightweight concrete varies between the two structures. The energy reduction between the M4 (lightweight) and M62 (standard concrete) buildings is 0.16 and 0.13 GJ/m^2 for the 7 and 3 floor structures respectively. The saving for superstructure is 0.35 and 0.11 GJ/m^2. The majority of the energy saving in superstructure comes from a lowering of the structural steel requirement from 1835 and 612 GJ for the 7 and 3 floor structures although the concrete energy increases from 1341 and 749 GJ for the same structures. These values are calculated at an energy value of

27.8 GJ/t for steel, 2.1 GJ/m^3 for C30 pump concrete and 3.0 GJ/m^3 for C30 Lytag pump. If the steel energy is reduced to 18.2 GJ/t while the concrete values are the same there is a net increase in both structures. Alternatively, lowering the concrete values, for example by using GGBS or PFA while the steel value is held constant would increase the saving.

Overall, although there are differences between the two designs, the similarities, including the structural grid, suggest that comparisons can be made. This suggests that while lightweight concrete is more energy intensive per m^3, in overall terms, an energy saving is made, although this will depend on the relative energy values of the materials. The energy saving in larger buildings will accrue mainly from a reduced structural steel requirement. For structures with fewer floors, the savings in other areas would have to be considered as well to balance the energy equation.

For all the structures concrete requires less energy than steel with, on a pair by pair basis, the increase for steel being between 30 - 38%. In real terms this represents an increase in energy required of around 8000 GJ for the M4 7 floor structure or 0.75 GJ/m^2. The effect of this is examined fully in section 9.6.

Table 9-4: M4 7 Floor Parametric Embodied Energy (Rank Order)

Parameter	GJ/m^2	
M4 Concrete 7 Floor, On Site Recycling & Batching, GGBS Concrete	1.73	
M4 Concrete 7 Floor, GGBS Concrete	1.78	103%
M4 Concrete 7 Floor, Low Cement & Aggregate Values	1.91	111%
M4 Concrete 7 Floor, On Site Recycling & Batching	2.02	117%
M4 Concrete 7 Floor	2.08	120%
M4 Steel 7 Floor, Recycled Structural Steel	2.33	135%
M4 Steel 7 Floor, On Site Recycling & Batching, GGBS Concrete	2.63	152%
M4 Steel 7 Floor, GGBS Concrete	2.64	153%
M4 Steel 7 Floor, Low Cement & Aggregate Values	2.72	157%
M4 Steel 7 Floor, On Site Recycling & Batching	2.77	160%
M4 Steel 7 Floor	2.78	161%
M4 Concrete 7 Floor, High Cement & Aggregate Values	2.97	172%
M4 Steel 7 Floor, High Cement & Aggregate Values	3.05	176%
M4 Steel 7 Floor, 30 mm Vicuclad	3.06	177%

The parametric data, shown in Table 9-4, reveals the possible range of data. Although it is possible to get higher and lower figures for both steel and concrete, this data is thought to represent the extreme figures which are most likely achievable.

The lowest figure overall was provided by using on site batching using OPC/GGBS mixes and on site recycled aggregates, which represents a reduction of 17% from the standard figure, however simply using OPC/GGBS mixes provides most of the reduction (14%) with out the 'on site' aspect. Using the low energy figures for cement and aggregates provides a reduction of only 8%. This is due to the calculated standard figure being relatively low and the small range of the BRE cement energy figures. On site batching and recycling provides only a small reduction (3%), although the majority of benefits from this set up would be expected to be in transportation reduction. The lowest value for the steel frame, using recycled steel, is higher than the standard figure for concrete, requiring an increase of 12%. The other factors which affect concrete have a relatively smaller effect for the steel frame, mainly thorough the substructure requirement. The lightweight concrete does not receive much benefit from the on site recycling because the Lytag would still have to be transported in from the production plant.

If the highest values for cement and aggregates are used, the concrete structure incurs more energy by 7% than the standard steel value. However, where the steel structure uses the same cement and aggregate figures the difference is much smaller than for the standard data set at 3%. The highest value occurs where 30 mm Vicuclad is used, incurring a 10% increase.

Clearly, fire protection represents a major energy expenditure item and this characterised the steel frame overall - a few higher energy items making up most of the total expenditure. This means that the correct calculation of the values is vitally important. For the concrete frame there are more relatively smaller items. The balance for both frames will depend to some extent on the relative proportions of the building.

9.5.2 Embodied CO_2

The breakdown of embodied CO_2 figures is shown in Table 9-5.

Table 9-5: Breakdown of Frame Embodied CO_2 (Rank Order)

	Total kg/m^2	Substructure kg/m^2		Superstructure kg/m^2		Demolition kg/m^2	
M4 Steel 7 Floor	243.4	38.2	15.7%	200.0	82.2%	5.2	2.1%
M4 Steel 3 Floor	250.9	53.0	21.1%	192.6	76.8%	5.3	2.1%
M4 Concrete 3 Floor	263.6	76.9	29.2%	179.1	67.9%	7.6	2.9%
M4 Concrete 7 Floor	263.8	61.1	23.2%	195.2	74.0%	7.5	2.8%
M62 Steel 3 Floor	268.3	74.3	27.7%	188.5	70.2%	5.5	2.1%
M62 Concrete 3 Floor	274.5	84.0	30.6%	182.9	66.6%	7.6	2.8%
M62 Steel 7 Floor	281.6	62.2	22.1%	214.0	76.0%	5.5	1.9%
M62 Concrete 7 Floor	309.4	83.9	27.1%	217.7	70.4%	7.8	2.5%

For each of the structural pairs, the steel version has a lower CO_2 requirement. The decrease ranges from 91 - 98%. The reversal of the results from embodied energy can be attributed almost entirely to the different rates of CO_2 generation for steel and cement. The differences between the 3 floor structures is less than that between the 7 floor structures because the substructure acts as a moderating factor. As the substructure become less important, the different values for cement and structural steel exert more pressure on the results. In practical terms it can be seen that the CO_2 from the superstructure slab for the larger building is more than the structural steel, where for the smaller building it was less.

The split between the sub and superstructure elements is smaller than for embodied energy with the substructure contributing between 16 - 31%. The demolition aspect is consistently 2 - 3% for all the structures, although the generation per m^2 is generally higher for the concrete structures by around 40 - 50%.

Analysis of the parametric data has been restricted to the items where an accurate calculation of the CO_2 was available. In practical terms this means that the high and low values for cement and aggregate have not been used because the BRE figures from which the data was taken provided only one average figure for CO_2. The parametric data results are shown in Table 9-6.

Table 9-6: M4 7 Floor Parametric Embodied CO_2 (Rank Order)

Parameter	kg/m^2	
M4 Concrete 7 Floor, On Site Recycling & Batching, GGBS Concrete	182.8	
M4 Concrete 7 Floor, GGBS Concrete	186.2	102%
M4 Steel 7 Floor, On Site Recycling & Batching, GGBS Concrete	204.5	112%
M4 Steel 7 Floor, GGBS Concrete	205.6	113%
M4 Steel 7 Floor, Recycled Structural Steel	209.0	114%
M4 Steel 7 Floor, On Site Recycling & Batching	242.3	133%
M4 Steel 7 Floor	243.4	133%
M4 Steel 7 Floor, 30 mm Vicuclad	251.5	138%
M4 Concrete 7 Floor, On Site Recycling & Batching	260.4	142%
M4 Concrete 7 Floor	263.8	144%

The standard data set represents the highest result shown, but as noted, the high values for aggregate and cement has been excluded and these could be expected to provide the worst case. The lowest overall figures are provided by the concrete frame where cement has been replaced by GGBS, thus eliminating the highest factor. Comparison of the steel and concrete frames where GGBS concrete has been used, the concrete frame incurs less by 10%. This is in contrast to the standard data set results where the concrete frame incurred 8% more CO_2. As with the embodied energy results, on site recycling and batching has only a small impact on the production of CO_2.

The values for the steel frame show that using scrap to make steel reduced the CO_2 incurred by 14%, while increasing the fire protection to 30 mm increases it by 3%.

Generally, using the standard data set means that concrete frames will incur higher CO_2 emissions than the steel counterpart. Substitution of GGBS (or PFA) for cement reduces the concrete requirements to the point where the steel frame incurs higher emissions.

9.5.3 Transportation Distances

The transportation distances for all the buildings are shown in Table 9-7, while the results of the parametric data study are shown in Table 9-8.

All the concrete options increase the transportation distances incurred, with the difference ranging from 37 to 60% for each pair of structures. The pattern of contributions from each element are different than for embodied energy and CO_2. The percentage contributed for demolition has increased to around 19% for concrete frames and is between 13 and 17% for steel frames. The contribution from the substructure has also increased to as much as 50% of the total transportation time, however there is a wide range for the steel buildings.

Table 9-7: Breakdown Of Frame Transportation Distance (Rank Order)

	Total	Substructure		Superstructure		Demolition	
	m/m^2	$miles/m^2$		$miles/m^2$		$miles/m^2$	
M4 Steel 7 Floor	3.9	0.9	22.6%	2.5	64.0%	0.5	13.4%
M62 Steel 7 Floor	4.4	1.4	32.4%	2.2	50.9%	0.7	16.7%
M4 Steel 3 Floor	4.5	1.4	30.4%	2.5	55.4%	0.6	14.2%
M62 Steel 3 Floor	4.6	1.9	41.5%	1.9	41.5%	0.8	17.1%
M4 Concrete 7 Floor	6.0	1.3	22.2%	3.6	59.2%	1.1	18.6%
M62 Concrete 3 Floor	6.3	2.1	33.5%	3.0	48.0%	1.2	18.5%
M4 Concrete 3 Floor	6.3	1.8	29.0%	3.3	51.9%	1.2	19.0%
M62 Concrete 7 Floor	7.0	1.9	26.4%	3.8	54.6%	1.3	19.0%

The parametric data reveals that, for the concrete frames, drastic reductions in the transportation distances can be achieved by using on site batching (around 40%), however even in this case the steel frame still incurs more transportation than steel. The Use of GGBS, while being very beneficial in terms of embodied energy and CO_2, actually increased the total transportation requirements by around 10%. This would also be true of PFA use, although the effect would be less because of the smaller quantities involved. The use of on site recycling has a relatively lower effect for the steel frame when using Lytag than would be the case if standard concrete is used because, even when recycled aggregates are available they could not be used in lightweight concrete.

Table 9-8: M4 7 Floor Parametric Transport Distance (Rank Order)

Parameter	mile/m^2	
M4 Steel 7 Floor, On Site Recycling & Batching	3.1	
M4 Steel 7 Floor, On Site Recycling & Batching, GGBS Concrete	3.4	110%
M4 Concrete 7 Floor, On Site Recycling & Batching	3.5	113%
M4 Concrete 7 Floor, On Site Recycling & Batching, GGBS Concrete	3.9	126%
M4 Steel 7 Floor	3.9	127%
M4 Steel 7 Floor, GGBS Concrete	4.2	136%
M4 Concrete 7 Floor	6.0	195%
M4 Concrete 7 Floor, GGBS Concrete	6.5	209%

The parametric data for transportation excludes data where only the energy values have been changed because the materials are all assumed to come from the same source. In reality the transportation distances would be expected to change if source plants were switched and this fact could be reflected by altering the rates in the Structural Embodied Energy Assessment Model.

9.5.4 Transportation Time

The transportation times, shown in Table 9-9, follow a similar pattern to the distances, however the differences are greater reflecting the fact that a higher proportion of the concrete traffic is relatively slow moving. The transportation time for the steel structure compared with the concrete incur only 56 -72% of the road time.

Although the use of Lytag incurs more transportation for the actual material itself, the savings in other areas more than offset this. This is reflected by the fact that both the M4 steel buildings movement times were lower than the M63 structures. The distribution of time between the substructure, superstructure and demolition is similar to the pattern for transportation distance.

Table 9-9: Breakdown of Frame Transportation Time

	Total	Substructure		Superstructure		Demolition	
	hr/m^2	hours/m^2		hours/m^2		hours/m^2	
M4 Steel 7 Floor	0.15	0.05	30.2%	0.09	55.8%	0.02	14.0%
M4 Steel 3 Floor	0.18	0.07	39.4%	0.08	46.3%	0.03	14.2%
M62 Steel 7 Floor	0.19	0.08	38.9%	0.09	45.6%	0.03	15.6%
M62 Steel 3 Floor	0.21	0.10	48.7%	0.08	36.0%	0.03	15.3%
M4 Concrete 7 Floor	0.27	0.07	25.6%	0.16	57.7%	0.05	16.7%
M62 Concrete 3 Floor	0.29	0.11	38.7%	0.13	44.9%	0.05	16.4%
M4 Concrete 3 Floor	0.29	0.10	33.0%	0.15	50.3%	0.05	16.7%
M62 Concrete 7 Floor	0.32	0.10	30.8%	0.17	52.1%	0.05	17.1%

The parametric data, shown in Table 9-10, reveals a similar pattern to the distances, with on site recycling and batching massively reducing the total time (by as much as 55%), but still being higher than the steel option, although the difference is reduced to 20%. Once again, the effect for steel is lessened by the use of Lytag.

Table 9-10: M4 7 Floor Parametric Transportation Time (Rank Order)

Parameter	hours/m^2	
M4 Steel 7 Floor, On Site Recycling & Batching	0.10	
M4 Steel 7 Floor, On Site Recycling & Batching, GGBS Concrete	0.11	108%
M4 Concrete 7 Floor, On Site Recycling & Batching	0.12	119%
M4 Concrete 7 Floor, On Site Recycling & Batching, GGBS Concrete	0.13	129%
M4 Steel 7 Floor	0.15	150%
M4 Steel 7 Floor, GGBS Concrete	0.16	158%
M4 Concrete 7 Floor	0.27	266%
M4 Concrete 7 Floor, GGBS Concrete	0.29	277%

9.6 Comparison Between Frame And Operational Energy

A range of energy use figures has been calculated for a range of buildings from the case studies shown in Appendix A and the energy efficient office data (1). This information is shown in Table 9-11. The data for the low energy structures represents energy targets rather than actual figures so there is a margin for error.

Table 9-11: Building Energy Use

Building	Delivered Electricity kWh/m^2/yr	 Gas	Primary Electricity kWh/m^2/yr	 Gas	Total kWh/m^2/yr	 GJ/m^2/yr.
Low Impact Buildings						
University Of East Anglia	24	26	65	29	94	0.339
BRE	36	47	98	52	150	0.540
APU Queens Building	50	108	136	120	256	0.921
University Of Lincolnshire	66	84	180	93	273	0.982
DeMontfort Queens Building	52	143	141	159	300	1.081
EEO Naturally Ventilated						
Type 1: Typical	48	200	131	222	353	1.269
Type 1: Good	36	95	98	105	203	0.732
Type 2: Typical	85	200	231	222	453	1.632
Type 2: Good	61	95	166	105	271	0.977
EEO Air Conditioned						
Type 3: Typical	202	222	549	246	796	2.865
Type 3: Good	132	100	359	111	470	1.692
Type 4: Typical	361	273	982	303	1285	4.626
Type 4: Good	261	132	710	147	856	3.083
Conversion Delivered - Primary	Gas	1.11	Electricity 2.72			

Clearly there is a huge range in operational energy requirements, from a low of 0.4 to a high of 4.6 GJ/m^2/year. This makes comparison with frame (and other structure) embodied energy more difficult. Obviously, a higher operational energy cost will make the frame embodied energy proportionally smaller. Structures which seek to minimise operational energy use will make the initial embodied energy relatively more important.

The expected life of a building is also important in determining the relative importance of the embodied energy. A building expected to be used for 50 years at 1 GJ/m^2/year will clearly use more energy over the life time than one used for 25 years at 1.6 GJ/m^2/year. The final factor in determining the relationship between operational and embodied energy is the frame energy itself.

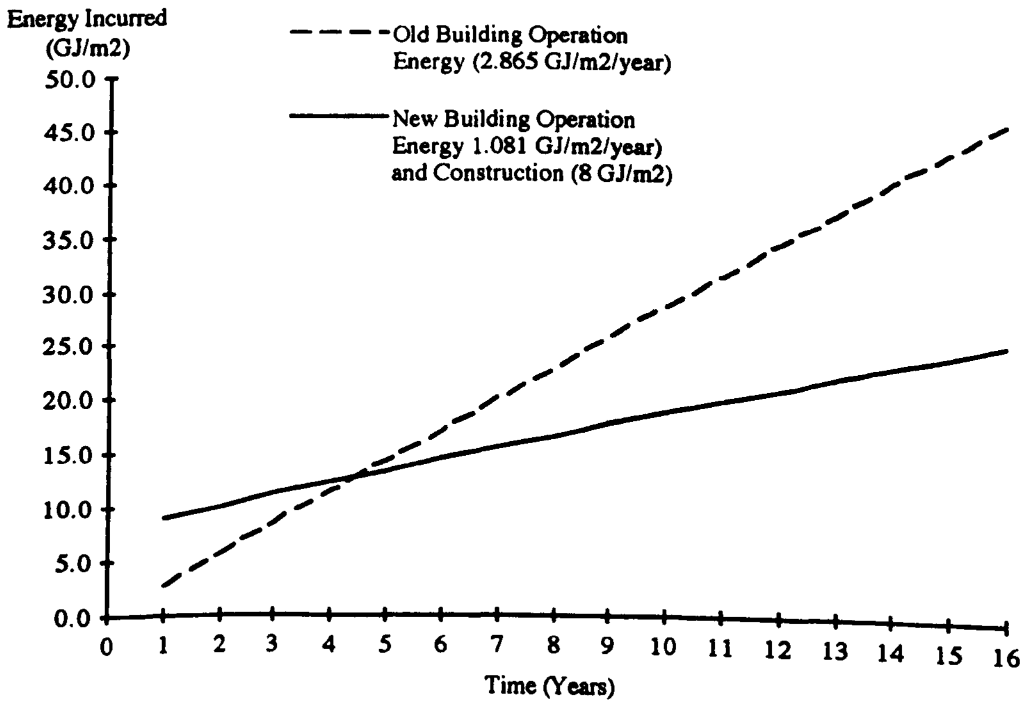
As shown by the results in this chapter, there is a considerable variety in results depending on the materials used. For the purposes of calculations a figure of 2.3 GJ/m^2 has been selected although a higher figure would be relatively more important and visa versa. A data table has been created comparing a building life of 35 years (the age of the structure examined as an example of demolition in this thesis) and one with a 50 year life. The results of this comparison are shown in Table 9-12. The frame energy ranges from a high of 19.4% of the total life time structure energy for a low energy 35 year life span building to 1.0% for a high energy 50 year building. The number of operational energy intensive buildings which are erected might be expected to decrease as environmental awareness increases. Clearly, if operational cost can be reduced further, the embodied energy becomes more important. A total structure embodied energy of 8 GJ/m^2 means the operational energy would be down to 60% of the total.

Using these figures it is also possible to calculate, in energy terms, when an old building should be replaced by a newer, low energy structure. For example, a building using 4 GJ/m^2/year replaced by one using 0.5 GJ/m^2/year, would make an energy saving of 3.5 GJ/m^2/year. If the new building had an energy cost of 8 GJ/m^2, then energy savings would be made within three years of use! This is a relatively extreme example, but other example with a longer payback time can be shown. For example, Figure 9-3 shows a situation where a building with running cost of 2.8 GJ/m^2/year is replaced by on with a operational costs of 1.1 GJ/m^2/year and embodied energy of 8 GJ/m^2. For this scenario the energy break-even period would be during the 4th year of operation. These calculations ignore the negative effects of demolition which are not directly measured, such as increased use of raw materials. However, where a high level of recycling is planned for these drawbacks can be largely mitigated.

Table 9-12: Operational and Frame Energy

Building	Annual Operational Energy GJ/m2/year	Operational Energy (35 Years) GJ/m2	Frame As % (%)	Operational Energy (50 Years) GJ/m2	Frame As % (%)	Payback Period (years)
Low Impact Buildings						
University Of East Anglia	0.339	12	19.4%	17	13.6%	6.8
BRE	0.540	19	12.2%	27	8.5%	4.3
APU Queens Building	0.921	32	7.1%	46	5.0%	2.5
University Of Lincolnshire	0.982	34	6.7%	49	4.7%	2.3
DeMontfort Queens Building	1.081	38	6.1%	54	4.3%	2.1
EEO Natural Ventilation						
Type 1: Typical	1.269	44	5.2%	63	3.6%	1.8
Type 1: Good	0.732	26	9.0%	37	6.3%	3.1
Type 2: Typical	1.632	57	4.0%	82	2.8%	1.4
Type 2: Good	0.977	34	6.7%	49	4.7%	2.4
EEO Air Conditioned						
Type 3: Typical	2.865	100	2.3%	143	1.6%	0.8
Type 3: Good	1.692	59	3.9%	85	2.7%	1.4
Type 4: Typical	4.626	162	1.4%	231	1.0%	0.5
Type 4: Good	3.083	108	2.1%	154	1.5%	0.7
Assumed Building Life	35	years				
Frame Energy	2.3	GJ/m2				

Figure 9-3: New Build Energy Payback



A similar analysis can be applied to the question of whether to refurbish or replace a structure. As shown in Chapter 4 and Appendix A, low impact structures tend to have features not present on standard buildings, for example chimneys to promote ventilation. They also tend to be less regular in shape, to take advantage of the local climate. It is therefore possible that a refurbished structure would have a larger energy requirement than if the building were replaced.

A range of frame energy figures has been selected from high (3.0 GJ/m^2) to low (1.8 GJ/m^2) and these have been compared to a range of energy differences between a new and refurbished structure. Even when the difference is as low as 0.1 GJ/m^2/year, the energy to rebuild is repaid within 30 years based on the highest frame energy. Where the frame energy is lower, or the operational energy difference greater the payback time can be as low as 2 years. This analysis assumes that the refurbishment requires a complete strip back to the frame. Lesser degrees of refurbishment would probably not be able to reduce the operational energy requirements to the degree required. If the refurbished building is able to match or better the new building operational energy then it will always be more energy efficient. The results of the analysis are shown in Table 9-13.

Table 9-13: Refurbish vs. New Build

Operational Energy Difference (GJ/m^2/year)	0.1	0.5	1	0.05	0.1	0.5	1	0.05	0.1	0.5	1
Frame Energy (GJ)	3.0	3.0	3.0	2.3	2.3	2.3	2.3	1.8	1.8	1.8	1.8
Payback Time Required (Years)	30	6	3	46	23	4.6	2.3	36	18	3.6	1.8

9.7 Conclusions

There are several conclusions which can be reached from analysis of these results. However the same limitations must be applied to these results as for all the other models - could the data have been derived differently and would this have altered the results. The conclusions derived are presented below.

1. The many different permutations possible mean that, until one system is chosen as definitive, there will always be room for doubt about the results.
2. Cement replacement materials should be used a much as possible to reduce the energy and CO$_2$ impacts from concrete, although they will probably increase transportation. Admixtures can also be used to reduce the cement content.
3. Concreting operations involving bulk materials should be carried out on site where possible, with the exception of reinforcement cutting and bending
4. Local suppliers should be used where possible, except where it can be demonstrated that environmental benefits will occur by using sources further away.

5. Where possible, goods vehicles should transport materials on both legs of a journey.
6. While Lytag requires considerably more energy per cubic metre, when considered in terms of the total building, the evidence points to an overall advantage. The material will not perform as well as standard concrete when used as thermal mass.
7. For the majority of structures and data parameters, the steel frame structures require a higher energy input. Where cement replacement materials are used, this advantage becomes more pronounced.
8. The CO_2 requirements are similar for both materials types but will depend to a large extent on the relative quantities of steel and cement required. Where OPC concrete is used the steel frame could have an advantage of around 10%. Where cement replacement materials are used, the concrete frame could have an advantage of 10%.
9. For the majority of structures and data parameters, concrete structures will incur more transportation, both in terms of on road time and distance travelled. Only where concrete is batched and aggregates recycled on site will the figures approach parity.
10. The frame environmental impacts represents a significant proportion of the total requirements over the whole life cycle, and will tend to become more important as operational impacts become smaller.

9.8 Reference

1 Energy Efficient Office: 'Energy Consumption Guide 19: Energy Efficiency In Offices', Department Of The Environment 1991

10. CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

The conclusions reached can be split into the areas of general, data specific and overall. The general conclusions cover the information found in literature and from the building studied. The data specific conclusions are drawn from the data gathering and operation of the model. The overall conclusions draw together the major facts which have been drawn from the project as a whole.

10.1 General Conclusions

1. The level of general environmental information available was disappointing overall and there is clearly room for much more work to be carried out.
2. Many assumptions need to be made about a wide variety of factors to enable a environmental impact assessment to be carried out. These need to be clearly stated with the results to eliminate confusion.
3. To make detailed energy assessments, a good working knowledge is required of construction and related processes which enable the manufacture of a building. In addition a range of information about environmental impacts is required. To do this properly requires the co-operation of relevant companies.
4. For a structure to take maximum advantage of the local conditions and thus reduce environmental impacts, modifications will be needed to both the outward appearance and inner functions. Low impact structures will normally need to be tailored more than other structures.
5. The conversion factors used to move between delivered and primary energy are very important. This is especially true for electricity, for which the ratio has changed considerably recently.
6. In general terms, thermal mass for use in structures can be provided by both steel and concrete frames as long as the design is tailored to allow this to happen.
7. In future assessment it will de desirable to differentiate the energy supplies used in both materials manufacture and building operation - electricity provided by a renewable resource is a very different proposition from that provided by, for example, coal.

10.2 Data Specific Conclusions

1. The model which has been created calculates four environmental impacts with a higher degree of control and transparency than has been available up to this point.
2. The results generated by the Structural Embodied Energy Assessment Model are reliant on a wide variety of data. Where this data has been calculated for this thesis

there is a high degree of confidence in the accuracy within the selected parameters. In cases where the data has been imported from other sources the same degree of confidence can not be maintained for a number of reasons which mainly stem from a lack of defined parameters.

3. Some materials are more important in determining the overall environmental impacts - steel, cementitious materials and aggregates. However the effect of other items should not be dismissed, especially when they are considered cumulatively.
4. Where some embodied energy figures have a large impact on the total values and there is a selection to choose from, it is possible to change the calculated total frame energy by a significant amount. Values used for the main results calculations, as opposed to use within a parametric study, have been selected to provide the closest possible result for the UK. It is possible to correctly select other values in other situations.
5. Some materials have a much larger influence than others. In most cases these larger figures, for example cement and steel, have been calculated with less precision than other smaller items, usually due to the difficulty of obtaining information from specific companies. Overall it is desirable to have the most accurate information available for all figures and so the lack of detail for some figures has not been viewed as a reason not to make accurate assessments for others. Many of the 'less important' impact items can be affected by the consumers of construction (contractors, specifiers, architects, etc.), while large items can not. Since it is not possible for individuals to affect the energy consumption of, for example, a steelworks but it is possible to select which company removes waste, the calculations where users can make a day to day difference might be considered more important.
6. Cement has significant environmental impacts and great improvements can be made in structure performance by the reduction of this material using replacement materials. Bulk operations should be carried out on or as near site where possible.

10.3 Overall Conclusions

1. Embodied impacts are more important than has been previously thought. In addition these factors will tend to increase in importance as operationally energy sources are switched to less environmentally damaging alternatives - there are no certainties about how materials or energy will be procured in 50 years time.
2. The majority of embodied impacts are incurred from materials procurement and construction incurring a 'front end' penalties, rather than gradual resource use as with operational energy.
3. The interaction between structure embodied and operational impacts are limited to thermal mass but not insignificant. A structure which is not designed to accommodate low energy operational modes may well incur less environmental penalties if demolished, rather than simply refurbished.

4. A steel frame has a higher embodied energy than a similar concrete structure for most of the parametric sets examined and most importantly for that considered as the most likely to occur.
5. Steel and concrete frames incur similar levels of CO_2. The concrete frame has a slightly higher requirement for the basic parametric data set.
6. Recycling should be encouraged, although care is required to plan the methods employed to minimise the environmental impacts.
7. In all cases a concrete frame will impose a higher transportation cost which can be as much as twice that for a similar steel frame.
8. In environmental terms, buildings with high operational impacts should be replaced as soon as possible by low impact structures. The embodied impacts are recouped very quickly by savings made from not running the old structure.
9. When converting from delivered to primary energy for electricity, it is necessary to use figures as up to date as possible, due to recent changes in power generation methods.
10. The frame represents a significant proportion of the total life cycle environmental cost and this proportion will tend to increase with expected reductions in the operational energy requirement.
11. Making many small changes can have as much effect as making one large one. Considerable progress can be made in increasing construction sustainability simply by optimising the factors which can easily be controlled by architects, designer and contractors.
12. A model has been developed which will allow a consistent analysis to be performed on a range of buildings with respect to the defined environmental impacts. The model is adaptable enough to reflect the prevailing conditions in the environmental impact assessment field.
13. The calculations, assumptions and background information upon which the figures provided in this thesis rest have been clearly laid out and could be replicated, allowing a margin for the inherent variability of the subject.

10.4 Suggestions For Further work

There is still a huge amount of work which could be carried out to increase the accuracy of embodied energy assessment, however several factors stand out in this case

The Structural Embodied Energy Assessment Model can be expanded. This includes both the range of data it can use, for example structural timber and brick, and also the range of construction and materials options. An item of primary interest would be the items for which no information is currently available, for example steel decking. There is considerable scope for refining the data by comparison with actual site works. In addition a wider range of building data could be input to expand the database available and derive a wider range of guidelines to reduce environmental impacts.

One of the major items which was not available for this thesis was the fabrication energy for plant. This might well be a significant item and the minimum work that is required is to get a basic figure to evaluate the significance.

Overall much more work is required gaining on site data for actual sites and in particular the energy of plant for different activities.

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Jones, D: 'Burning Desire', New Civil Engineer, January 1996, pp 36-37

Looks at the range of waste materials that are being burnt in cement kilns.

Kay, T: 'Euro Recycling', Architect, Builder, Contractor & Developer, November 1994, pp 25-26

Examines recycling in Europe and suggests that of all demolition waste the following split applies -15% reclaimable, 65% recyclable, 15% beneficially destructive, 5% toxic/hazardous.

'Refurbishment: The Natural Way', Building Services (Supplement), November 1996, pp 29 - 31

Reviews the possibilities for refurbishment, including assessing technical barriers. Looks at the types of windows available and the pro and cons of each. Suggests that 10% is a realistic figure for energy saved on a refurbished building.

Kintner-Meyer, M & Emery, AF: 'Optimal Control Of An HVAC System Using Cold Storage And Building Thermal Capacitance', Energy And Buildings, Vol.23 1995, pp 19 - 31

Looks at minimising the cost involved in running a HVAC system by using cold storage and thermal mass

Kishore, VVN: 'Assessment Of Natural Cooling Potential For Buildings In Different Climatic Conditions', Building & Environment, Vol.23 No.3 1988, pp 215-223

Provides rules and equations for assessing the natural cooling potential for different climatic regions.

Kut & Hare: 'Waste Recycling & Energy Conservation'

Lawson, D: 'Energy Efficient Buildings', Architects' Journal, 9 June 1993, pp 17-18

Talks about the building envelope in Dwellings and how to improve deficiencies therein.

Leaman, A: 'Probe 10: Occupancy Survey Analysis', Building Services, May 1997, pp 37-41

Reports the results of the probe survey carried out by the Building Services Journal. This set of reports looked at the post occupation performance of a range of buildings (including four of a green design)

Leaman, A & Bordass, W: 'Building Design, Complexity and Management', Facilities, July 1994, pp 1-15

A review of building performance with respect to complexity. Areas of complexity identified.

Leeds School Of The Environment: 'Computational Tools For Building Environmental Performance Analysis', Study Guide, Leeds Metropolitan University

Outlines the factors involved in thermal modelling and discusses the tools available for for use.

Levermore, G & Sibley, J & Barbour, P: 'Programs Under Test', Building Services, May 1995, pp 49-54

Compares favourably the CISBE method for passive air conditioning design with other dynamic models, but notes it's lack of flexibility.

Lion, E : 'Building Renovation & Recycling'

'A Guiding Light', Building Services, March 1996, pp 45-46

Looks at the factors which need to be taken into account when designing, installing and maintaining day lighting systems. Includes a summary of system types and their performance.

'Tower Of Babel Or Promised Lane', Building Services, January 1995, pp 23-49

A series of articles in Building Services dealing with thermal modelling and validation of models. A large number of models are tested and some large variations found.

'Wasted Opportunities', Building, 19 March 1992, pp 48-49

Assesses the possibilities for recycling aggregates including reuse as concrete.

'Control Naturally', Building Services, June 1995, pp 39-40

Examines how effective passive controls are and lays out a suggested mixed mode (passive assisted) command flow diagram.

Mathews, EH: 'Empiricism In The Thermal Analysis Of Naturally Ventilated Buildings', Building & Environment, Vol.23 No.1 1988, pp 57-61

Compares a technique involving empirical data to systems using modelling and a mixed method when analysing natural ventilation.

McCormack, S: 'Waste Of Opportunities', Construction News, 22 September 1994

Assesses the state of recycling and possible future developments including future legislation, specification, transportation and the wider environment.

McLaughlin, T: 'Point Of Law', Building Services, February 1995, pp 17-20

Case study of a low energy County Court building in Hampshire which uses a heavyweight construction and thermal stacks.

'Predicting Energy Use: How Accurate Can You Be?', Building Services, March 1995, pp 35-36

Compares computer modelling vs empirical as methods of predicting energy use. It finds that computer modelling makes very large time requirements requiring great quantities of details.

Mitchel, J: 'Energy Engineering', ISBN 507384601

Evaluating technical and economic aspects of energy usage

'Energy Efficiency In Practice', Building Services, October 1995, pp 29-30

Inclusion of environmental features from a developers perspective, specifically cost implications.

Moss, SA: 'Potential Carbon Emission Savings From Energy Efficiency In Commercial Buildings', BRE information Paper, IP3/96 1996

Outlines possible areas of reduction of CO2 in commercial buildings with costed case studies - for example switching to double glazing or increasing insulation.

National Academies Policy Advisory Group: 'Energy & The Environment In The 21st Century', ISBN 0854034986, Royal Society 1995

Outlines the requirements for a successful energy policy, including security of supply, price, demand, environmental impact, etc.

Nesmith, L: 'Ready Or Not, Constructional Recycling Is On It's Way', Architectural Record, December 1993, pp 18-23

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Norton, B & Lo, S & Cronin, KP & Yohanis, YG: 'Towards The Harmonious Integration Of Information Technology In Building Design And Construction', International Journal Of Ambient Energy, Vol.16 No.2 1995, pp 95-109

Looks at how information technology will be used in future and suggests methods which can improve this link.

'Air Freshener', Building Doors & Windows Supplement, 29 October 1993, pp 10-11

Looks at the role played by window design in green buildings particularly with regard to passive ventilation.

Parker, D: 'Exclusion Zone', New Builder, July 19943, pp 22-23

looks at product blacklisting and suggests that environmental concerns are best served by gaining more information rather than simply deselecting materials.

Parker, D: 'Mass Appeal', New Builder Concrete Supplement, November 1994, pp 49-51

Examines the construction process at the PowerGen building.

Patterson, W: 'The energy alternative, changing the way the world works', ISBN 1852832843, Boxtree 1990

Assesses the broad picture for energy provision in light of environmental concerns.

Pheng, LS & Tan SKL: 'The Measurement Of 'Just In Time' Wastage For A Public Housing Project in Singapore', Research & Building Information, Vol.25 No.2 1997, pp 67 - 81

How to minimise the production of waste through a JIT waste management system

Pitts, GC: 'Medium Rise Timber Framing', Architects' Journal, 4 July 1996, pp 62-63

Examines designs for medium rise (4-8 story) timber construction.

Randall, T (ed): 'Environmental Design: An Introduction For Architects And Engineers', ISBN 0419199306, Spon 1996

Provides design details and other information for green buildings

Rawson, J: 'Fire Protecting Steel off Site', Architects' Journal, 28 November 1996, pp 53

Looks at using prefabrication of intumescent coatings on steel members.

Reiner: 'How To Recycle Buildings'

Examines the techniques available to maximise the quantity of materials from a building which can be reused and outlines some problems.

Reinforced Concrete Council: 'Cement, Concrete And The Environment', Trade Literature, Reinforced Concrete Council 1994

Contains the view from the concrete industry of environmental concerns.Also contains figures emissions.

Reinforced Concrete Council: 'PowerGen Headquarters : Project Profile', ISBN 0721014984, Reinforced Concrete Council

Case study of the PowerGen HQ which has a number of green features including innovative shaped soffits which channel heat and light. This is trade literature from the Reinforced concrete council.

Richardson, C: 'Timber As An Environmentally Friendly Structural Alternative', Conference - Buildings & The Environment, Materials Session Paper 24, CIB 1994

Energy examples for construction of warehouse - Timber 1480, Concrete 2550, Steel 3150 GJ

'Timber V Blocks', Building, 8 February 1991, pp 41-43

Appraises the competition between the timber and block construction materials with an historical perspective and provides figures for the share for each material for dwellings.

'Flaw To Sealing', Building, 31 July 1993, pp 48-49

A case study of extensive repair work carried out on a steel framed building in London detailing the areas of concern and outlining the remedies applied.

'Blow By Blow Account', Building, 30 April 1993, pp 48

Compares the cost of a range of air conditioning systems.

Robertson, G: 'Energy Efficient Commercial Buildings - A Realistic Market Objective', Architectural Science Review, Vol.34, pp 139-142

Environmental economic options for developers in New Zealand

Roche, L: 'Smart Glass', Building Services Journal, August 1997, pp 27-28

Looks at the use of advanced glass design which respondes dynamically to heat and light

Roskow, B: 'Industry Shocked By 30-50% Landfill Tax', Contract Journal, 30 March 1995, pp 1

Speculates about the announced a landfill tax of 30-50% and speculates on future trends and how cost will change from the current range of £2.50 to £17.50.

Russell, H: 'Filling In The Tax Form', New Civil Engineer, 26 September 1996, pp 20-23

Looks at the implications of the land fill tax.

Salazar, JH: 'Sunlight Evaluation In Buildings', Building Research & Information, Vol.23 No.3 1995, pp 183-187

A shading device evaluation method with qualitative comparisons between various shading alternatives to aid the selection process.

Shorrock, LD: 'Potential Carbon Emission Savings From Energy Efficiency In Housing', BRE information Paper, IP15/95 1995

Outlines possible areas of reduction of CO2 in domestic buildings with costed case studies - for example switching to double glazing or increasing insulation.

Shorrock, LD: 'Future Energy Use And Carbon Dioxide Emissions For UK Housing', BRE information Paper, IP9/94 1994

Estimates the future energy use and carbon emissions as we move towards the year 2000 and beyond. This estimate can be used to judge progress towards lowering emissions.

Shorrock, LD & Henderson, G: 'Energy Use In Buildings And Carbon Dioxide Emissions', ISBN 0851254365, BRE 1990

This document contains data and information quoted in many other articles.

Slater, AI & Bordass, WT & Heasman, TA: 'People And Lighting Controls', BRE information Paper, IP6/96 1996

Outlines the possibilities for automatic control of lighting for different user groups and suggests methods to optimise efficiency.

Soelami, FXN & Ballinger, JA: 'Study Of The Influence Of Furniture On The Thermal Behaviour Of Internal Thermal Mass', Architectural Science Review, Vol.35, pp 101-105

This might be useful when comparing the thermal effects of the structure to other effects

Soronis, G: 'Problem Of Durability In Building Design (The)', Construction & Building Materials, Vol.6 No.4 1992, pp 205 - 211

Assesses the factors which effect the durability of buildings and materials used in them and looks at the implications with respect to design and cost.

Soronis, G: 'Standard For The Design Life Of Buildings', Construction & Building Materials, Vol.10 No.7 1996, pp 487 - 490

Reviews current standards for building design life.

Spooner, D: 'Thermal Capacity', Building Research & Practise, May/June 1979, pp 164-170

Examines the difference between light and heavy weight buildings in terms of thermal mass and different heating strategies.

'Working Order', Building, 14 June 1996, pp 50-55

Examines a number of prestige HQ type buildings and lists the broad trends in design

'Breath Test', Building, 6 June 1997, pp 44-50

Revisits the DeMontfort University Queens Building and assesses hoe the design stands up.

'Probe 5: Cable & Wireless College', Building Services Journal, June 1996, pp 35 - 39

Reports on a post occupancy review of a naturally ventilated 'green' building to see how it scores in terms of overall user satisfaction.

Standeven, M & Cohen, R & Leaman, A: 'Probe 6 : Woodhouse Medical Centre', Building Services, August 1996, pp 35-38

A case study of a small (one story) medical centre in Sheffield, including user satisfaction ratings.

'A Testing Time For Natural Ventilation', Building Services, November 1994, pp 51-52

Contains technical details of the design of the green building at DeMontfort University.

Stevens, B & Willis, S: 'Building For The Future', Building Services, May 1995, pp 33-34

Case review of the design of the BRE low energy building, including details of the heat and ventilation system (similar to Termodeck).

Stevens, B & Willis, S: 'Building For The Future', Building Services, May 1995, pp 33-34

looks at the feature involved in the Energy Efficient Office Of The Future Specification which include; extensive glazing (south & north with solar shading), opening windows & trickle vents, solar pressure stacks, supplementary fans, using thermal mass (

'Greening Of An Industry ', Building Services (Supplement), November 1996, pp 23 - 29

Looks at the changing standards for boiler design and at how these are forcing changes in design.

'Silence In Class', Building, 7 May 1993, pp 42

Looks at the Grove Road Primary School building in Hounslow (under the flight path to Heathrow airport. Designed by Plincke, Leaman & Browning. The interesting feature of this building is the green design in a very noisy area.

Suman, BM & Saxena, BK: 'Role Of Roof Treatment In Thermal Design Of Buildings', Architectural Science Review, Vol.35, pp 111-114

The interaction of the roof and internal environment using examples from India

'The Case Of The Missing Joules', Building, 22 March 1996, pp 51

Provides a short overview of the range of figures available for embodied energy.

Thorp, M: 'Green buildings: The Cost Effects Of Going Green', pp 89-114, ISBN q2151737, CICC 1992

A cost study of green construction.

Tickell, O: 'Lets Blast Away At Unpopular Taxes', New Scientist, 23 October 1993, pp 43-44

A tax on extracting raw materials could raise £1 billion. Estimated usage 250m tonnes per year virgin materials

Timber & Brick Information Council: 'Timber & Brick', Fact Sheet, Timber & Brick Information Council

Embodied energy of timber and brick domestic dwellings.

Tindale, A & Kolotroni, M & Irving, S: 'Ventilation Solutions The Quick Way', Building Services, February 1996, pp 43 - 44

Examines a design tool which evaluates building ventilation strategies.

Troy, J: 'The Development Of The Ready Mixed Concrete Indusrty', Concrete, February 1997, pp 8-13

A review of the history of the ready mix industry in the UK.

Turrent, D: 'Green Building Materials', Architects' Journal, June 1995, pp 37-39

A guide indicating the environmental impact and embodied energy requirement for a range of materials with some selected recommendations for each.

'Future Buildings', Building Services, March 1996, pp 25 - 29

A Series of articles looking at various aspects of green building design.

'Urban Office Of The Future', Building Services, March 1996, pp 25 - 27

Suggests how in the future environmental concerns will shape office design.

Watson, RL: 'Car Fuel Consumption: It's Relationship To Official List Consumption', Research Report 155, ISBN z0557895, Transport And Road Research Laboratory 1989

Discusses the relationship between the average fuel economy figures provided by the Government for cars and actual fuel useage. Provides a standard equation for conversion between the two figures.

Webb, C: 'Paying The Green Bill', NFDC Yearbook 1994, pp 35-38

Examines the impact of the Environmental Protection Bill on demolition and recycling from the perspective of demolition contractors

West, J: 'Assessing The Worth Of Embodied Energy', Building Services, January 1995, pp 49

Looking at creating a standard method for calculation of embodied energy

Wild, S: 'Observations On The Use Of Ground Waste Clay Brick As A Cement Replacement Material', Building Research And Information, Vol.24 1996, pp 35 - 40

Documents work looking at any cementitious effect in using ground waste clay bricks as cement replacement in concrete. It concludes that there is a contribution to strength.

Wilhite, H & Ling, R: 'Measured Energy Savings From A More Informative Energy Bill', Energy & Buildings, Vol. 22 1995, pp 145-155

Significant savings are made by giving people more informative bills and energy tips

Willis, S: 'Cool Of The Night', Building Services, May 1995, pp 53-54

This underlines the importance of good information and control systems to manage the environmental features of a building.

'Fuel For Thought', Building, 31 May 1991, pp 56 - 57

Provides some comparisons of embodied energy. (NB in the form of graphs rather than figures)

'What's In Store For Termodeck', Building Services Journal, June 1996, pp 45 - 46

Update on the insitu performance of the termodeck system at the Weidmuller HQ in West Malling, Sussex.

'Modelling The Thermal Flywheel', Building Services, October 1994, pp 47-48

Provides a technical assessment of the Termodeck hollow slab system for passive ventilation.

Woodward, A: 'Window Of Opportunity', Perspectives, April 1995, pp 42-45

Assesses the ideas involved in passive ventilation including the move to more controllable environment and suggests that tolerable conditions increase with the amount of control given to occupants.

'Energy Indices And Performance Targets For Housing Design', Energy & Buildings, No.23 1996, pp 237 - 249

Examines and energy index which has been designed to assess the environmental performance of new and existing domestic dwellings

Yeang, K: 'Bioclimatic skyscrapers', ISBN 1874056560

Looks at how tall buildings can be designed to minimise environmental impact and provides basic design details.

APPENDIX A: CASE STUDIES

Notes For Case Studies

The quantity and quality of data available for each building was variable and this is reflected in the text. More information has been given where it is available. For each of the quoted cases, enough information was available to make a reasonable analysis possible. Many of the features occur for many buildings and so where features have been previously discussed, they are not looked at again except where a new feature is incorporated.

Headings have been used in the tables to save space. Each of the heading and notes explaining the meaning are shown below.

Use Of Thermal Mass	Indicates where use has been made of thermal mass to assist in temperature control. This is usually used in conjunction with intelligent controls.
Use Of Shading	Indicates that shading has been employed either to minimise glare and control heat gain. These can be internal, external or integral in the window units.
Use Of Daylight	Indicates that natural daylighting has been maximised either through building orientation, window design or light channelling.
Type Of Glazing	Single (x1) double (x2) or triple (x3) glazing. Window units can also incorporate shading and ventilation features.
Shallow Plan Building	This indicates an office depth of less than 12m side to side. The use of an atrium to improve light through the middle of the building is also acknowledged
Low Energy Use Equipment	This indicates that low energy fixtures have been used where possible, for instance lighting fixtures.
Provision Of Atrium	Shows the number of atria the building contains. These are used in two main ways - to provide stack ventilation or bring in light
Energy Management System	This indicates the use of automatic controls or a computer control system. Advanced examples have a learning aspect
Solar Panels	This indicates the use of Photovoltaics (for power generation) or water heating solar panels (as a preheating system)
Use Of Reclaimed Materials	This denotes if reclaimed materials have been used in any major way in the construction.
Design	Select from Regular (square, rectangular), Irregular or Semi Regular indicating the general building shape.
Frame	This indicates the major frame material(s)
*	The result is qualified in some way. For example a building might use some intelligent features but in a more limited way than most other examples.

Anglia Polytechnic University, Queens Building

Gross Area (m^2)	6100
Number Of Floors	4
Frame Material	Concrete
Shape	Semi Regular

	Use Of Thermal Mass	Use Of Shading	Use Of Daylight	Type Of Glazing	Shallow Plan Building	Low Energy Use Equipment	Provision Of An Atrium	Building Energy Management System	Solar Panels	Use Of Reclaimed Materials
Features Included	•	•	•	x3	•*	•	•	•		

This building combines the functions of library, student study areas, TV studio and recreational facility for Anglia Polytechnic University. The building, which was completed in 1994, is similar to a building at DeMontfort University (see page 288).

There is a large amount of information about this buildings, including post occupancy results, which make it a good building for study. The design also contains most of the features that are identified with low impact design - use of thermal mass, low energy fittings and intelligent building control.

This design goes further than many in the use of thermal mass, with even the wooded roof having concrete in fill panels which are can be used as part of the building morning preheat or released during night ventilation. It is estimated that 90% of the building cooling load is satisfied by the thermal mass, although this would be lower without the other energy features. The building has been described as being visually uninspiring and this can be partly attributed to the reliance on thermal mass, although there was also a tight budget, limiting the possibilities for extra detailing.

The window units are triple glazed, which is still relatively uncommon, even in green structures, and include internal blind as well as being user operable. The minimum summer air change rate of 4 per hour is achieved using these windows in conjunction with the thermal stack effect provided by the two atriums. These atria also allow for light penetration, mitigating the relatively deep plan depth of 30m maximum. Some of the ventilation, including the rooflights in the atriums, are controlled by the BEM system. In winter, ventilation is provided by trickle ventilators. Not all the building is naturally ventilated, with mechanical ventilation for the student bar and TV studio.

The building has a relatively low density of office equipment, resulting in a measured load during occupancy of 2.6 W/m^2 which reflects the intermittent student use. Lighting level drop rapidly from the perimeter not helped by the waffle deck soffit. The original design called for a ribbed system perpendicular to the perimeter, but this had to be dropped.

When the user occupancy study was carried out, the building had not been fully occupied and this may account for the low loads found, including a total electricity consumption of 50 kWh/m^2 and a figure for lighting of 16 kWh/m^2 (this compares to a good practice figure of 32 kWh/m^2). Total corrected gas consumption was 108 kWh/m^2 of which 11 kWh/m^2 was for hot water and 10 kWh/m^2 for catering. This is slightly more than the figure for a good practice office.

The building performance overall mixed with some areas experiencing overheat in summer and generally the building design needed to be more completely integrated to be fully successful.

<u>References</u>

'Integrating Fabric And Function', Architects' Journal, 2 June 1993, pp 44-48
'Making Light Work', Building Services, November 1994, pp 20-24
'Learning Resources Centre', Building, January. 20 1995, pp 39-46
'Teaching Low Energy', Building Services, April 1995, pp 19-23
Cohen R & Leaman, A & Robinson, D & Standeven, M: 'Probe 8: Anglia Polytechnic University Learning Resources Centre', Building Services, December 1996, pp 27-31
Evans, B: 'Learning From Learning', Architects' Journal, 9 January 1997

Association For Consumer Research

Gross Area (m^2)	700
Number Of Floors	3
Frame Material	
Shape	Regular

	Use Of Thermal Mass	Use Of Shading	Use Of Daylight	Type Of Glazing	Shallow Plan Building	Low Energy Use Equipment	Provision Of An Atrium	Building Energy Management System	Solar Panels	Use Of Reclaimed Materials
Features Included	•	•	•	x1	•	•	•	•		

This building, designed to be used as a centre for consumer research, was not actually built due to client cancellation. The design reach a sufficiently advanced stage, however, for the main features to have been well mapped out.

The structure was to have made use of a number of features, most interestingly two sided access to the thermal mass (soffit and top face of the slab). The top face was to have provided the major cooling by forced ventilation, with the soffit only accessed via natural convection.

The building was expected to have relatively high internal gains due to computer equipment (20 W/m^2) with extensive use of natural light and ventilation to partly off set this. The relatively deep plan design (12m across) was partly mitigated by a central open courtyard and a covered atrium, which was also used to provide stack ventilation.

Reference

Evans, B: 'Cooling With Thermal Capacity', Architects' Journal, 5 May 1993, pp 45-48

Building Research Establishment Low Energy Building

Gross Area (m2)	2000
Number Of Floors	3
Frame Material	Mixed
Shape	Regular

	Use Of Thermal Mass	Use Of Shading	Use Of Daylight	Type Of Glazing	Shallow Plan Building	Low Energy Use Equipment	Provision Of An Atrium	Building Energy Management System	Solar Panels	Use Of Reclaimed Materials
Features Included	•	•	•	x2	•	•		•	•	•

This design makes use of both recycled materials and solar power - features which are used on relatively few buildings. The structure is a compound design, using concrete and timber (top floor only) floor slabs with steel columns. Other features include the use of shaped (sinusoidal) soffits oriented at 90° to the windows, designed to increase thermal transfer and improve the thermal mass utilisation. The soffits also incorporate internal duct work.

The recycling made use of materials from a number of sources, however due to the lack of local materials, this did not provide the energy reductions which might have been possible and still incurred significant transportation costs.

The photovoltaic capacity provides a peak output of 3 kV, but required the installation of special inverters to change the current supplied from direct to alternating.

Although there is no atrium, the building makes use of five wind towers to generate air flow. Some mechanical ventilation is provided in case the natural ventilation is inadequate at some points. The windows are double glazed and use argon filling and low emissivity glass. Lower panes are user operable, while the upper panes are operated by the control system.

References

'Green Demo', Building Services, March 1997, pp 18-23
Stevens, B & Willis, S: 'Building For The Future', Building Services, May 1995, pp 33-34
Collins, RJ: 'The Use Of Recycled Aggregates In Concrete', BRE information Paper, IP5/94 1994
Hobbs, G: 'Management Of Construction And Demolition Waste', BRE information Paper, IP1/96 1996

Britannic Assurance Chief Office

Gross Area (m^2)	40165
Number Of Floors	3*
Frame Material	Concrete
Shape	Semi Regular

	Use Of Thermal Mass	Use Of Shading	Use Of Daylight	Type Of Glazing	Shallow Plan Building	Low Energy Use Equipment	Provision Of An Atrium	Building Energy Management System	Solar Panels	Use Of Reclaimed Materials
Features Included	•	•	•	x2	•		•			

This building might not, at first, be thought to be a low impact structure because it makes use of significant quantities of servicing, however it features a number of designs which mark it as such.

The office is 15m deep and generally open plan, although there are some cellular offices. Despite this the design takes advantage on dayighting via two atrium's and two smaller courtyards. The building has large amount of glazing and thus requires shading measures to reduce glare and solar gain. These measures include an overhanging roof, external columns and fixed shades.

The lower floors has a quantity of thermal mass through the concrete frame, however the second floor does not have this feature, making use of a lightweight roof. To counter this concrete panels were placed at this level, suspended from the centre of the second floor roof. Although it was estimated that 50 mm thick panels would suffice for this need, they are actually 75 mm thick for reasons of transport and installation.

The ventilation is provided by fan assisted cross flow segregated into three zones - outer perimeter, internal and atrium perimeter. Lights are initially switched by occupants using a telephone keypad, with a backup manual system, they could however be controlled by a management system.

<u>Reference</u>

'Clean Bold', Building Services, November 1996

British Gas Properties

Gross Area (m^2)	6500
Number Of Floors	3*
Frame Material	
Shape	Regular

Features Included	
Use Of Thermal Mass	•
Use Of Shading	
Use Of Daylight	
Type Of Glazing	x2
Shallow Plan Building	
Low Energy Use Equipment	
Provision Of An Atrium	•
Building Energy Management System	
Solar Panels	
Use Of Reclaimed Materials	

This building, developed by British Gas, makes used of low energy natural ventilation and is built on contaminated land, formerly used for gas storage. The site is in a relatively run down industrial area, so the design includes and enclosed atrium area. There is also provision for underground car parking.

With the site being in an industrial area, full natural ventilation could not be used, so ventilation air is drawn in from roof level and circulated via an under floor diffusion system. The ventilation design makes use of a exposed trough concrete soffit, with provision for increasing night air changes to increase heat exchange. The windows are not opened at night to increase cooling for security reasons, however they are manually operable during the day. The atrium is designed to provide a stack effect to vent used air, supplemented by a fan. This air is passed thorough a heat exchanger.

Light levels are controlled by external light shelves, with the internal lighting being zoned to perimeter and internal conditions. To ensure that lighting is not left on when not required, a session was planned to educate the occupants.

The building received an excellent rating under the BREEAM labelling system.

<u>Reference</u>

Evans, B: 'Low Cost, Low Energy Offices', Architects' Journal, 6 April 1994, pp 19-21

Cable And Wireless

Gross Area (m^2)	**12019**
Number Of Floors	**1/3**
Frame Material	
Shape	**Semi Regular**

	Use Of Thermal Mass	Use Of Shading	Use Of Daylight	Type Of Glazing	Shallow Plan Building	Low Energy Use Equipment	Provision Of An Atrium	Building Energy Management System	Solar Panels	Use Of Reclaimed Materials
Features Included		•		x2						

The cable and wireless building is a relatively early example of low energy design and as such has few features than other structures. The principle feature of the of the design is the waveform roof on the single floor blocks, which were designed to promote natural ventilation. The building was designed to cope with equipment loads that are well above those that might normally encountered, because of the building owners are a high technology company.

The double glazed windows are motorised but manually controlled, but the probe report found that windows were moved infrequently. The building is thermally lightweight and thus there is not requirement for night cooling.

The probe report also found that the actual energy consumption exceeded the typical and even the poor benchmarks for the structure type. The building was thought to have too much glazing. The occupants rated the winter performance as average and the summer performance as poor, particularly with regard to overheating and lighting levels

<u>References</u>

'Cable Talk', Building Services, November 1993, pp 22-26
'Probe 5: Cable & Wireless College', Building Services Journal, June 1996, pp 35 - 39

Co-Op Headquarters

Gross Area (m^2)	17000
Number Of Floors	5
Frame Material	
Shape	

	Use Of Thermal Mass	Use Of Shading	Use Of Daylight	Type Of Glazing	Shallow Plan Building	Low Energy Use Equipment	Provision Of An Atrium	Building Energy Management System	Solar Panels	Use Of Reclaimed Materials
Features Included	•*	•*		x3	•		•			

The Co-op building represents a slightly different model to the other building assessed because, although it makes use of a design that would be considered low energy, it also uses an air conditioning system.

The design is zonal in nature with more services in the areas with excessive heat gains. The distribution of services is under floor rather than at ceiling level. The building makes use of an ice storage system, rather than structural concrete to provide the thermal mass for cooling. The initial design has not strategy for night cooling, but this may be incorporated at some time in the future. The walls are heavily insulated.

The window units are triple glazed with internal blinds. However there is no external shading. The windows have a limited opening capability, but this does not contribute significantly to the ventilation.

The lighting design is predominantly artificial controlled by a lighting control system. This allows separate switching of the lighting for the east and west elevations. This system also turns lights off at night.

<u>Reference</u>

'It's All At The Co-op', Building Services, August 1996, pp 15-19

DeMontfort University Queens Building

Gross Area (m²)	10000
Number Of Floors	4
Frame Material	Brick
Shape	Irregular

Features Included	
Use Of Thermal Mass	•
Use Of Shading	•
Use Of Daylight	•
Type Of Glazing	x2
Shallow Plan Building	•
Low Energy Use Equipment	•
Provision Of An Atrium	•
Building Energy Management System	•*
Solar Panels	
Use Of Reclaimed Materials	

The DeMontfort queens building is one of the most widely known and reported of all the low impact buildings constructed. The building makes use of many of all the basic design features, lacking only solar panels and recycled materials.

The structure has both a BEMS and manually operated windows and has been designed to maximise the light ingress. Thermal chimneys a placed along the spine of the building to promote stack ventilation, while minimal backup mechanical and electrical services are installed.

Energy consumption figures were compiled from bills for the second year of operation and equate to 143 kWh/m² and 52 kWh/m² for gas and electric respectively which is batter than the benchmarks for this building type.

The user reaction to the building, as measured in the probe report showed that thermal quality was considered average while the winter air quality was significantly better than average. The combination of thermal mass and natural ventilation was considered effective in maintaining the comfort environment during the summer of 1994. The lighting was reported as variable, with too much in some areas and too little in others. The automatic controls have in some cases been overridden.

<u>References</u>

'A Testing Time For Natural Ventilation', Building Services, November 1994, pp 51-52
Asbridge, R & Cohen R: 'Probe 4: Queens Building', Building Services, April 1996, pp 35-38
'Learning Curve', Building Services, April 1996, pp 35-38
'Breath Test', Building, 6 June 1997, pp 44-50
Hawkes, D: 'User Controls In A Passive Building', Architects' Journal, 9 March 1994, pp 27-29
Randall, T (ed): 'Environmental Design: An Introduction For Architects And Engineers', ISBN 0419199306, Spon 1996

Hampshire County Court

Gross Area (m^2)	**2568**
Number Of Floors	**3**
Frame Material	**Concrete**
Shape	**Regular**

Features Included	**Use Of Thermal Mass**	**Use Of Shading**	**Use Of Daylight**	**Type Of Glazing**	**Shallow Plan Building**	**Low Energy Use Equipment**	**Provision Of An Atrium**	**Building Energy Management System**	**Solar Panels**	**Use Of Reclaimed Materials**
	•		•	x2						

This design of this building was slightly constrained by the requirements of a Law Court, specifically security. The building is deep plan and has no atrium, although lightwells are used to increase the daylight penetration.

The structure was deigned to be thermal heavyweight to soak up excess heat in summer. A noise survey rules out using natural ventilation in the courtrooms themselves, but public and administration areas are partially ventilated using the lightwells as thermal stacks. The degree of opening of these vents is controlled by manual switches located throughout the building.

In use, the feedback has been mostly positive, with users appreciating the simple controls. There was some suggestion that mechanical ventilation should have been used in the courtrooms, rather than simple mechanical ventilation.

<u>Reference</u>

McLaughlin, T: 'Point Of Law', Building Services, February 1995, pp 17-20

Housing 21 Headquarters

Gross Area (m^2)	
Number Of Floors	2
Frame Material	Concrete
Shape	Regular

	Use Of Thermal Mass	Use Of Shading	Use Of Daylight	Type Of Glazing	Shallow Plan Building	Low Energy Use Equipment	Provision Of An Atrium	Building Energy Management System	Solar Panels	Use Of Reclaimed Materials
Features Included	•	•	•	x2	•	•		•*		

This building uses thermal mass and high ceilings to promote natural ventilation. It also uses a rooflight which also promotes the stack effect. A BEMS controls the night time opening of panels which allow night time purging. The windows are made from aluminium rather than uPVC due to the perceived environmental problems of the latter. Concrete is used as the frame material due to its high thermal mass.

Reference

'Second Nature', Building, 20 September 1996, pp 56-57

Inland Revenue Headquarters

Gross Area (m^2)	
Number Of Floors	3
Frame Material	Concrete
Shape	Regular

	Use Of Thermal Mass	Use Of Shading	Use Of Daylight	Type Of Glazing	Shallow Plan Building	Low Energy Use Equipment	Provision Of An Atrium	Building Energy Management System	Solar Panels	Use Of Reclaimed Materials
Features Included	•	•	•	x2	•			•		

This was the fist to score maximum points in a BREEAM assessment. The building uses both triple glazing and natural daylight, but also get its power from a combined heat and power plant which burns domestic refuse.

The building makes use of the stack effect induced by chimneys assisted by a fan which draws air in. Lightshelves are used, in conjunction with the exposed concrete soffit, to provide a diffuse light source.

Reference

'Breeze Blocks', Building, 23 April 1993, pp 48-49

Ionica Building

Gross Area (m²)	4100
Number Of Floors	3
Frame Material	Steel
Shape	Semi Regular

	Use Of Thermal Mass	Use Of Shading	Use Of Daylight	Type Of Glazing	Shallow Plan Building	Low Energy Use Equipment	Provision Of An Atrium	Building Energy Management System	Solar Panels	Use Of Reclaimed Materials
Features Included	•	•	•	x2	•		•			

Ionica is a telecommunications company, which had a requirement for a new low energy building which could cope with relatively high quantities of IT equipment including raised service floors. The total cooling load estimated for VDU's and lighting was estimated as 22 W/m².

The ventilation system is mixed mode, using both thermal mass and atrium's with wind towers, but also mechanical ventilation which could be used to run the building if required. Thermal mass (260 mm concrete planks) is accessed via exposed concrete soffits which also have hollow cores. The hollow core system used is Termodeck. The thermal mass is used both for summer cooling and winter warming. Steel has been used as the frame material.

The architects estimate that up to 80% of the lighting can be provided by daylight, but artificial light use is not BEMS controlled, although some automation occurs via light sensors. Solar shading is provides by fixed external blinds. The ground floor suffers slightly from lack of natural daylight, despite the reflective panels in the atrium.

References

Woodward, A: 'Window Of Opportunity', Perspectives, April 1995, pp 42-45
Evans, B: 'Low Energy Design For A High Tech Office', Architects' Journal, 17 November 1993, pp 29-32
Jackaway, A & Greene, D: 'PowerGen In The Light Of Day', Architects' Journal, 14 March 1996, pp 46-47
'Shedding Light On Ionica', Architects' Journal, 28 March 1996, pp 51-53

Linacre College, Oxford

Gross Area (m²)	985
Number Of Floors	5
Frame Material	Concrete, Block
Shape	Regular

	Use Of Thermal Mass	Use Of Shading	Use Of Daylight	Type Of Glazing	Shallow Plan Building	Low Energy Use Equipment	Provision Of An Atrium	Building Energy Management System	Solar Panels	Use Of Reclaimed Materials
Features Included	•		•	x3	•	•				•

This accommodation block was designed with environmental performance in mind from the start. In addition, it is one of the few structures to have been assessed for materials energy, rather than only operational energy.

The building makes use of passive solar gain and exposed concrete and block masses. The building is unusual, being relatively small and more like a house than an office.

<u>References</u>

Evans, B: 'Counting The Global Cost', Architects' Journal, 24 February 1993, pp 57-58
Edwards, B: 'Towards Sustainable Architecture: European Directives And Building Design', ISBN 0750624922, Butterworth Architecture 1996

Pfizer Offices

Gross Area (m²)	7415
Number Of Floors	5-Jan
Frame Material	Concrete
Shape	Semi Regular

	Use Of Thermal Mass	Use Of Shading	Use Of Daylight	Type Of Glazing	Shallow Plan Building	Low Energy Use Equipment	Provision Of An Atrium	Building Energy Management System	Solar Panels	Use Of Reclaimed Materials
Features Included		•	•	x3			•			

This building makes use of a concrete frame to provide thermal mass and flexibility of openings. However the slab has a flat soffit, rather than the troughs usually preferred in this type of structure.

The building is designed to be naturally ventilated and the windows are triple glazed and have mid pane blinds. However to satisfy the working environment conditions displacement ventilation was used.

The lights are controlled by a central switching system, but this can be overridden by the users.

Reference

'Pfizer Offices & Restaurant', Building, 31 March 1995

Portland Building, Portsmouth University

Gross Area (m^2)	
Number Of Floors	4
Frame Material	
Shape	Semi Regular

	Use Of Thermal Mass	Use Of Shading	Use Of Daylight	Type Of Glazing	Shallow Plan Building	Low Energy Use Equipment	Provision Of An Atrium	Building Energy Management System	Solar Panels	Use Of Reclaimed Materials
Features Included		•*	•	x2		•	•	•*	•	

The building is unusual because it is one of only two to make use of solar panels (the other being the BRE). In this case the panels are used to preheat for hot water cylinders.

Other features include a high level of natural lighting, use of thermal mass and natural ventilation (supplemented by mechanical ventilation where required). Once again thermal stacks are used to promote ventilation.

The atrium light ingress is controlled by remotely actuated blinds or by the sum. The conference and seminar rooms contain both dimmable lights and room mounted photocells for daylight linking.

Reference

'University Challenge', Building Services, February 1997, pp 16-21

PowerGen Headquarters

Gross Area (m^2)	15402
Number Of Floors	3
Frame Material	Concrete
Shape	Regular

	Use Of Thermal Mass	Use Of Shading	Use Of Daylight	Type Of Glazing	Shallow Plan Building	Low Energy Use Equipment	Provision Of An Atrium	Building Energy Management System	Solar Panels	Use Of Reclaimed Materials
Features Included	•	•	•	x2	•	•	•	•		

The new headquarters building for the PowerGen company called for a "quality, naturally lit environment, with no direct sunlight on the working plane". The main objective was to produce a building which maximised occupant well being while reducing environmental impact. The way this brief was fulfilled can be expressed simply as night cooling of and exposed concrete coffer and a narrow plan allows office plan to be predominantly naturally ventilated with openable windows and good lighting supported by a number of other design features.

These design ideas are not in themselves new, but represents a grouping of ideas and concepts in a standard office building, which might historically have been made deep plan. This is a building where form follows function and externally at least looks similar to other, non low energy, buildings. The design early on took into account the requirements for space planning, circulation, work groups and environmental conditions. This assessment might not have been possible in a speculative building where more simple consideration of gross and net area would have been of more importance. The narrow plan design was initially suggested to avoid the producing circulation patterns which would divide working groups and fail to integrate staff and because PowerGen expressed a preference for openable windows, rather than for possible environmental benefits.

The building is rectangular in , running east to west,, with an atrium in the centre around which circulation routes run. The distance from window to structural column is 10.8m with the inner circulation route increasing the width to 12.6m. Each floor provides 12 floor plates 7.2m in width. The eastern end contains the computer suites and communications centre, while the western end contains the reception, restaurant and conference facilities. The eastern and western ends are the most difficult to provide natural ventilation for because of the high possible gains from the low angle of the sun during morning and evening. These areas can then be easily mechanically ventilated, with the open plan office areas being naturally ventilated. Where possible, heat emitting equipment has been grouped into 'hot spots' near service cores to allow for easier cooling

The natural ventilation feature are a mix of high and low tech, with openable windows during the day supplemented by a building energy management system (BEM) controlled night time purging. The window design plays a crucial part in this process to strike the correct balance between daylight, solar gain and ventilation requirements. The window to wall ratio is approximately 50:50 and the design calls for double glazed, low emmisivity units with motorised top pane (accounting for approximately 1/6 of the total glazed area) and two manually opening lower panes. The two lower pains are solar shaded on the south side by external louvers and allow for progressive opening of the total area

To control the nigh time cooling of the building, the BEMS is fed information from a number of sensors: for rain, external temperature, wind speed and wind direction. The control algorithm was fine tuned over the year after commissioning. The BEMS will open windows according to the internal temperature, but can also respond to external wind and rain conditions, closing windows if there is a danger of water of excessive wind penetration. In a building of this section cross ventilation was calculated to be more important than any stack effect provided by the atrium. The stack effect would be most important on hot, windless days, although statistical analysis of the prevailing weather conditions around the site suggest that still days rarely occur when it is hot (both during the day and to allow for night cooling). The estimates for heat gain were based on equipment loads of 14W/m^2 although analysis of existing facilities showed that 7W/m^2 was more realistic. It is possible that one factor holding back increased use is letting agents call for systems to cope with 30W/m^2 which makes natural ventilation a problem.

The lighting design was shaped by three goals. These were ranked as primary and secondary.

Primary :

- Maximisation of diffuse light at the workspace.
- Promotion of even daylighting.
- Promotion of occupant well being thorough daylighting.
- Minimisation of glare from contrasts in the visual field
- Minimisation of electric lighting loads and operation costs
- Increasing occupant connection to the natural environment

Secondary :

- Minimisation of glare from direct sunlight
- Utilisation of bright surface finishes to promote daylight distribution

To fulfil these design goals, the lighting has been closely integrated with the coffered ceiling and equipment mains have been minimised by using 36W florescent sources and high frequency control gear. The design aim is to provide 350-500 lux depending on location and the 2.4m trough spacing was found to be ideal to provide this light level on the working plane. Each luminaire is split into three switchable elements. Individual lights can be turned on from each desk, but are turned off by sweeps during the day. Perimeter units can be controlled by photocell. The shape of the coffer was altered to maximise the light distribution. The outer lamps have the option to run with higher power bulbs if there is found to be a shortfall in illumination further away from the luminaire. In addition to providing lighting the luminaires incorporate acoustic absorbency calculated to provide the correct damping. The glazed area of the atrium was altered (reduced) as the design progressed to try and ensure that the best daylighting solution was provided. This also slightly reduced the possibility for using the thermal stack effect, because of the reduction in air heating.

In addition to the natural cooling potential the raised flooring also provides twin speed air handling units and diffusers. This is used as a peak lopping to provide extra cooling as required. The raised floor had been designed to provide enough space to accommodate a full mechanical system if required at a later time.

A number of different equipment models were assessed to find which would provide the lowest cost and energy consumption. The mechanical cooling potential has been linked to the winter heating system to minimise the excess cost of installation, with hot air passing through the heat diffusers. This is supplemented with point heating under the windows to combat heat loss there. There are also radiators in the atrium to counter down draughts from the large glazing area. This system is expected to cost £18.6K per year to run and require an 16 kWh/m^2/y energy input.

Clearly there are a number of factors at work in this design which helped the designers provide a low energy building, not least the willingness of the occupier to use such a solution. More specific areas where problems could have occurred but were avoided are in the east west nature of the site, allowing maximum use of the sun and the lack of cellular offices which would have reduced the cross ventilation potential.

References

'The New Generation', Building Services, March 1995, pp 19-23
'PowerGen Headquarters : Project Profile', ISBN 0721014984, Reinforced Concrete Council
Jackaway, A & Greene, D: 'PowerGen In The Light Of Day', Architects' Journal, 14 March 1996, pp 46-47
'Sounding Out The Soffit', Architects' Journal, 7 March 1996, pp 43-44
Parker, D: 'Mass Appeal', New Builder Concrete Supplement, November 1994, pp 49-51
'PowerGen's Heat Bus: Servicing A Green Building', Building Services, March 1995, pp 43-44
'Shedding Light On Ionica', Architects' Journal, 28 March 1996, pp 51-53
'The Choice Of A New Generation', Architects' Journal, 2 March 1995, pp 43-55

RSPB Headquarters

Gross Area (m^2)	1800
Number Of Floors	2
Frame Material	Concrete
Shape	Regular

	Use Of Thermal Mass	Use Of Shading	Use Of Daylight	Type Of Glazing	Shallow Plan Building	Low Energy Use Equipment	Provision Of An Atrium	Building Energy Management System	Solar Panels	Use Of Reclaimed Materials
Features Included	•		•	x2	•	•				

This building has limited low impact features, but does make use of the Termodeck ventilation air handling system.

Reference

'Low Energy Takes Flight', Building Services, March 1996, pp 27 - 29

University Of East Anglia, Elizabeth Fry Building

Gross Area (m^2)	2568
Number Of Floors	3
Frame Material	Concrete
Shape	Regular

	Use Of Thermal Mass	Use Of Shading	Use Of Daylight	Type Of Glazing	Shallow Plan Building	Low Energy Use Equipment	Provision Of An Atrium	Builsing Energy Management System	Solar Panels	Use Of Reclaimed Materials
Features Included	•			x3				•		

This building makes use of the Termodeck system, but also has low emissivity tripe glazed windows. It is notable that the window units were imported from Sweden.

Reference

'Teaching Low Energy', Building Services, April 1995, pp 19-23

University Of Lincolnshire

Gross Area (m²)
Number Of Floors 4
Frame Material
Shape Regular

	Use Of Thermal Mass	Use Of Shading	Use Of Daylight	Type Of Glazing	Shallow Plan Building	Low Energy Use Equipment	Provision Of An Atrium	Building Energy Management System	Solar Panels	Use Of Reclaimed Materials
Features Included	•		•	x2				•		

This building makes use of a standard range of features including heavyweight construction, use of heat recovery and high thermal insulation. The design makes use of natural ventilation where possible and lightwells are used to promote natural lighting. The whole system is controlled by a BEMS which is linked to the space booking service to ensure that excess energy use is minimised.

Reference

'University Challenge', Building Services, March 1996, pp 30-31

Victoria Quay

Gross Area (m²) 32000
Number Of Floors 4
Frame Material Concrete
Shape Regular

	Use Of Thermal Mass	Use Of Shading	Use Of Daylight	Type Of Glazing	Shallow Plan Building	Low Energy Use Equipment	Provision Of An Atrium	Building Energy Management System	Solar Panels	Use Of Reclaimed Materials
Features Included	•		•	x2	•		•			

This large structure has both exposed concrete frame and cladding and simple natural air supply via open internal courtyards..

Reference

Hayward, D: 'Natural Regression', New Builder, 24 February 1995, pp 26-26

Weidmuller

Gross Area (m^2)	
Number Of Floors	3
Frame Material	Concrete
Shape	Regular

	Use Of Thermal Mass	Use Of Shading	Use Of Daylight	Type Of Glazing	Shallow Plan Building	Low Energy Use Equipment	Provision Of An Atrium	Building Energy Management System	Solar Panels	Use Of Reclaimed Materials
Features Included	•			x3						

This building makes use of the Termodeck ventilation system.

<u>Reference</u>

'Slab & Trickle', Building Services, February 1994, pp 30-32

Woodhouse Medical Centre

Gross Area (m^2)	640
Number Of Floors	1
Frame Material	Brick
Shape	Regular

	Use Of Thermal Mass	Use Of Shading	Use Of Daylight	Type Of Glazing	Shallow Plan Building	Low Energy Use Equipment	Provision Of An Atrium	Building Energy Management System	Solar Panels	Use Of Reclaimed Materials
Features Included			•	x2	•	•				

The building is more like a house than an office and makes use of high thermal insulation and double glazing. Rooflights in the passageways are used to provide the natural lighting. The probe report carried out suggests that the systems used for heating were not properly understood, overall levels of user satisfaction were high.

<u>References</u>

'Introducing The Thick Building', Building Services, January 1990, pp 17-
Edwards, B: 'Towards Sustainable Architecture: European Directives And Building Design', ISBN 0750624922, Butterworth Architecture 1996
Standeven, M & Cohen, R & Leaman, A: 'Probe 6 : Woodhouse Medical Centre', Building Services, August 1996, pp 35-38

APPENDIX B : CONCRETE IMPACTS BY MIX DESIGN

LIST OF FIGURES

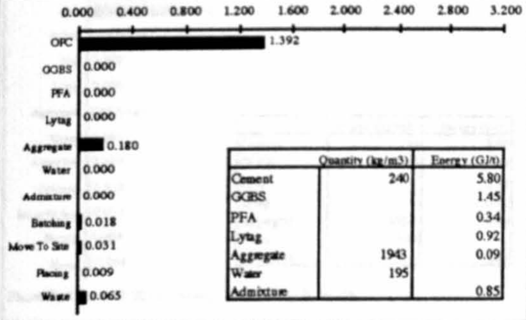
Table 1: Summary Of Results

	Embodied Energy GJ/m^3	Embodied CO$_2$ kg/m^3	Transportation Distance miles/m^3	Transportation Time hours/m^3
C20	1.695	313.64	6.89	0.377
C20 PFA	1.244	216.31	7.39	0.391
C20 GGBS	1.153	174.54	7.54	0.395
C30	1.982	374.16	6.79	0.368
C30 GGBS	1.348	209.78	7.64	0.391
C30 GGBS Pump	1.409	221.46	7.94	0.402
C30 Lytag	2.999	493.23	14.34	0.504
C30 Lytag Fines	3.368	514.92	18.47	0.573
C30 Lytag GGBS Pump	2.264	312.46	14.17	0.503
C30 Lytag PFA	2.564	398.09	14.77	0.506
C30 Lytag PFA Pump	2.475	401.01	13.30	0.481
C30 Lytag Pump	3.104	540.30	12.23	0.451
C30 PFA	1.509	271.64	7.38	0.383
C30 PFA Pump	1.571	264.99	7.64	0.393
C30 Pump	2.112	400.84	7.08	0.377
C40	2.220	424.30	6.72	0.360
C40 GGBS	1.620	258.56	7.84	0.390
C40 GGBS Pump	1.697	271.72	8.26	0.406
C40 Lytag	3.544	608.01	13.99	0.481
C40 Lytag Fines	3.844	627.00	17.47	0.546
C40 Lytag GGBS Pump	2.728	398.35	14.29	0.500
C40 Lytag PFA	3.006	490.49	14.86	0.501
C40 Lytag PFA Pump	3.054	518.62	13.71	0.482
C40 Lytag Pump	3.899	705.66	12.38	0.448
C40 PFA	1.675	306.32	7.40	0.378
C40 PFA Pump	1.808	313.34	7.72	0.392
C40 Pump	2.338	448.50	7.01	0.370
C60	2.979	580.75	7.07	0.368

Table 2: C20

C20 Embodied Energy

Total Embodied Energy: 1.7 GJ/m3

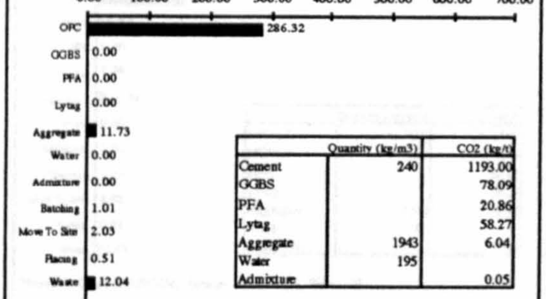


	Quantity (kg/m3)	Energy (GJ/t)
Cement	240	5.80
GGBS		1.45
PFA		0.34
Lytag		0.92
Aggregate	1943	0.09
Water	195	
Admixture		0.85

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 4%

C20 Embodied CO2

Total Embodied CO2: 313.6 kg/m3

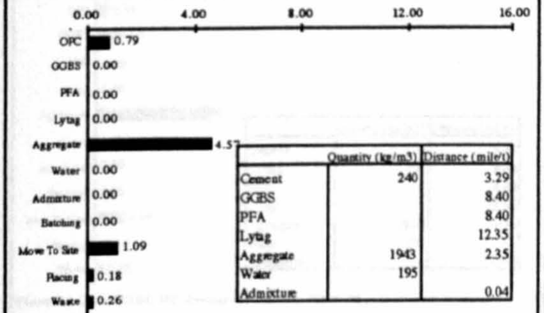


	Quantity (kg/m3)	CO2 (kg/t)
Cement	240	1193.00
GGBS		78.09
PFA		20.86
Lytag		58.27
Aggregate	1943	6.04
Water	195	
Admixture		0.05

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 4%

C20 Transportation Distance

Total Transportation Distance: 6.89 miles/m3

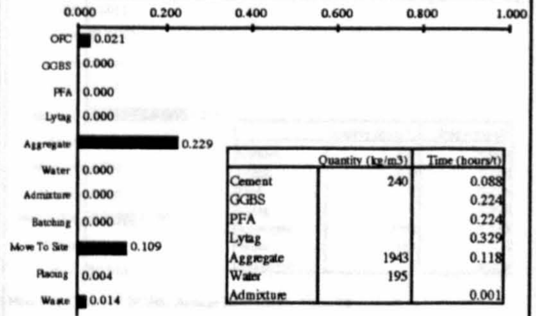


	Quantity (kg/m3)	Distance (mile/t)
Cement	240	3.29
GGBS		8.40
PFA		8.40
Lytag		12.35
Aggregate	1943	2.35
Water	195	
Admixture		0.04

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 4%

C20 Transportation Time

Total Transportation Time: 0.377 hours/m3



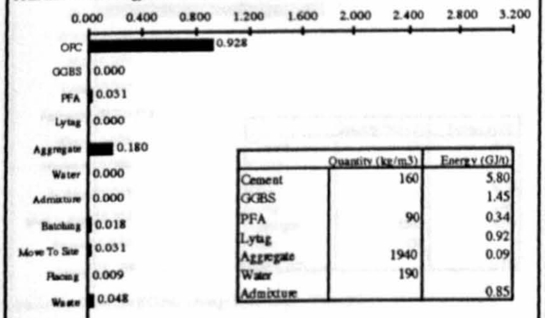
	Quantity (kg/m3)	Time (hours/t)
Cement	240	0.088
GGBS		0.224
PFA		0.224
Lytag		0.329
Aggregate	1943	0.118
Water	195	
Admixture		0.001

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 4%

Table 3: C20 PFA

C20 PFA Embodied Energy

Total Embodied Energy: 1.24 GJ/m3

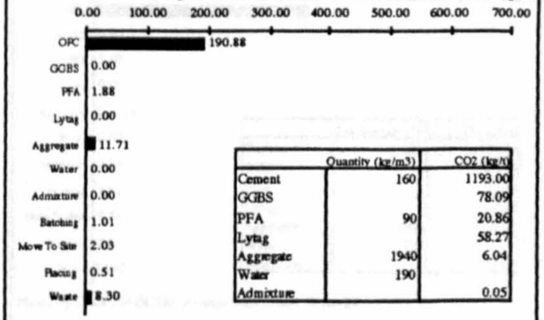


	Quantity (kg/m3)	Energy (GJ/t)
Cement	160	5.80
GGBS		1.45
PFA	90	0.34
Lytag		0.92
Aggregate	1940	0.09
Water	190	
Admixture		0.85

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 4%

C20 PFA Embodied CO2

Total Embodied CO2: 216.3 kg/m3

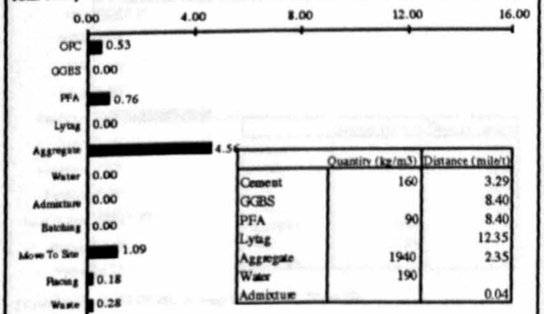


	Quantity (kg/m3)	CO2 (kg/t)
Cement	160	1193.00
GGBS		78.09
PFA	90	20.86
Lytag		58.27
Aggregate	1940	6.04
Water	190	
Admixture		0.05

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 4%

C20 PFA Transportation Distance

Total Transportation Distance: 7.39 miles/m3

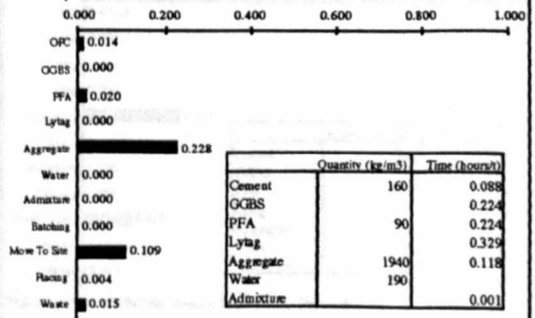


	Quantity (kg/m3)	Distance (mile/t)
Cement	160	3.29
GGBS		8.40
PFA	90	8.40
Lytag		12.35
Aggregate	1940	2.35
Water	190	
Admixture		0.04

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 4%

C20 PFA Transportation Time

Total Transportation Time: 0.391 hours/m3



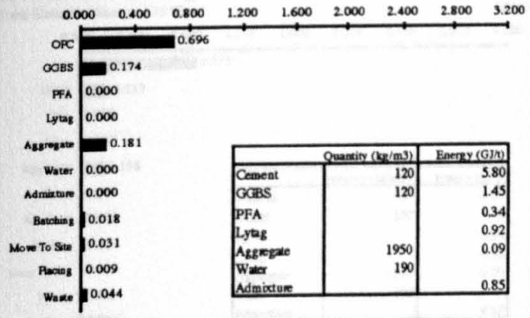
	Quantity (kg/m3)	Time (hours/t)
Cement	160	0.088
GGBS		0.224
PFA	90	0.224
Lytag		0.329
Aggregate	1940	0.118
Water	190	
Admixture		0.001

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 4%

Table 4: C20 GGBS

C20 GGBS Embodied Energy

Total Embodied Energy: 1.15 GJ/m3

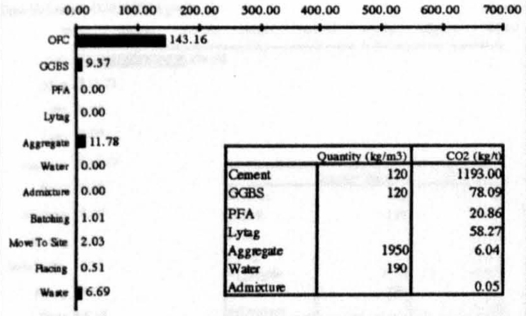


	Quantity (kg/m3)	Energy (GJ/t)
Cement	120	5.80
GGBS	120	1.45
PFA		0.34
Lytag		0.92
Aggregate	1950	0.09
Water	190	
Admixture		0.85

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 4%

C20 GGBS Embodied CO2

Total Embodied CO2: 174.5 kg/m3

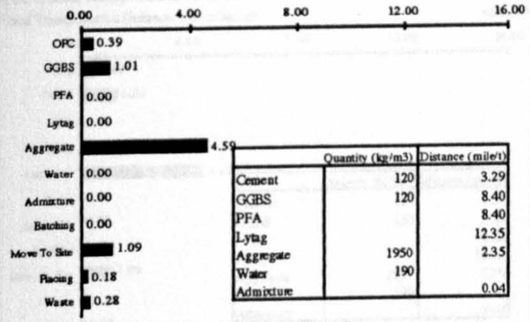


	Quantity (kg/m3)	CO2 (kg/t)
Cement	120	1193.00
GGBS	120	78.09
PFA		20.86
Lytag		58.27
Aggregate	1950	6.04
Water	190	
Admixture		0.05

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 4%

C20 GGBS Transportation Distance

Total Transportation Distance: 7.54 miles/m3

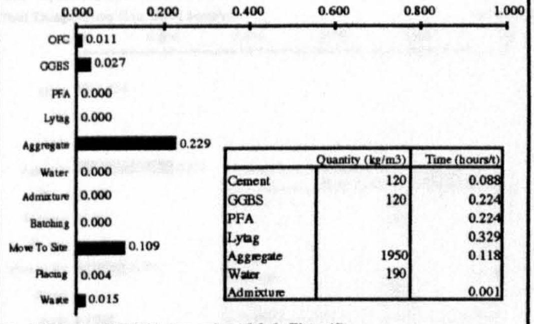


	Quantity (kg/m3)	Distance (mile/t)
Cement	120	3.29
GGBS	120	8.40
PFA		8.40
Lytag		12.35
Aggregate	1950	2.35
Water	190	
Admixture		0.04

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 4%

C20 GGBS Transportation Time

Total Transportation Time: 0.395 hours/m3



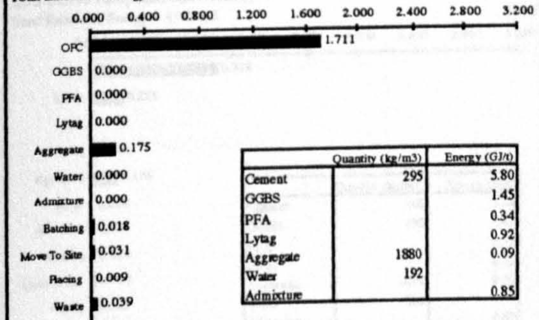
	Quantity (kg/m3)	Time (hours/t)
Cement	120	0.088
GGBS	120	0.224
PFA		0.224
Lytag		0.329
Aggregate	1950	0.118
Water	190	
Admixture		0.001

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 4%

Table 5: C30

C30 Embodied Energy

Total Embodied Energy: 1.98 GJ/m3

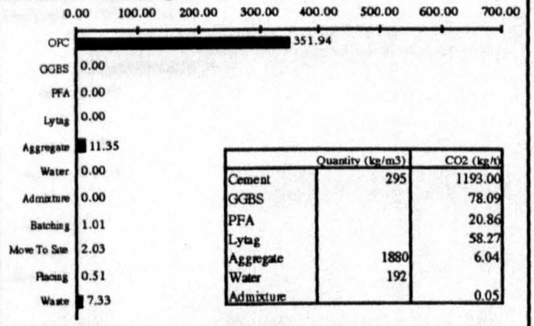


	Quantity (kg/m3)	Energy (GJ/t)
Cement	295	5.80
GGBS		1.45
PFA		0.34
Lytag		0.92
Aggregate	1880	0.09
Water	192	
Admixture		0.85

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 2%

C30 Embodied CO2

Total Embodied CO2: 374.2 kg/m3

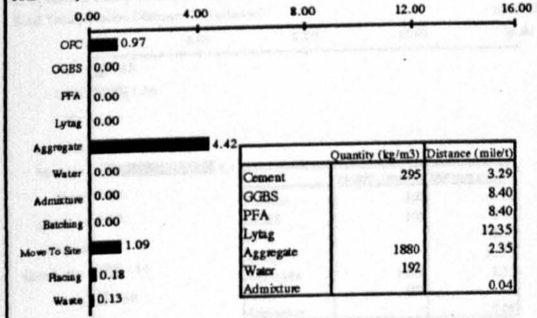


	Quantity (kg/m3)	CO2 (kg/t)
Cement	295	1193.00
GGBS		78.09
PFA		20.86
Lytag		58.27
Aggregate	1880	6.04
Water	192	
Admixture		0.05

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 2%

C30 Transportation Distance

Total Transportation Distance: 6.79 miles/m3

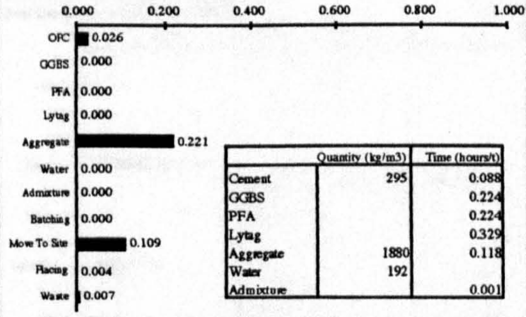


	Quantity (kg/m3)	Distance (mile/t)
Cement	295	3.29
GGBS		8.40
PFA		8.40
Lytag		12.35
Aggregate	1880	2.35
Water	192	
Admixture		0.04

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 2%

C30 Transportation Time

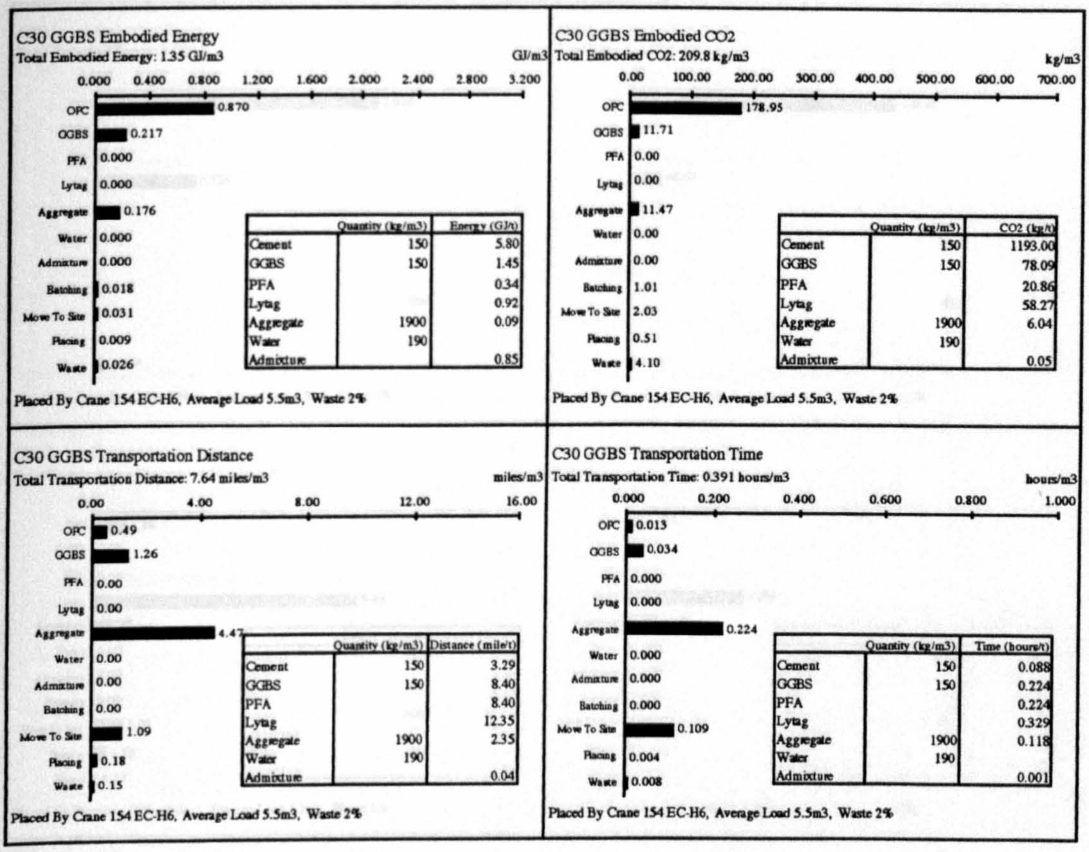
Total Transportation Time: 0.368 hours/m3



	Quantity (kg/m3)	Time (hours/t)
Cement	295	0.088
GGBS		0.224
PFA		0.224
Lytag		0.329
Aggregate	1880	0.118
Water	192	
Admixture		0.001

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 2%

Table 6: C30 GGBS



C30 GGBS Embodied Energy

Total Embodied Energy: 1.35 GJ/m3

	Quantity (kg/m3)	Energy (GJ/t)
Cement	150	5.80
GGBS	150	1.45
PFA		0.34
Lytag		0.92
Aggregate	1900	0.09
Water	190	
Admixture		0.85

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 2%

C30 GGBS Embodied CO2

Total Embodied CO2: 209.8 kg/m3

	Quantity (kg/m3)	CO2 (kg/t)
Cement	150	1193.00
GGBS	150	78.09
PFA		20.86
Lytag		58.27
Aggregate	1900	6.04
Water	190	
Admixture		0.05

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 2%

C30 GGBS Transportation Distance

Total Transportation Distance: 7.64 miles/m3

	Quantity (kg/m3)	Distance (mile/t)
Cement	150	3.29
GGBS	150	8.40
PFA		8.40
Lytag		12.35
Aggregate	1900	2.35
Water	190	
Admixture		0.04

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 2%

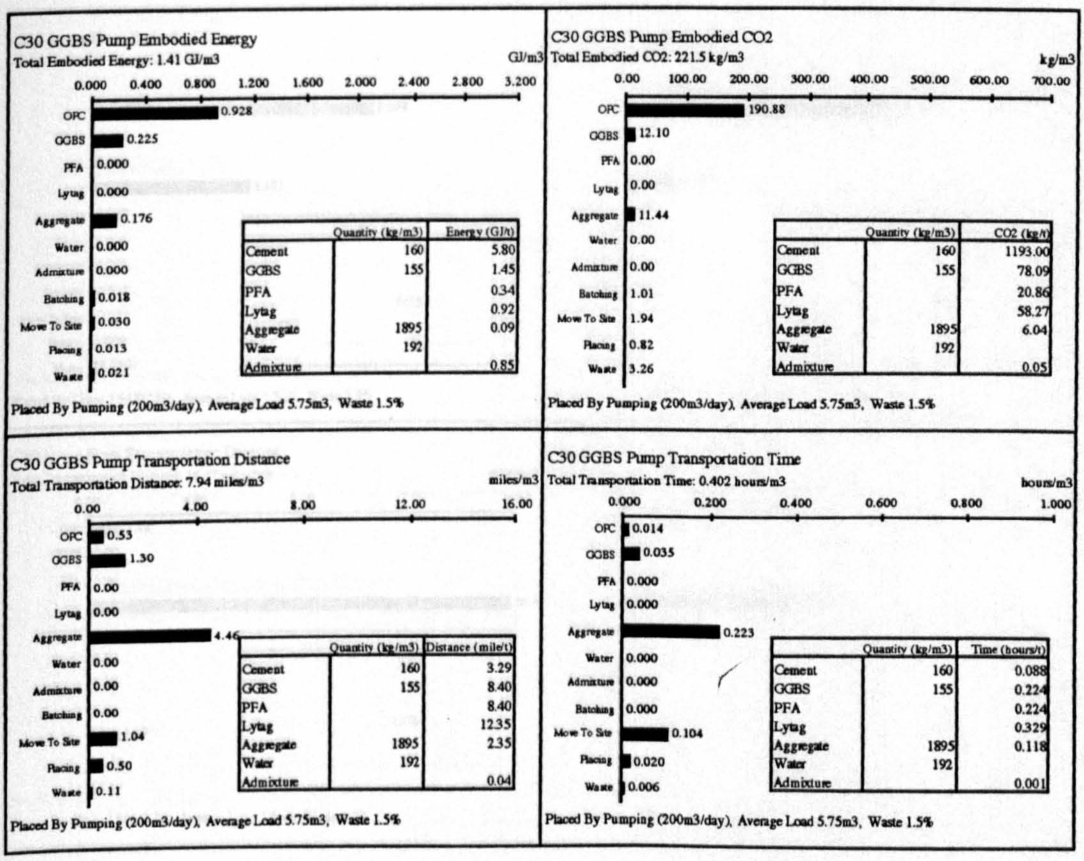
C30 GGBS Transportation Time

Total Transportation Time: 0.391 hours/m3

	Quantity (kg/m3)	Time (hours/t)
Cement	150	0.088
GGBS	150	0.224
PFA		0.224
Lytag		0.329
Aggregate	1900	0.118
Water	190	
Admixture		0.001

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 2%

Table 7: C30 GGBS Pump



C30 GGBS Pump Embodied Energy

Total Embodied Energy: 1.41 GJ/m3

	Quantity (kg/m3)	Energy (GJ/t)
Cement	160	5.80
GGBS	155	1.45
PFA		0.34
Lytag		0.92
Aggregate	1895	0.09
Water	192	
Admixture		0.85

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1.5%

C30 GGBS Pump Embodied CO2

Total Embodied CO2: 221.5 kg/m3

	Quantity (kg/m3)	CO2 (kg/t)
Cement	160	1193.00
GGBS	155	78.09
PFA		20.86
Lytag		58.27
Aggregate	1895	6.04
Water	192	
Admixture		0.05

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1.5%

C30 GGBS Pump Transportation Distance

Total Transportation Distance: 7.94 miles/m3

	Quantity (kg/m3)	Distance (mile/t)
Cement	160	3.29
GGBS	155	8.40
PFA		8.40
Lytag		12.35
Aggregate	1895	2.35
Water	192	
Admixture		0.04

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1.5%

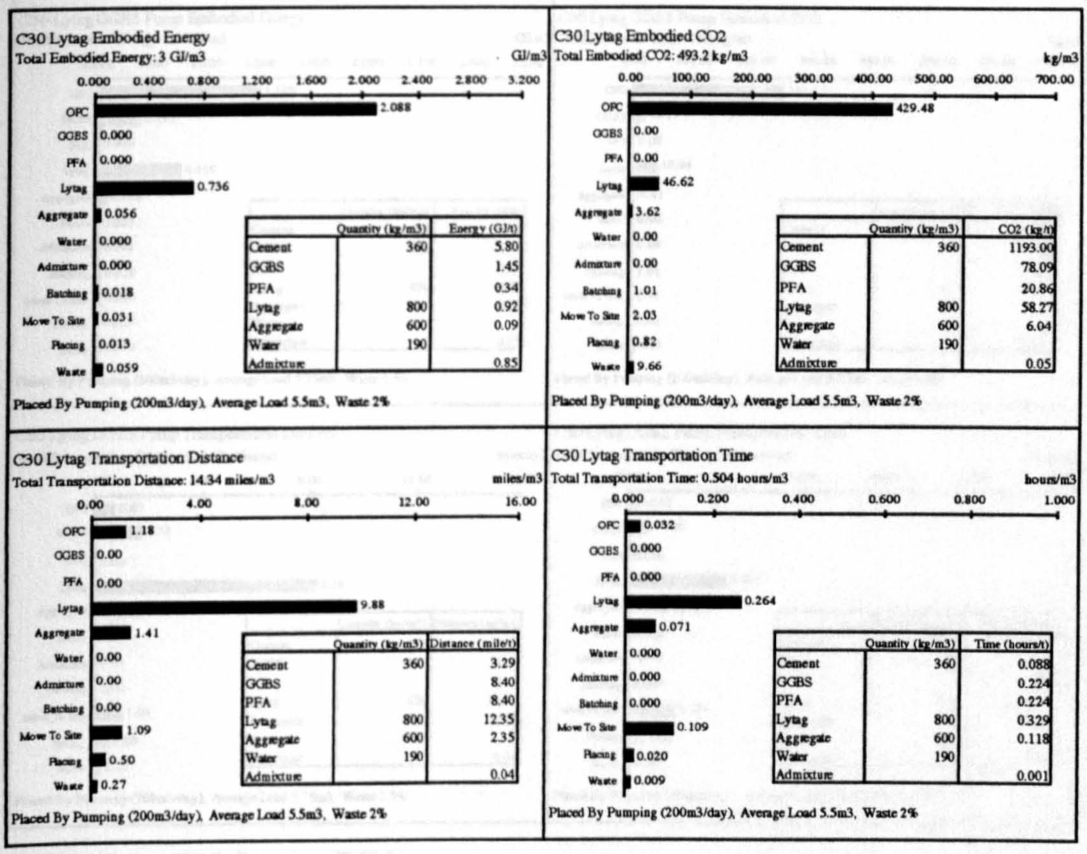
C30 GGBS Pump Transportation Time

Total Transportation Time: 0.402 hours/m3

	Quantity (kg/m3)	Time (hours/t)
Cement	160	0.088
GGBS	155	0.224
PFA		0.224
Lytag		0.329
Aggregate	1895	0.118
Water	192	
Admixture		0.001

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1.5%

Table 8: C30 Lytag



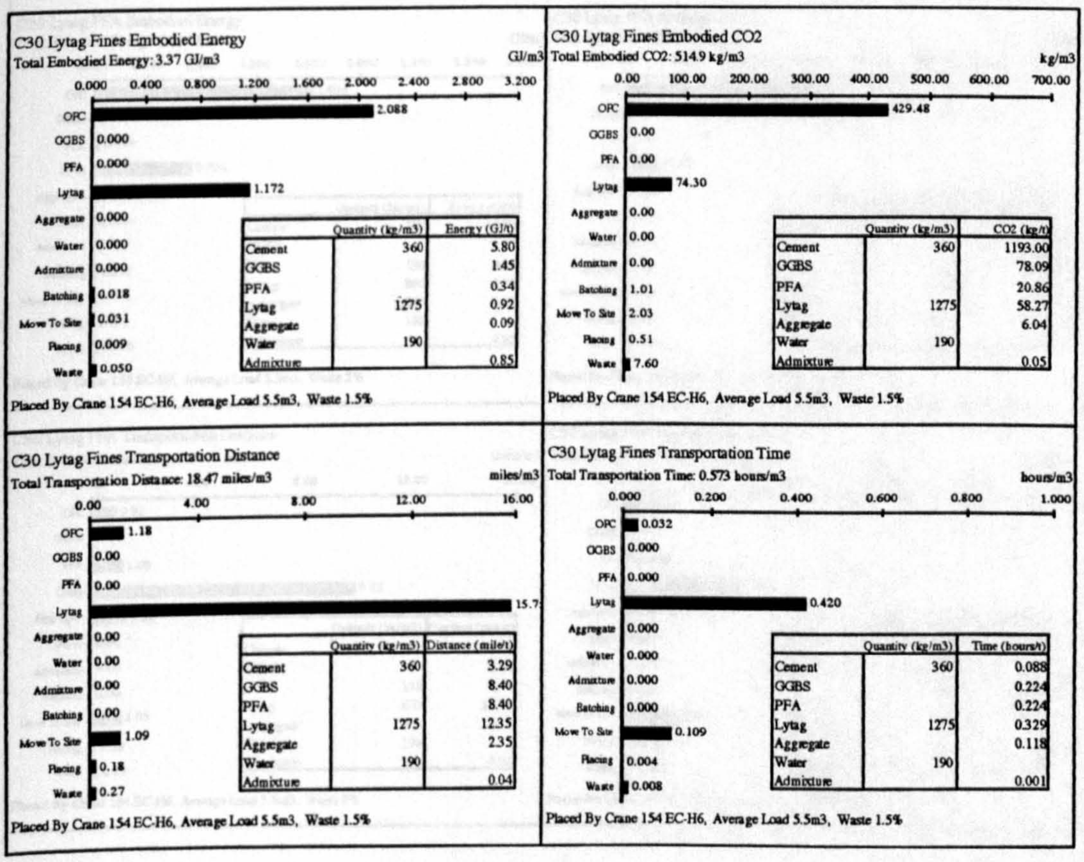
	Quantity (kg/m3)	Energy (GJ/t)
Cement	360	5.80
GGBS		1.45
PFA		0.34
Lytag	800	0.92
Aggregate	600	0.09
Water	190	
Admixture		0.85

	Quantity (kg/m3)	CO2 (kg/t)
Cement	360	1193.00
GGBS		78.09
PFA		20.86
Lytag	800	58.27
Aggregate	600	6.04
Water	190	
Admixture		0.05

	Quantity (kg/m3)	Distance (mile/t)
Cement	360	3.29
GGBS		8.40
PFA		8.40
Lytag	800	12.35
Aggregate	600	2.35
Water	190	
Admixture		0.04

	Quantity (kg/m3)	Time (hours/t)
Cement	360	0.088
GGBS		0.224
PFA		0.224
Lytag	800	0.329
Aggregate	600	0.118
Water	190	
Admixture		0.001

Table 9: C30 Lytag Fines



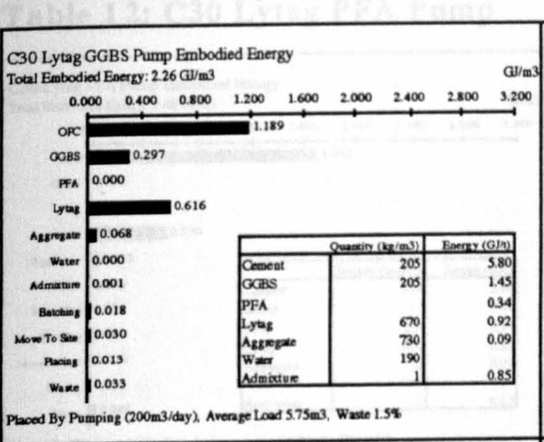
	Quantity (kg/m3)	Energy (GJ/t)
Cement	360	5.80
GGBS		1.45
PFA		0.34
Lytag	1275	0.92
Aggregate		0.09
Water	190	
Admixture		0.85

	Quantity (kg/m3)	CO2 (kg/t)
Cement	360	1193.00
GGBS		78.09
PFA		20.86
Lytag	1275	58.27
Aggregate		6.04
Water	190	
Admixture		0.05

	Quantity (kg/m3)	Distance (mile/t)
Cement	360	3.29
GGBS		8.40
PFA		8.40
Lytag	1275	12.35
Aggregate		2.35
Water	190	
Admixture		0.04

	Quantity (kg/m3)	Time (hours/t)
Cement	360	0.088
GGBS		0.224
PFA		0.224
Lytag	1275	0.329
Aggregate		0.118
Water	190	
Admixture		0.001

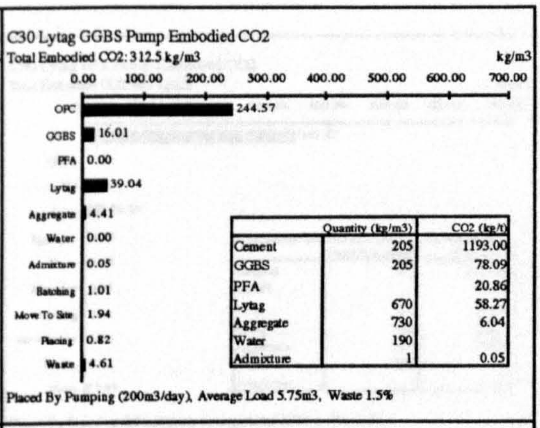
Table 10: C30 Lytag GGBS Pump


C30 Lytag GGBS Pump Embodied Energy

Total Embodied Energy: 2.26 GJ/m3

	Quantity (kg/m3)	Energy (GJ/t)
Cement	205	5.80
GGBS	205	1.45
PFA		0.34
Lytag	670	0.92
Aggregate	730	0.09
Water	190	
Admixture	1	0.85

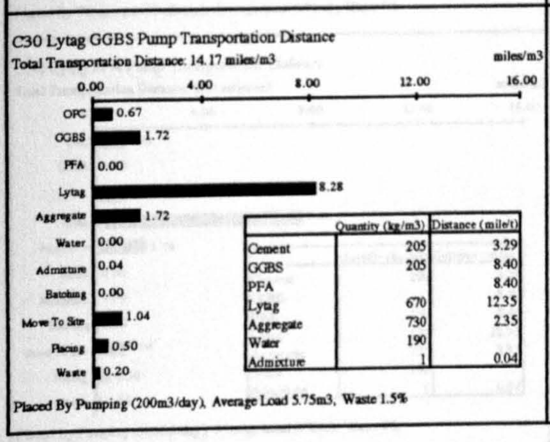
Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1.5%


C30 Lytag GGBS Pump Embodied CO2

Total Embodied CO2: 312.5 kg/m3

	Quantity (kg/m3)	CO2 (kg/t)
Cement	205	1193.00
GGBS	205	78.09
PFA		20.86
Lytag	670	58.27
Aggregate	730	6.04
Water	190	
Admixture	1	0.05

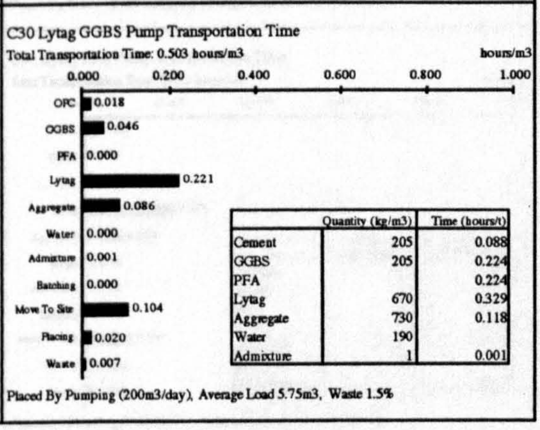
Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1.5%


C30 Lytag GGBS Pump Transportation Distance

Total Transportation Distance: 14.17 miles/m3

	Quantity (kg/m3)	Distance (mile/t)
Cement	205	3.29
GGBS	205	8.40
PFA		8.40
Lytag	670	12.35
Aggregate	730	2.35
Water	190	
Admixture	1	0.04

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1.5%

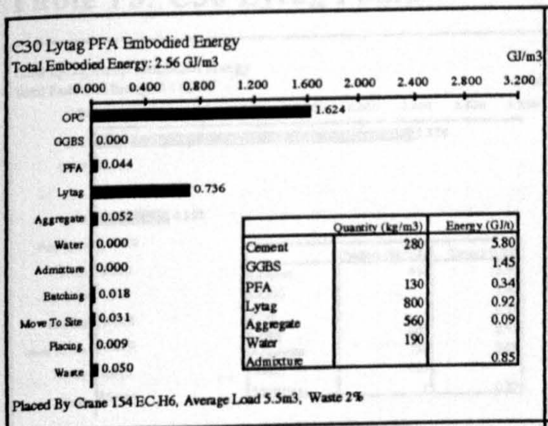

C30 Lytag GGBS Pump Transportation Time

Total Transportation Time: 0.503 hours/m3

	Quantity (kg/m3)	Time (hours/t)
Cement	205	0.088
GGBS	205	0.224
PFA		0.224
Lytag	670	0.329
Aggregate	730	0.118
Water	190	
Admixture	1	0.001

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1.5%

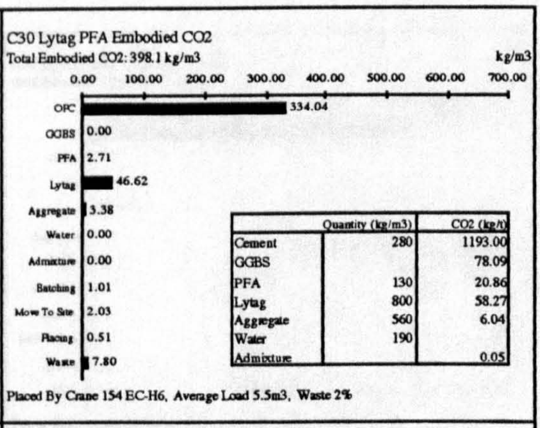
Table 11: C30 Lytag PFA


C30 Lytag PFA Embodied Energy

Total Embodied Energy: 2.56 GJ/m3

	Quantity (kg/m3)	Energy (GJ/t)
Cement	280	5.80
GGBS		1.45
PFA	130	0.34
Lytag	800	0.92
Aggregate	560	0.09
Water	190	
Admixture		0.85

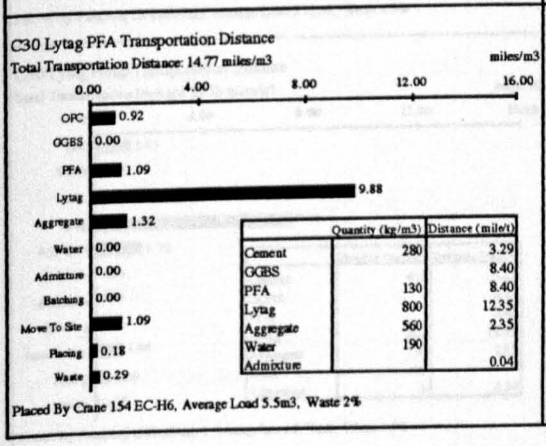
Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 2%


C30 Lytag PFA Embodied CO2

Total Embodied CO2: 398.1 kg/m3

	Quantity (kg/m3)	CO2 (kg/t)
Cement	280	1193.00
GGBS		78.09
PFA	130	20.86
Lytag	800	58.27
Aggregate	560	6.04
Water	190	
Admixture		0.05

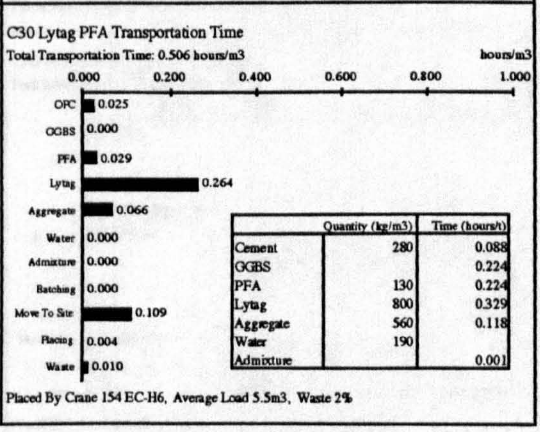
Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 2%


C30 Lytag PFA Transportation Distance

Total Transportation Distance: 14.77 miles/m3

	Quantity (kg/m3)	Distance (mile/t)
Cement	280	3.29
GGBS		8.40
PFA	130	8.40
Lytag	800	12.35
Aggregate	560	2.35
Water	190	
Admixture		0.04

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 2%

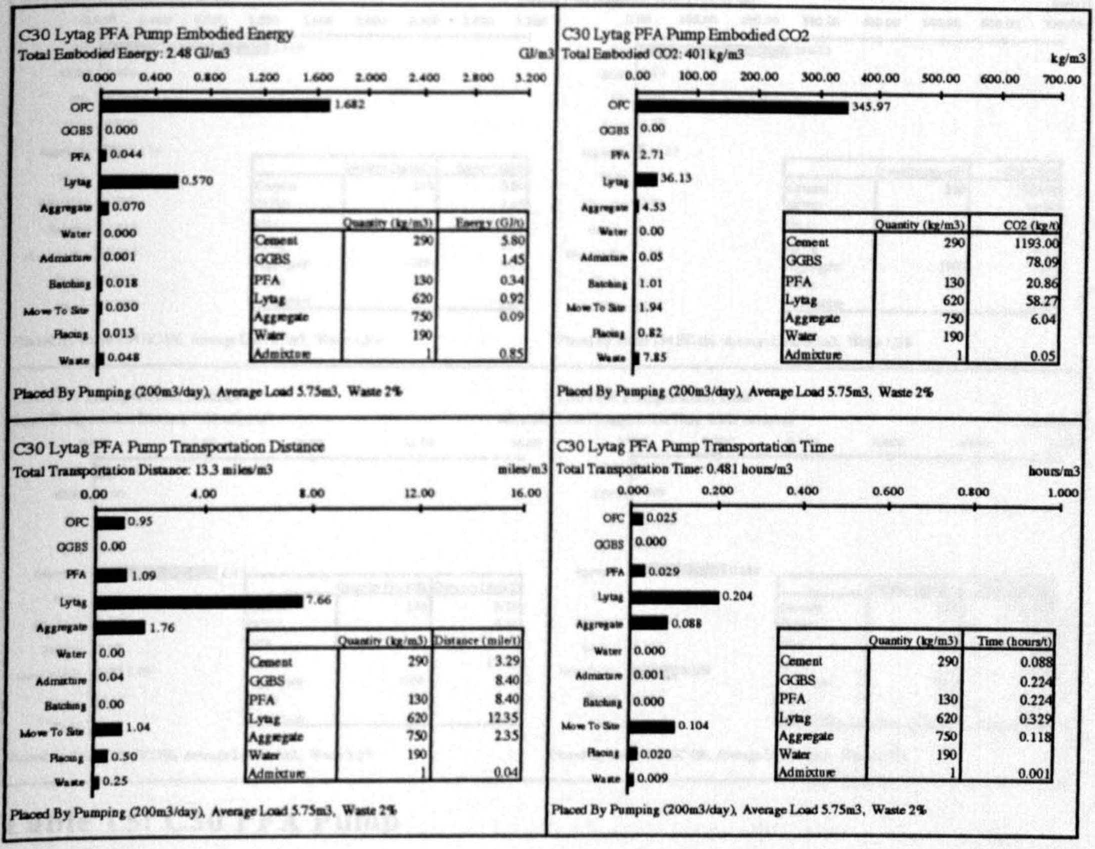

C30 Lytag PFA Transportation Time

Total Transportation Time: 0.506 hours/m3

	Quantity (kg/m3)	Time (hours/t)
Cement	280	0.088
GGBS		0.224
PFA	130	0.224
Lytag	800	0.329
Aggregate	560	0.118
Water	190	
Admixture		0.001

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 2%

Table 12: C30 Lytag PFA Pump



C30 Lytag PFA Pump Embodied Energy

Total Embodied Energy: 2.48 GJ/m3

	Quantity (kg/m3)	Energy (GJ/t)
Cement	290	5.80
GGBS		1.45
PFA	130	0.34
Lytag	620	0.92
Aggregate	750	0.09
Water	190	
Admixture	1	0.85

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 2%

C30 Lytag PFA Pump Embodied CO2

Total Embodied CO2: 401 kg/m3

	Quantity (kg/m3)	CO2 (kg/t)
Cement	290	1193.00
GGBS		78.09
PFA	130	20.86
Lytag	620	58.27
Aggregate	750	6.04
Water	190	
Admixture	1	0.05

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 2%

C30 Lytag PFA Pump Transportation Distance

Total Transportation Distance: 13.3 miles/m3

	Quantity (kg/m3)	Distance (mile/t)
Cement	290	3.29
GGBS		8.40
PFA	130	8.40
Lytag	620	12.35
Aggregate	750	2.35
Water	190	
Admixture	1	0.04

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 2%

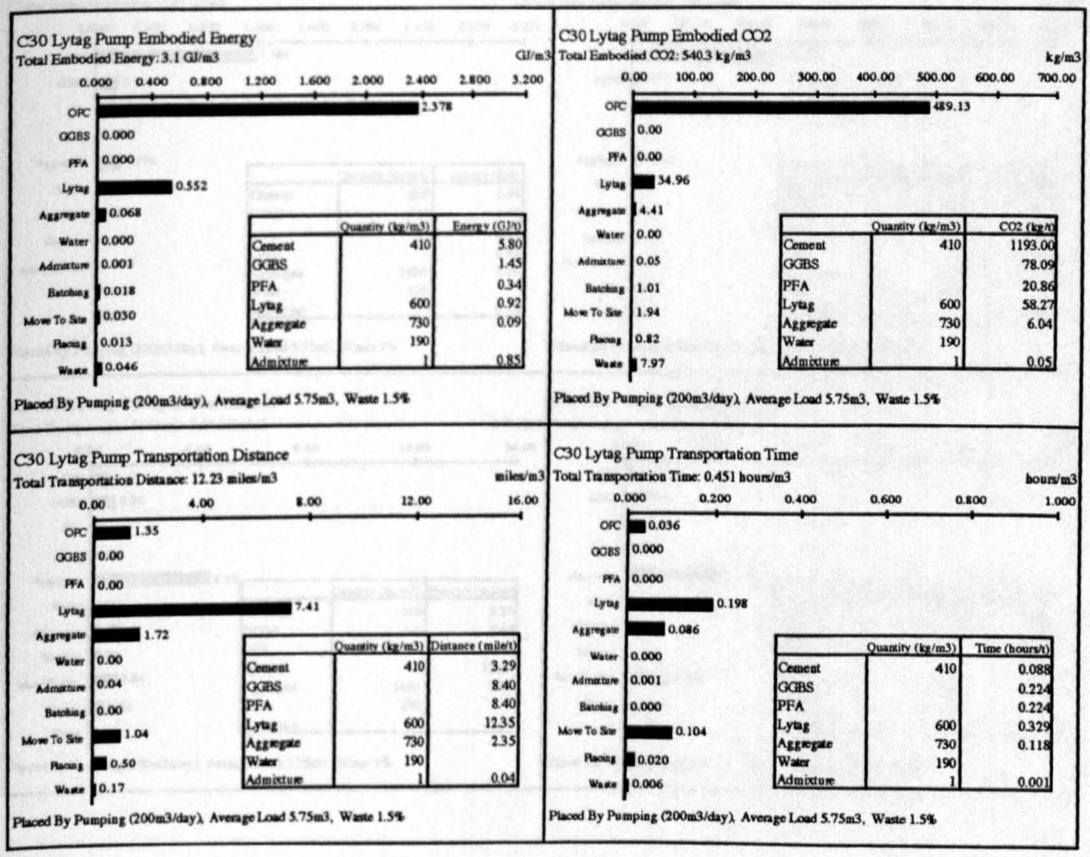
C30 Lytag PFA Pump Transportation Time

Total Transportation Time: 0.481 hours/m3

	Quantity (kg/m3)	Time (hours/t)
Cement	290	0.088
GGBS		0.224
PFA	130	0.224
Lytag	620	0.329
Aggregate	750	0.118
Water	190	
Admixture	1	0.001

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 2%

Table 13: C30 Lytag Pump



C30 Lytag Pump Embodied Energy

Total Embodied Energy: 3.1 GJ/m3

	Quantity (kg/m3)	Energy (GJ/t)
Cement	410	5.80
GGBS		1.45
PFA		0.34
Lytag	600	0.92
Aggregate	730	0.09
Water	190	
Admixture	1	0.85

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1.5%

C30 Lytag Pump Embodied CO2

Total Embodied CO2: 540.3 kg/m3

	Quantity (kg/m3)	CO2 (kg/t)
Cement	410	1193.00
GGBS		78.09
PFA		20.86
Lytag	600	58.27
Aggregate	730	6.04
Water	190	
Admixture	1	0.05

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1.5%

C30 Lytag Pump Transportation Distance

Total Transportation Distance: 12.23 miles/m3

	Quantity (kg/m3)	Distance (mile/t)
Cement	410	3.29
GGBS		8.40
PFA		8.40
Lytag	600	12.35
Aggregate	730	2.35
Water	190	
Admixture	1	0.04

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1.5%

C30 Lytag Pump Transportation Time

Total Transportation Time: 0.451 hours/m3

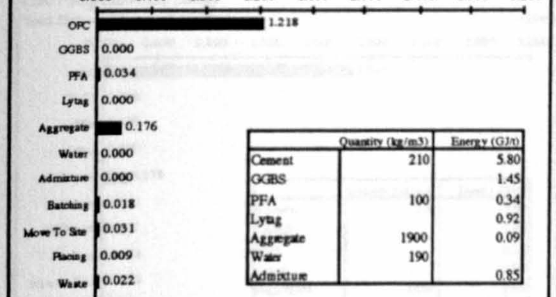
	Quantity (kg/m3)	Time (hours/t)
Cement	410	0.088
GGBS		0.224
PFA		0.224
Lytag	600	0.329
Aggregate	730	0.118
Water	190	
Admixture	1	0.001

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1.5%

Table 14: C30 PFA

C30 PFA Embodied Energy

Total Embodied Energy: 1.51 GJ/m3 **GJ/m3**

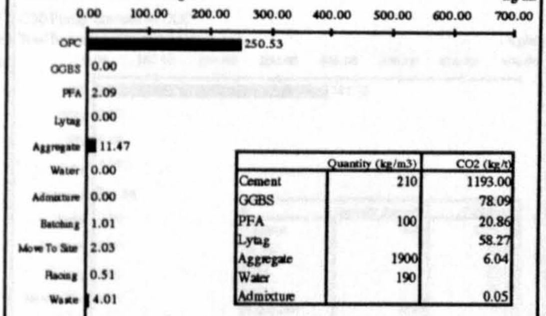


	Quantity (kg/m3)	Energy (GJ/t)
Cement	210	5.80
GGBS		1.45
PFA	100	0.34
Lytag		0.92
Aggregate	1900	0.09
Water	190	
Admixture		0.85

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1.5%

C30 PFA Embodied CO2

Total Embodied CO2: 271.6 kg/m3 **kg/m3**

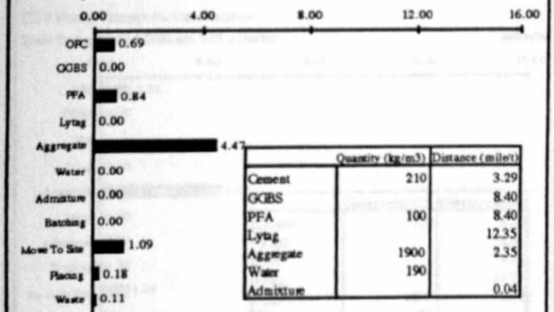


	Quantity (kg/m3)	CO2 (kg/t)
Cement	210	1193.00
GGBS		78.09
PFA	100	20.86
Lytag		58.27
Aggregate	1900	6.04
Water	190	
Admixture		0.05

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1.5%

C30 PFA Transportation Distance

Total Transportation Distance: 7.38 miles/m3 **miles/m3**

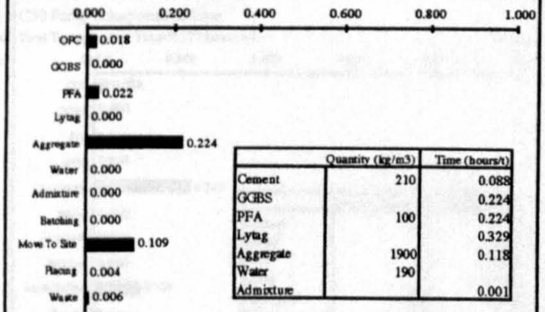


	Quantity (kg/m3)	Distance (mile/t)
Cement	210	3.29
GGBS		8.40
PFA	100	8.40
Lytag		12.35
Aggregate	1900	2.35
Water	190	
Admixture		0.04

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1.5%

C30 PFA Transportation Time

Total Transportation Time: 0.383 hours/m3 **hours/m3**



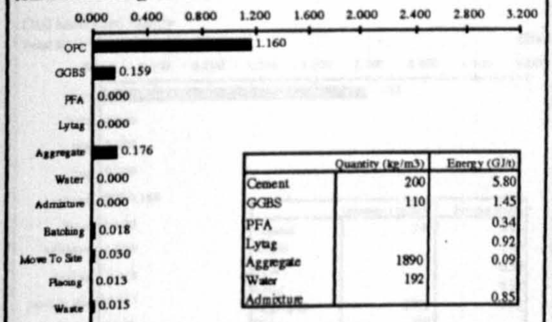
	Quantity (kg/m3)	Time (hours/t)
Cement	210	0.088
GGBS		0.224
PFA	100	0.224
Lytag		0.329
Aggregate	1900	0.118
Water	190	
Admixture		0.001

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1.5%

Table 15: C30 PFA Pump

C30 PFA Pump Embodied Energy

Total Embodied Energy: 1.57 GJ/m3 **GJ/m3**

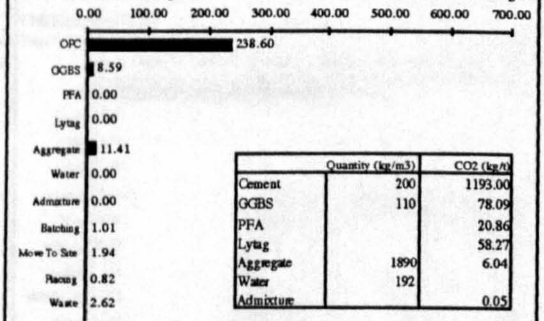


	Quantity (kg/m3)	Energy (GJ/t)
Cement	200	5.80
GGBS	110	1.45
PFA		0.34
Lytag		0.92
Aggregate	1890	0.09
Water	192	
Admixture		0.85

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%

C30 PFA Pump Embodied CO2

Total Embodied CO2: 265 kg/m3 **kg/m3**

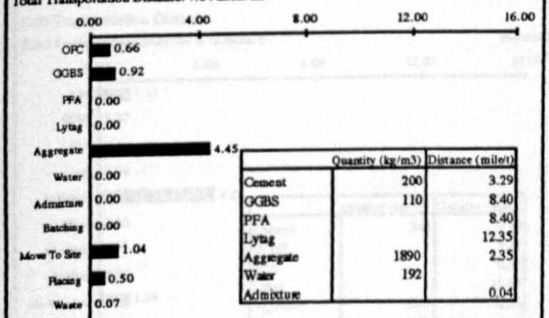


	Quantity (kg/m3)	CO2 (kg/t)
Cement	200	1193.00
GGBS	110	78.09
PFA		20.86
Lytag		58.27
Aggregate	1890	6.04
Water	192	
Admixture		0.05

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%

C30 PFA Pump Transportation Distance

Total Transportation Distance: 7.64 miles/m3 **miles/m3**

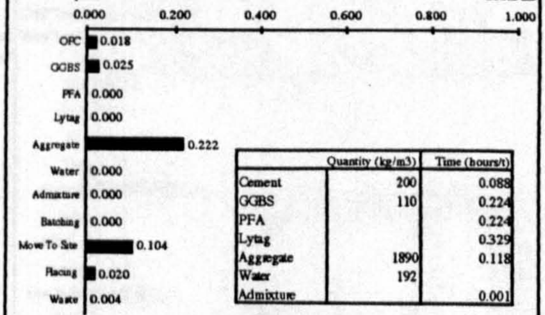


	Quantity (kg/m3)	Distance (mile/t)
Cement	200	3.29
GGBS	110	8.40
PFA		8.40
Lytag		12.35
Aggregate	1890	2.35
Water	192	
Admixture		0.04

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%

C30 PFA Pump Transportation Time

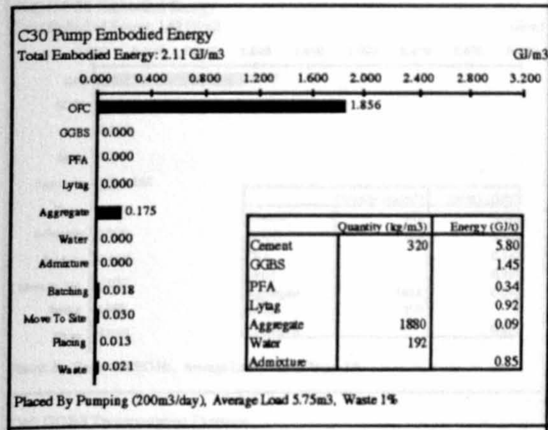
Total Transportation Time: 0.393 hours/m3 **hours/m3**



	Quantity (kg/m3)	Time (hours/t)
Cement	200	0.088
GGBS	110	0.224
PFA		0.224
Lytag		0.329
Aggregate	1890	0.118
Water	192	
Admixture		0.001

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%

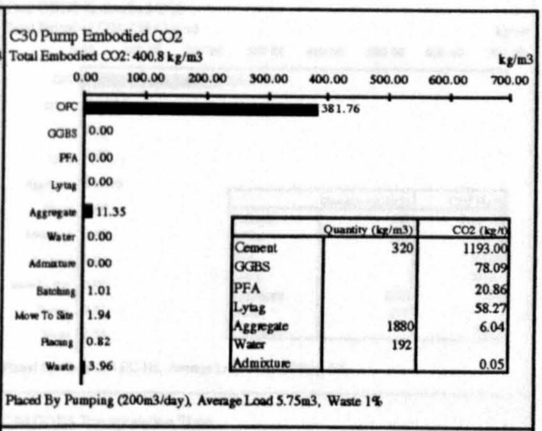
Table 16: C30 Pump


C30 Pump Embodied Energy

Total Embodied Energy: 2.11 GJ/m3

	Quantity (kg/m3)	Energy (GJ/t)
Cement	320	5.80
GGBS		1.45
PFA		0.34
Lytag		0.92
Aggregate	1880	0.09
Water	192	
Admixture		0.85

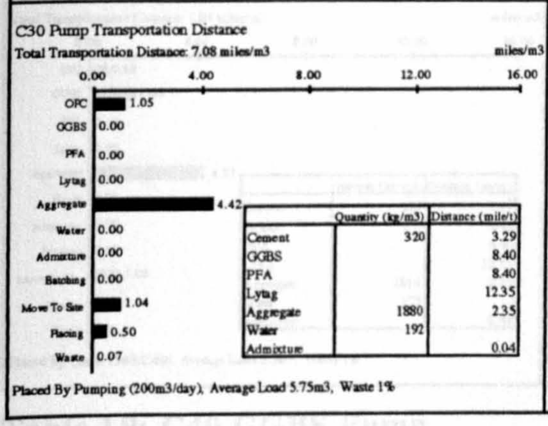
Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%


C30 Pump Embodied CO2

Total Embodied CO2: 400.8 kg/m3

	Quantity (kg/m3)	CO2 (kg/t)
Cement	320	1193.00
GGBS		78.09
PFA		20.86
Lytag		58.27
Aggregate	1880	6.04
Water	192	
Admixture		0.05

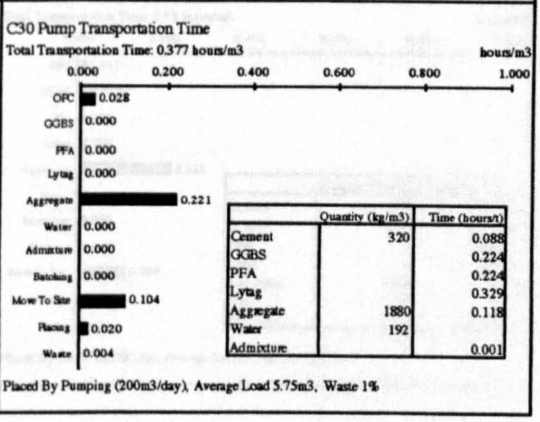
Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%


C30 Pump Transportation Distance

Total Transportation Distance: 7.08 miles/m3

	Quantity (kg/m3)	Distance (mile/t)
Cement	320	3.29
GGBS		8.40
PFA		8.40
Lytag		12.35
Aggregate	1880	2.35
Water	192	
Admixture		0.04

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%

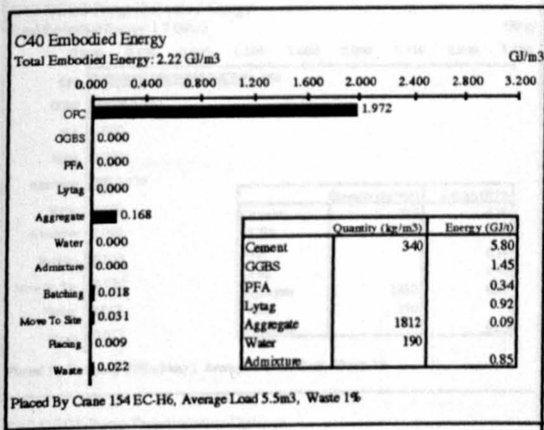

C30 Pump Transportation Time

Total Transportation Time: 0.377 hours/m3

	Quantity (kg/m3)	Time (hours/t)
Cement	320	0.088
GGBS		0.224
PFA		0.224
Lytag		0.329
Aggregate	1880	0.118
Water	192	
Admixture		0.001

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%

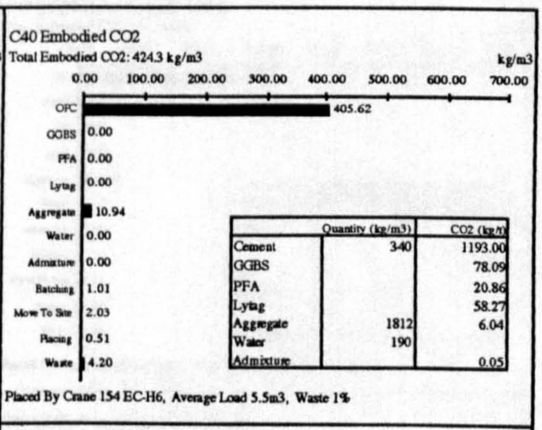
Table 17: C40


C40 Embodied Energy

Total Embodied Energy: 2.22 GJ/m3

	Quantity (kg/m3)	Energy (GJ/t)
Cement	340	5.80
GGBS		1.45
PFA		0.34
Lytag		0.92
Aggregate	1812	0.09
Water	190	
Admixture		0.85

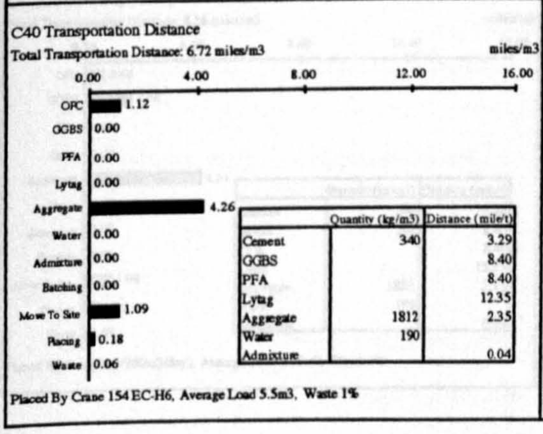
Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%


C40 Embodied CO2

Total Embodied CO2: 424.3 kg/m3

	Quantity (kg/m3)	CO2 (kg/t)
Cement	340	1193.00
GGBS		78.09
PFA		20.86
Lytag		58.27
Aggregate	1812	6.04
Water	190	
Admixture		0.05

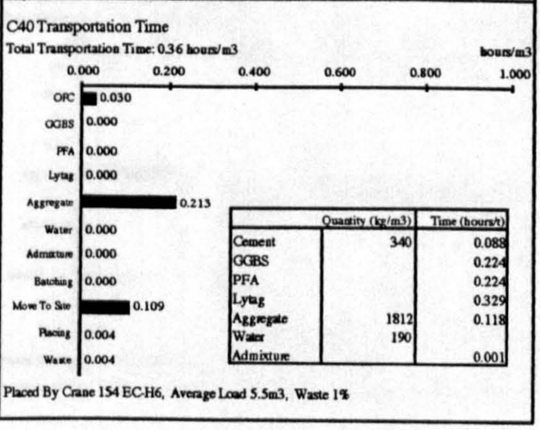
Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%


C40 Transportation Distance

Total Transportation Distance: 6.72 miles/m3

	Quantity (kg/m3)	Distance (mile/t)
Cement	340	3.29
GGBS		8.40
PFA		8.40
Lytag		12.35
Aggregate	1812	2.35
Water	190	
Admixture		0.04

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%

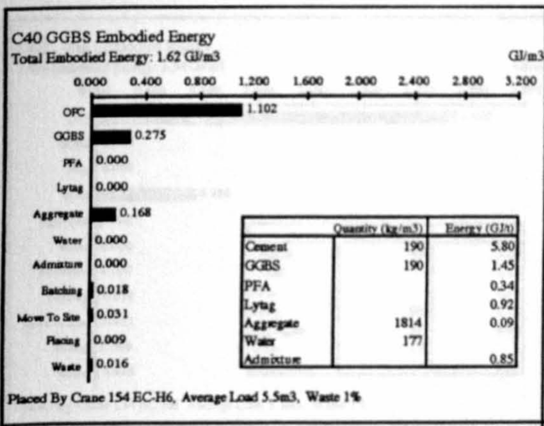

C40 Transportation Time

Total Transportation Time: 0.36 hours/m3

	Quantity (kg/m3)	Time (hours/t)
Cement	340	0.088
GGBS		0.224
PFA		0.224
Lytag		0.329
Aggregate	1812	0.118
Water	190	
Admixture		0.001

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%

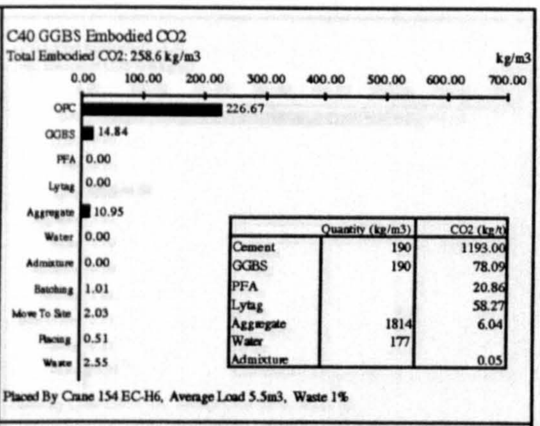
Table 18: C40 GGBS



C40 GGBS Embodied Energy
Total Embodied Energy: 1.62 GJ/m3

	Quantity (kg/m3)	Energy (GJ/t)
Cement	190	5.80
GGBS	190	1.45
PFA		0.34
Lytag		0.92
Aggregate	1814	0.09
Water	177	
Admixture		0.85

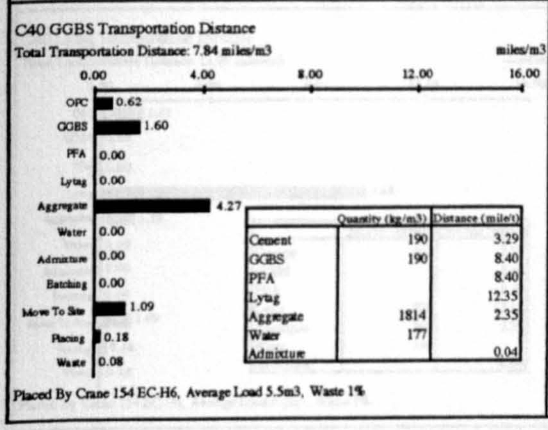
Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%



C40 GGBS Embodied CO2
Total Embodied CO2: 258.6 kg/m3

	Quantity (kg/m3)	CO2 (kg/t)
Cement	190	1193.00
GGBS	190	78.09
PFA		20.86
Lytag		58.27
Aggregate	1814	6.04
Water	177	
Admixture		0.05

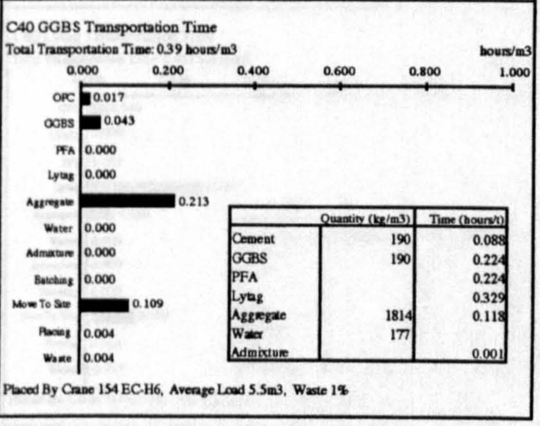
Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%



C40 GGBS Transportation Distance
Total Transportation Distance: 7.84 miles/m3

	Quantity (kg/m3)	Distance (mile/t)
Cement	190	3.29
GGBS	190	8.40
PFA		8.40
Lytag		12.35
Aggregate	1814	2.35
Water	177	
Admixture		0.04

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%

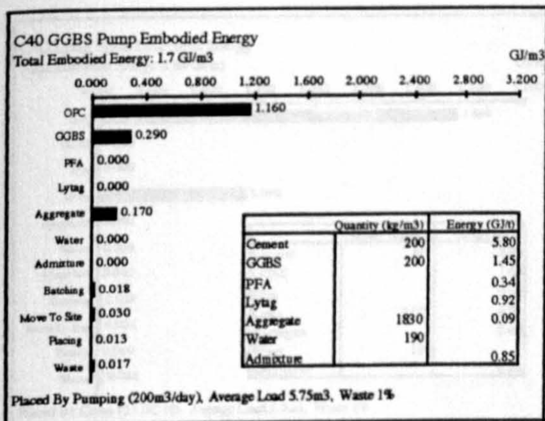


C40 GGBS Transportation Time
Total Transportation Time: 0.39 hours/m3

	Quantity (kg/m3)	Time (hours/t)
Cement	190	0.088
GGBS	190	0.224
PFA		0.224
Lytag		0.329
Aggregate	1814	0.118
Water	177	
Admixture		0.001

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%

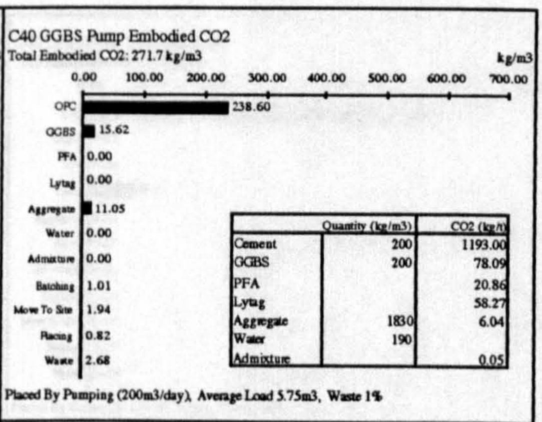
Table 19: C40 GGBS Pump



C40 GGBS Pump Embodied Energy
Total Embodied Energy: 1.7 GJ/m3

	Quantity (kg/m3)	Energy (GJ/t)
Cement	200	5.80
GGBS	200	1.45
PFA		0.34
Lytag		0.92
Aggregate	1830	0.09
Water	190	
Admixture		0.85

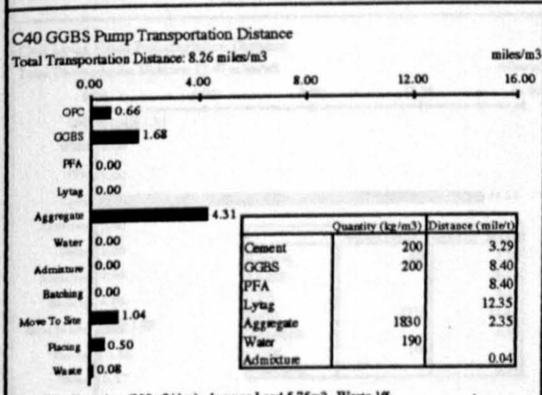
Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%



C40 GGBS Pump Embodied CO2
Total Embodied CO2: 271.7 kg/m3

	Quantity (kg/m3)	CO2 (kg/t)
Cement	200	1193.00
GGBS	200	78.09
PFA		20.86
Lytag		58.27
Aggregate	1830	6.04
Water	190	
Admixture		0.05

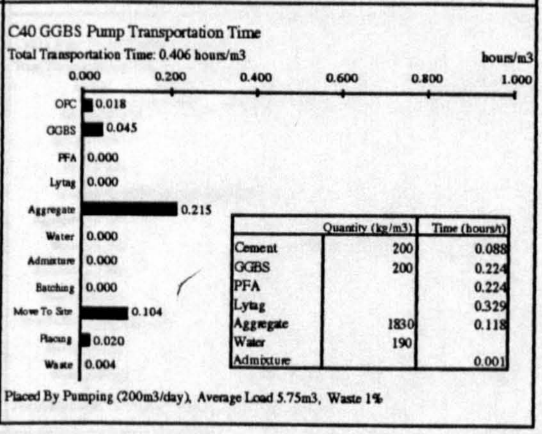
Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%



C40 GGBS Pump Transportation Distance
Total Transportation Distance: 8.26 miles/m3

	Quantity (kg/m3)	Distance (mile/t)
Cement	200	3.29
GGBS	200	8.40
PFA		8.40
Lytag		12.35
Aggregate	1830	2.35
Water	190	
Admixture		0.04

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%



C40 GGBS Pump Transportation Time
Total Transportation Time: 0.406 hours/m3

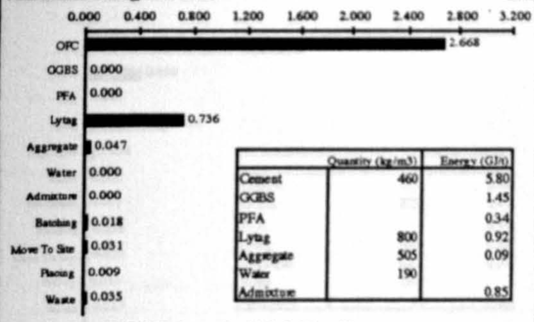
	Quantity (kg/m3)	Time (hours/t)
Cement	200	0.088
GGBS	200	0.224
PFA		0.224
Lytag		0.329
Aggregate	1830	0.118
Water	190	
Admixture		0.001

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%

Table 20: C40 Lytag

C40 Lytag Embodied Energy

Total Embodied Energy: 3.54 GJ/m3

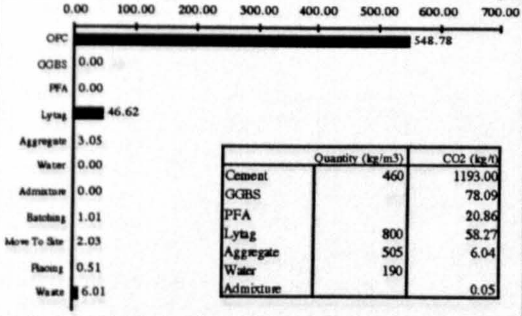


	Quantity (kg/m3)	Energy (GJ/t)
Cement	460	5.80
GGBS		1.45
PFA		0.34
Lytag	800	0.92
Aggregate	505	0.09
Water	190	
Admixture		0.85

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%

C40 Lytag Embodied CO2

Total Embodied CO2: 608 kg/m3

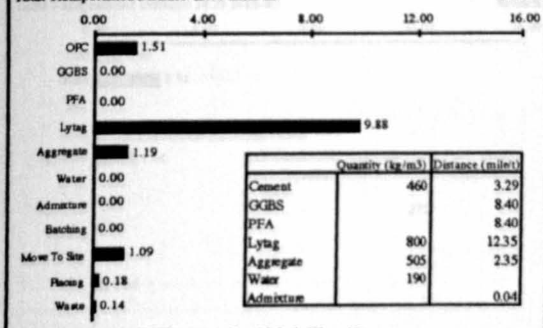


	Quantity (kg/m3)	CO2 (kg/t)
Cement	460	1193.00
GGBS		78.09
PFA		20.86
Lytag	800	58.27
Aggregate	505	6.04
Water	190	
Admixture		0.05

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%

C40 Lytag Transportation Distance

Total Transportation Distance: 13.99 miles/m3

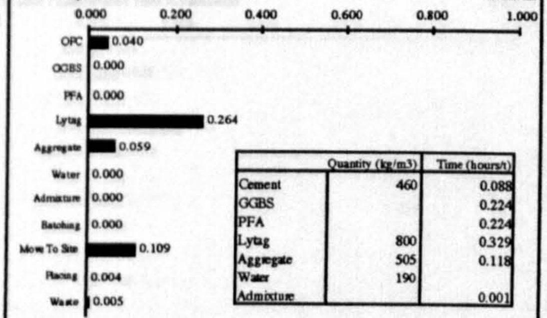


	Quantity (kg/m3)	Distance (mile/t)
Cement	460	3.29
GGBS		8.40
PFA		8.40
Lytag	800	12.35
Aggregate	505	2.35
Water	190	
Admixture		0.04

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%

C40 Lytag Transportation Time

Total Transportation Time: 0.481 hours/m3



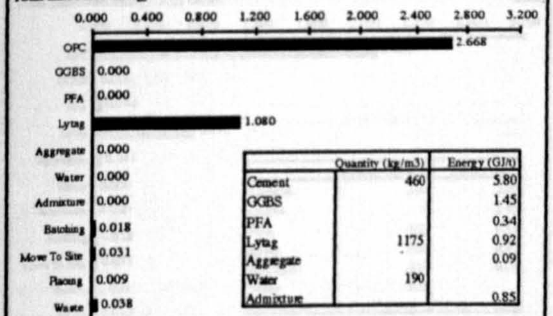
	Quantity (kg/m3)	Time (hours/t)
Cement	460	0.088
GGBS		0.224
PFA		0.224
Lytag	800	0.329
Aggregate	505	0.118
Water	190	
Admixture		0.001

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%

Table 21: C40 Lytag Fines

C40 Lytag Fines Embodied Energy

Total Embodied Energy: 3.84 GJ/m3

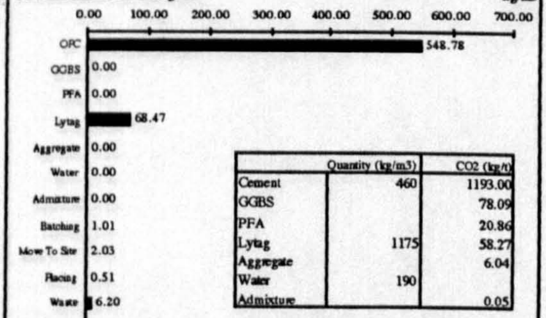


	Quantity (kg/m3)	Energy (GJ/t)
Cement	460	5.80
GGBS		1.45
PFA		0.34
Lytag	1175	0.92
Aggregate		0.09
Water	190	
Admixture		0.85

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%

C40 Lytag Fines Embodied CO2

Total Embodied CO2: 627 kg/m3

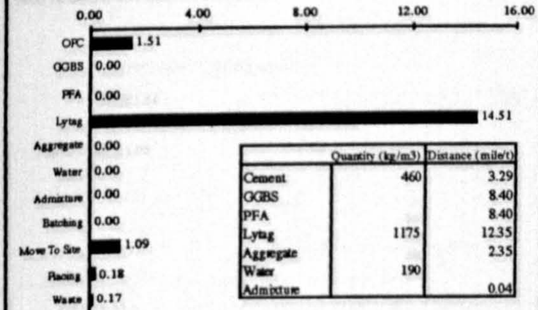


	Quantity (kg/m3)	CO2 (kg/t)
Cement	460	1193.00
GGBS		78.09
PFA		20.86
Lytag	1175	58.27
Aggregate		6.04
Water	190	
Admixture		0.05

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%

C40 Lytag Fines Transportation Distance

Total Transportation Distance: 17.47 miles/m3

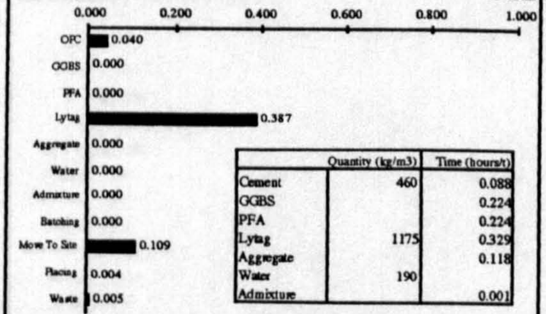


	Quantity (kg/m3)	Distance (mile/t)
Cement	460	3.29
GGBS		8.40
PFA		8.40
Lytag	1175	12.35
Aggregate		2.35
Water	190	
Admixture		0.04

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%

C40 Lytag Fines Transportation Time

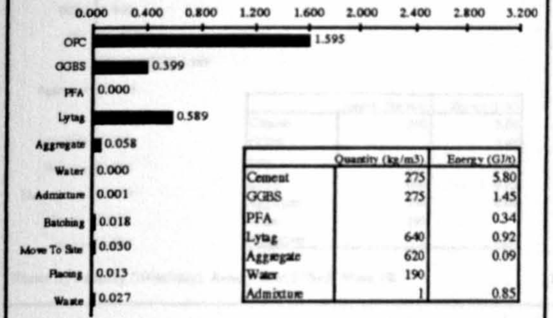
Total Transportation Time: 0.546 hours/m3



	Quantity (kg/m3)	Time (hours/t)
Cement	460	0.088
GGBS		0.224
PFA		0.224
Lytag	1175	0.329
Aggregate		0.118
Water	190	
Admixture		0.001

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%

Table 22: C40 Lytag GGBS Pump

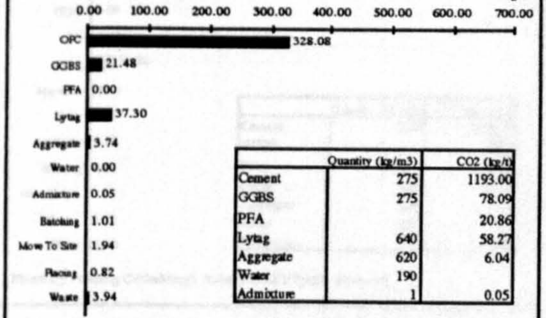


C40 Lytag GGBS Pump Embodied Energy

Total Embodied Energy: 2.73 GJ/m3

	Quantity (kg/m3)	Energy (GJ/t)
Cement	275	5.80
GGBS	275	1.45
PFA		0.34
Lytag	640	0.92
Aggregate	620	0.09
Water	190	
Admixture	1	0.85

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%

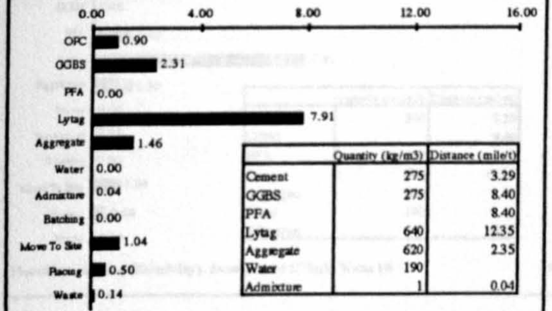


C40 Lytag GGBS Pump Embodied CO2

Total Embodied CO2: 398.3 kg/m3

	Quantity (kg/m3)	CO2 (kg/t)
Cement	275	1193.00
GGBS	275	78.09
PFA		20.86
Lytag	640	58.27
Aggregate	620	6.04
Water	190	
Admixture	1	0.05

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%

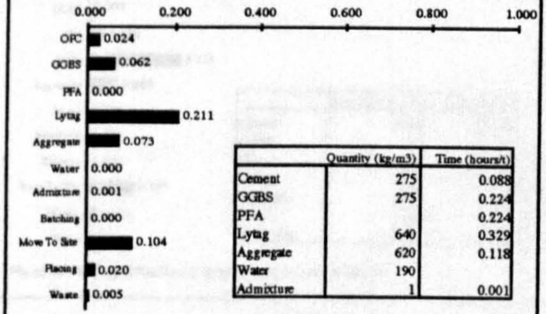


C40 Lytag GGBS Pump Transportation Distance

Total Transportation Distance: 14.29 miles/m3

	Quantity (kg/m3)	Distance (mile/t)
Cement	275	3.29
GGBS	275	8.40
PFA		8.40
Lytag	640	12.35
Aggregate	620	2.35
Water	190	
Admixture	1	0.04

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%



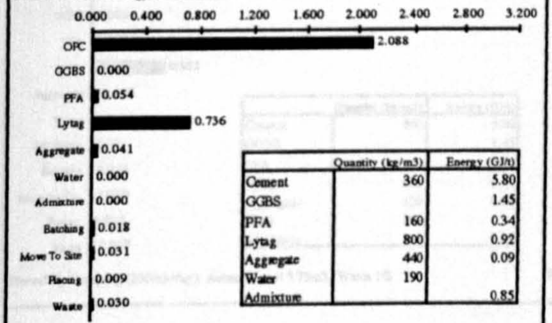
C40 Lytag GGBS Pump Transportation Time

Total Transportation Time: 0.5 hours/m3

	Quantity (kg/m3)	Time (hours/t)
Cement	275	0.088
GGBS	275	0.224
PFA		0.224
Lytag	640	0.329
Aggregate	620	0.118
Water	190	
Admixture	1	0.001

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%

Table 23: C40 Lytag PFA

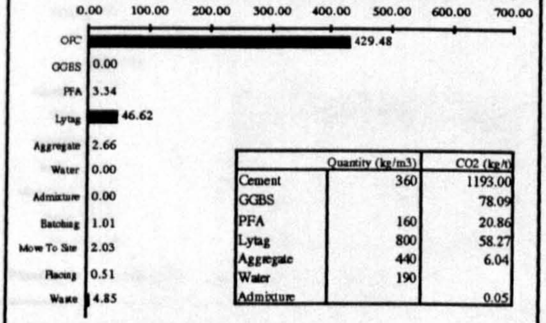


C40 Lytag PFA Embodied Energy

Total Embodied Energy: 3.01 GJ/m3

	Quantity (kg/m3)	Energy (GJ/t)
Cement	360	5.80
GGBS		1.45
PFA	160	0.34
Lytag	800	0.92
Aggregate	440	0.09
Water	190	
Admixture		0.85

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%

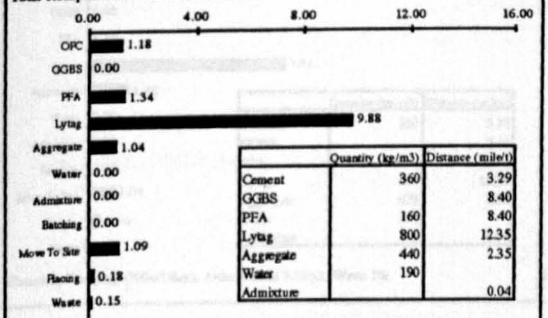


C40 Lytag PFA Embodied CO2

Total Embodied CO2: 490.5 kg/m3

	Quantity (kg/m3)	CO2 (kg/t)
Cement	360	1193.00
GGBS		78.09
PFA	160	20.86
Lytag	800	58.27
Aggregate	440	6.04
Water	190	
Admixture		0.05

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%

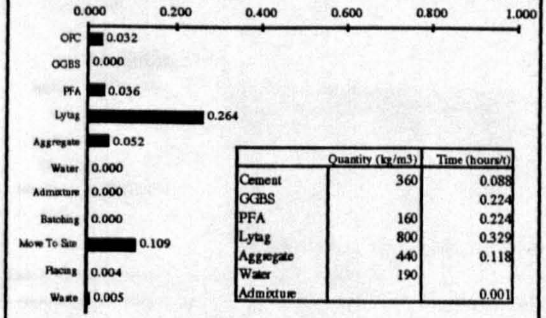


C40 Lytag PFA Transportation Distance

Total Transportation Distance: 14.86 miles/m3

	Quantity (kg/m3)	Distance (mile/t)
Cement	360	3.29
GGBS		8.40
PFA	160	8.40
Lytag	800	12.35
Aggregate	440	2.35
Water	190	
Admixture		0.04

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%



C40 Lytag PFA Transportation Time

Total Transportation Time: 0.501 hours/m3

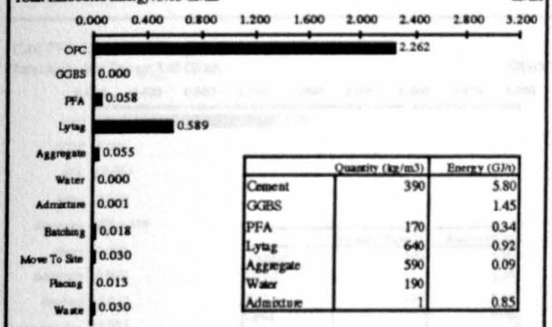
	Quantity (kg/m3)	Time (hours/t)
Cement	360	0.088
GGBS		0.224
PFA	160	0.224
Lytag	800	0.329
Aggregate	440	0.118
Water	190	
Admixture		0.001

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%

Table 24: C40 Lytag PFA Pump

C40 Lytag PFA Pump Embodied Energy

Total Embodied Energy: 3.05 GJ/m3

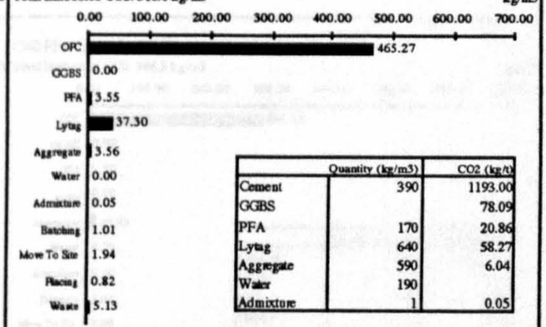


	Quantity (kg/m3)	Energy (GJ/t)
Cement	390	5.80
GGBS		1.45
PFA	170	0.34
Lytag	640	0.92
Aggregate	590	0.09
Water	190	
Admixture	1	0.85

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%

C40 Lytag PFA Pump Embodied CO2

Total Embodied CO2: 518.6 kg/m3

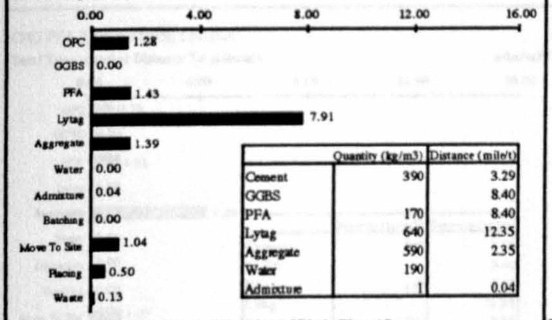


	Quantity (kg/m3)	CO2 (kg/t)
Cement	390	1193.00
GGBS		78.09
PFA	170	20.86
Lytag	640	58.27
Aggregate	590	6.04
Water	190	
Admixture	1	0.05

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%

C40 Lytag PFA Pump Transportation Distance

Total Transportation Distance: 13.71 miles/m3

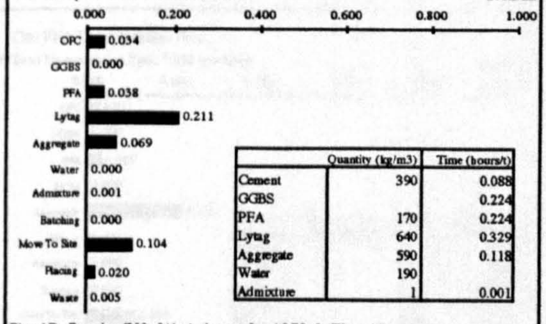


	Quantity (kg/m3)	Distance (mile/t)
Cement	390	3.29
GGBS		8.40
PFA	170	8.40
Lytag	640	12.35
Aggregate	590	2.35
Water	190	
Admixture	1	0.04

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%

C40 Lytag PFA Pump Transportation Time

Total Transportation Time: 0.482 hours/m3



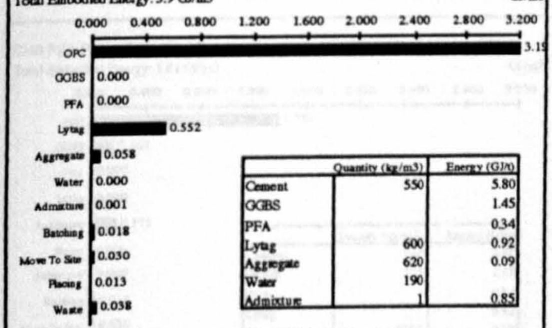
	Quantity (kg/m3)	Time (hours/t)
Cement	390	0.088
GGBS		0.224
PFA	170	0.224
Lytag	640	0.329
Aggregate	590	0.118
Water	190	
Admixture	1	0.001

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%

Table 25: C40 Lytag Pump

C40 Lytag Pump Embodied Energy

Total Embodied Energy: 3.9 GJ/m3

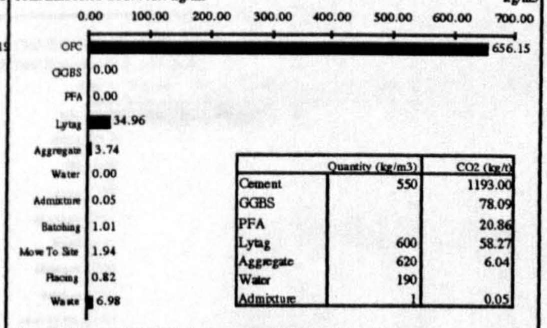


	Quantity (kg/m3)	Energy (GJ/t)
Cement	550	5.80
GGBS		1.45
PFA		0.34
Lytag	600	0.92
Aggregate	620	0.09
Water	190	
Admixture	1	0.85

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%

C40 Lytag Pump Embodied CO2

Total Embodied CO2: 705.7 kg/m3

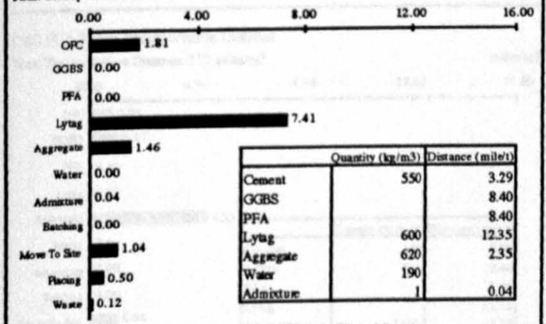


	Quantity (kg/m3)	CO2 (kg/t)
Cement	550	1193.00
GGBS		78.09
PFA		20.86
Lytag	600	58.27
Aggregate	620	6.04
Water	190	
Admixture	1	0.05

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%

C40 Lytag Pump Transportation Distance

Total Transportation Distance: 12.38 miles/m3

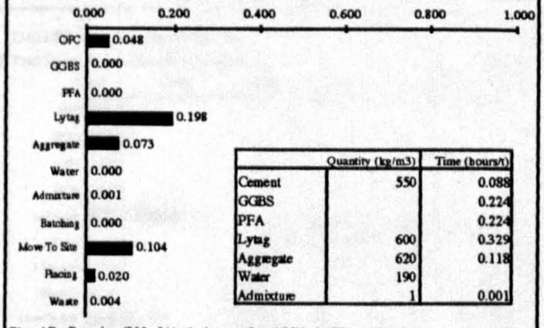


	Quantity (kg/m3)	Distance (mile/t)
Cement	550	3.29
GGBS		8.40
PFA		8.40
Lytag	600	12.35
Aggregate	620	2.35
Water	190	
Admixture	1	0.04

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%

C40 Lytag Pump Transportation Time

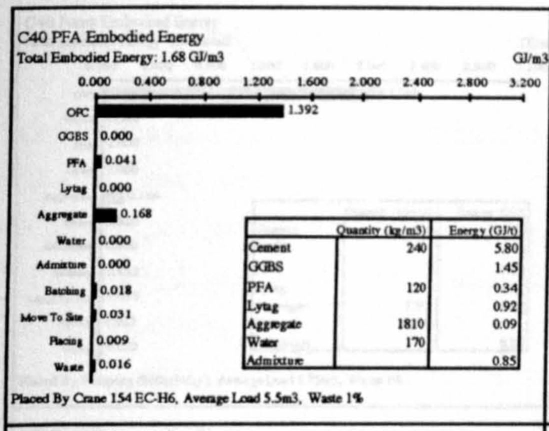
Total Transportation Time: 0.448 hours/m3



	Quantity (kg/m3)	Time (hours/t)
Cement	550	0.088
GGBS		0.224
PFA		0.224
Lytag	600	0.329
Aggregate	620	0.118
Water	190	
Admixture	1	0.001

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%

Table 26: C40 PFA

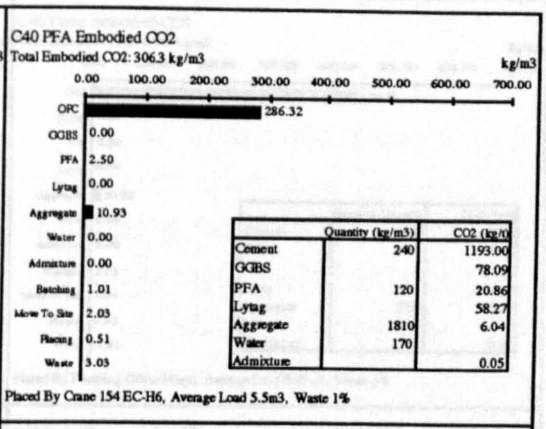


C40 PFA Embodied Energy

Total Embodied Energy: 1.68 GJ/m3

	Quantity (kg/m3)	Energy (GJ/t)
Cement	240	5.80
GGBS		1.45
PFA	120	0.34
Lytag		0.92
Aggregate	1810	0.09
Water	170	
Admixture		0.85

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%

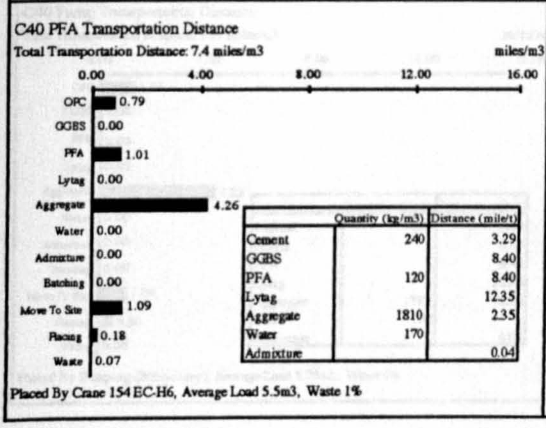


C40 PFA Embodied CO2

Total Embodied CO2: 306.3 kg/m3

	Quantity (kg/m3)	CO2 (kg/t)
Cement	240	1193.00
GGBS		78.09
PFA	120	20.86
Lytag		58.27
Aggregate	1810	6.04
Water	170	
Admixture		0.05

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%

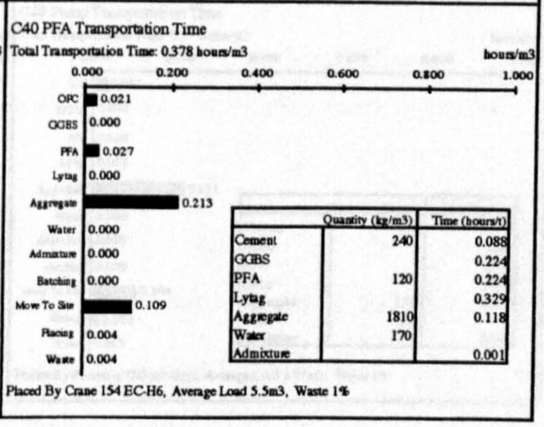


C40 PFA Transportation Distance

Total Transportation Distance: 7.4 miles/m3

	Quantity (kg/m3)	Distance (mile/t)
Cement	240	3.29
GGBS		8.40
PFA	120	8.40
Lytag		12.35
Aggregate	1810	2.35
Water	170	
Admixture		0.04

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%



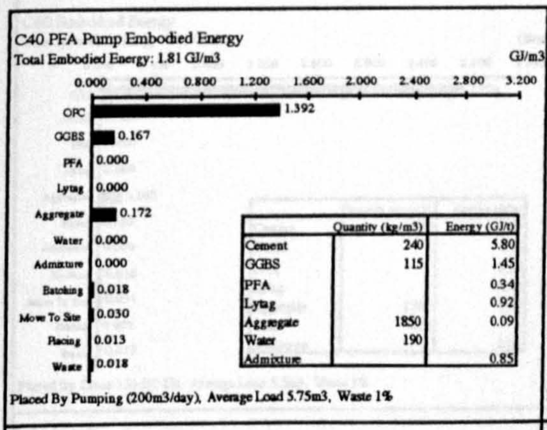
C40 PFA Transportation Time

Total Transportation Time: 0.378 hours/m3

	Quantity (kg/m3)	Time (hours/t)
Cement	240	0.088
GGBS		0.224
PFA	120	0.224
Lytag		0.329
Aggregate	1810	0.118
Water	170	
Admixture		0.001

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%

Table 27: C40 PFA Pump

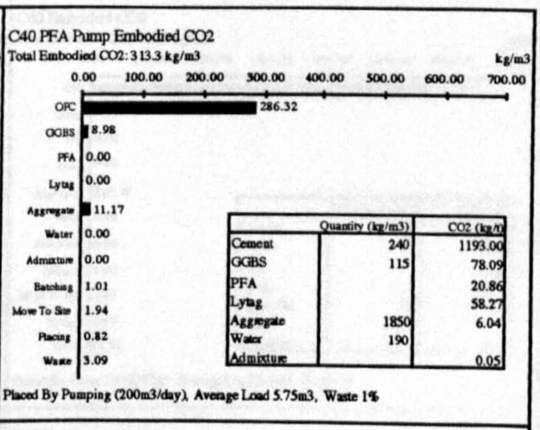


C40 PFA Pump Embodied Energy

Total Embodied Energy: 1.81 GJ/m3

	Quantity (kg/m3)	Energy (GJ/t)
Cement	240	5.80
GGBS	115	1.45
PFA		0.34
Lytag		0.92
Aggregate	1850	0.09
Water	190	
Admixture		0.85

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%

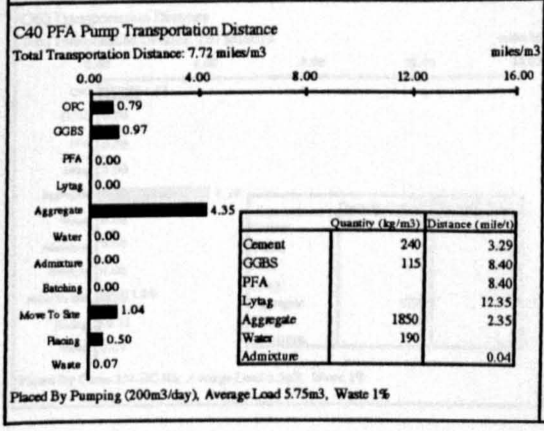


C40 PFA Pump Embodied CO2

Total Embodied CO2: 313.3 kg/m3

	Quantity (kg/m3)	CO2 (kg/t)
Cement	240	1193.00
GGBS	115	78.09
PFA		20.86
Lytag		58.27
Aggregate	1850	6.04
Water	190	
Admixture		0.05

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%

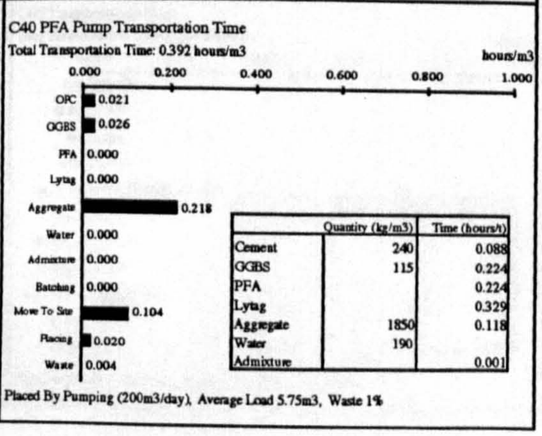


C40 PFA Pump Transportation Distance

Total Transportation Distance: 7.72 miles/m3

	Quantity (kg/m3)	Distance (mile/t)
Cement	240	3.29
GGBS	115	8.40
PFA		8.40
Lytag		12.35
Aggregate	1850	2.35
Water	190	
Admixture		0.04

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%



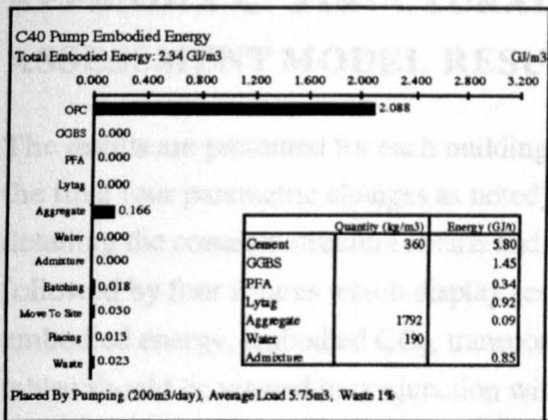
C40 PFA Pump Transportation Time

Total Transportation Time: 0.392 hours/m3

	Quantity (kg/m3)	Time (hours/t)
Cement	240	0.088
GGBS	115	0.224
PFA		0.224
Lytag		0.329
Aggregate	1850	0.118
Water	190	
Admixture		0.001

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%

Table 28: C40 Pump

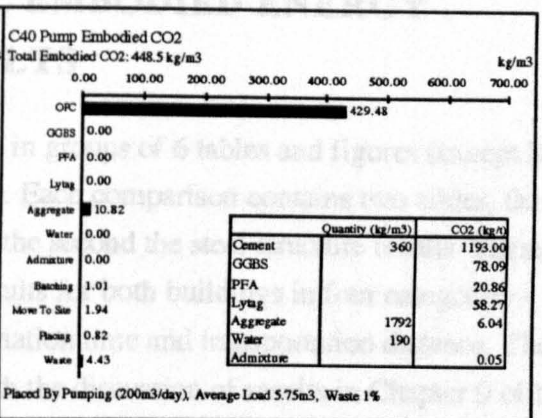


C40 Pump Embodied Energy

Total Embodied Energy: 2.34 GJ/m3

	Quantity (kg/m3)	Energy (GJ/t)
Cement	360	5.80
GGBS		1.45
PFA		0.34
Lytag		0.92
Aggregate	1792	0.09
Water	190	
Admixture		0.85

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%

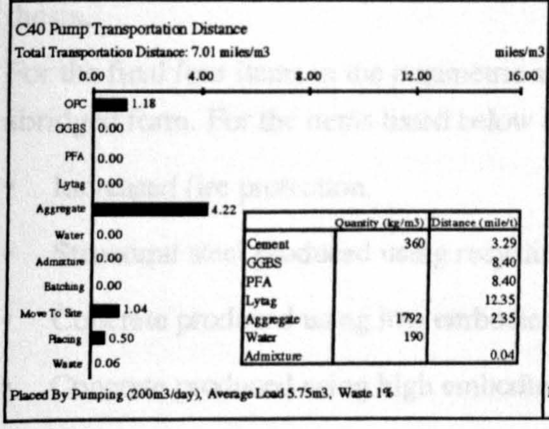


C40 Pump Embodied CO2

Total Embodied CO2: 448.5 kg/m3

	Quantity (kg/m3)	CO2 (kg/t)
Cement	360	1193.00
GGBS		78.09
PFA		20.86
Lytag		58.27
Aggregate	1792	6.04
Water	190	
Admixture		0.05

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%

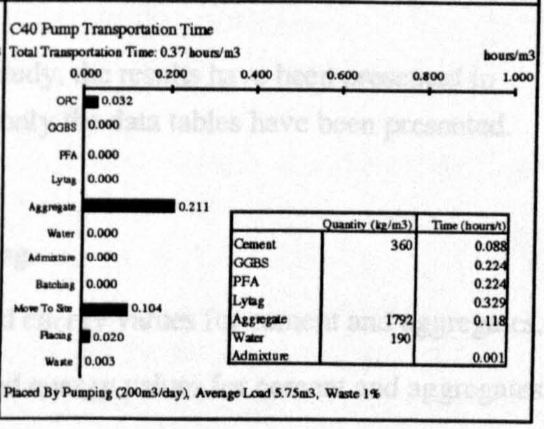


C40 Pump Transportation Distance

Total Transportation Distance: 7.01 miles/m3

	Quantity (kg/m3)	Distance (mile/t)
Cement	360	3.29
GGBS		8.40
PFA		8.40
Lytag		12.35
Aggregate	1792	2.35
Water	190	
Admixture		0.04

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%



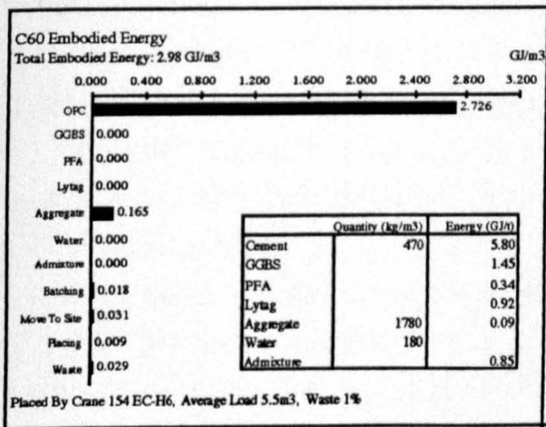
C40 Pump Transportation Time

Total Transportation Time: 0.37 hours/m3

	Quantity (kg/m3)	Time (hours/t)
Cement	360	0.088
GGBS		0.224
PFA		0.224
Lytag		0.329
Aggregate	1792	0.118
Water	190	
Admixture		0.001

Placed By Pumping (200m3/day), Average Load 5.75m3, Waste 1%

Table 29: C60

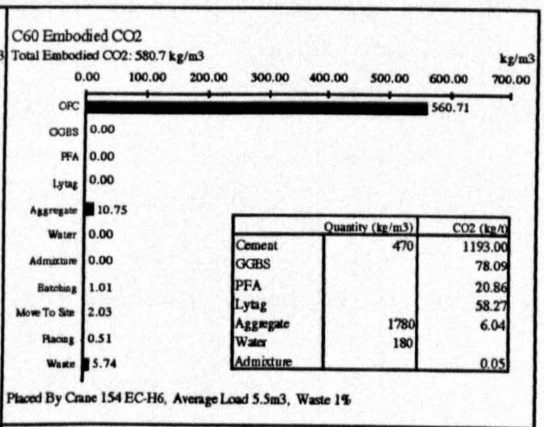


C60 Embodied Energy

Total Embodied Energy: 2.98 GJ/m3

	Quantity (kg/m3)	Energy (GJ/t)
Cement	470	5.80
GGBS		1.45
PFA		0.34
Lytag		0.92
Aggregate	1780	0.09
Water	180	
Admixture		0.85

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%

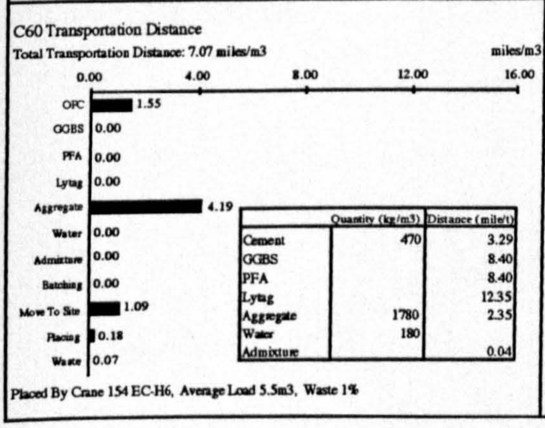


C60 Embodied CO2

Total Embodied CO2: 580.7 kg/m3

	Quantity (kg/m3)	CO2 (kg/t)
Cement	470	1193.00
GGBS		78.09
PFA		20.86
Lytag		58.27
Aggregate	1780	6.04
Water	180	
Admixture		0.05

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%

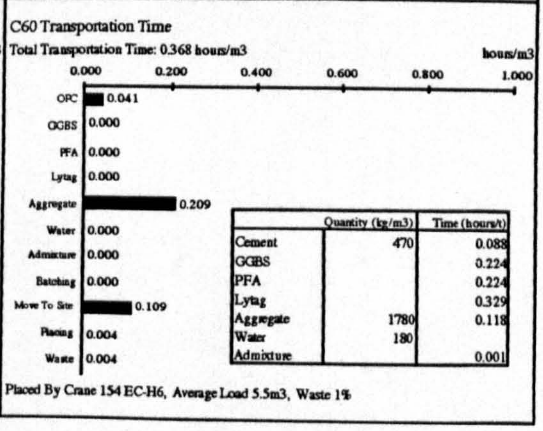


C60 Transportation Distance

Total Transportation Distance: 7.07 miles/m3

	Quantity (kg/m3)	Distance (mile/t)
Cement	470	3.29
GGBS		8.40
PFA		8.40
Lytag		12.35
Aggregate	1780	2.35
Water	180	
Admixture		0.04

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%



C60 Transportation Time

Total Transportation Time: 0.368 hours/m3

	Quantity (kg/m3)	Time (hours/t)
Cement	470	0.088
GGBS		0.224
PFA		0.224
Lytag		0.329
Aggregate	1780	0.118
Water	180	
Admixture		0.001

Placed By Crane 154 EC-H6, Average Load 5.5m3, Waste 1%

APPENDIX C: STRUCTURAL EMBODIED ENERGY ASSESSMENT MODEL RESULTS

The results are presented for each building in groups of 6 tables and figures (except for the final four parametric changes as noted). Each comparison contains two tables, the first detailing the concrete structure results and the second the steel structure results. These are followed by four figures which display results for both buildings in four categories - embodied energy, embodied CO_2, transportation time and transportation distance. These tables should be viewed in conjunction with the discussion of results in Chapter 9 of the thesis.

For the final four items in the parametric study, the results have been presented in abridged form. For the items listed below only the data tables have been presented.

- Increased fire protection.
- Structural steel produced using recycling.
- Concrete produced using low embodied energy values for cement and aggregates.
- Concrete produced using high embodied energy values for cement and aggregates.

LIST OF TABLES

LIST OF FIGURES

Table 1: M62 Concrete 3 Floor Structure using Standard Data

Summary		M62 Concrete 3 Floor	Notes	STANDARD DATA SET			
Structure Gross Area	m2	4355					
Materials Weight	t	4672	Total	Substructure	Superstructure	Demolition	Total
Embodied Energy	GJ/m2	2.32	GJ	2304	7298	502	10104
Embodied CO2	kg/m2	274.53	kg	365866	796746	32963	1195575
Transportation Distance	miles/m2	6.30	miles	9187	13153	5083	27424
Transportation Time	hr/m2	0.29	hr	489	567	207	1263
Transportation Speed	MPH	21.71					

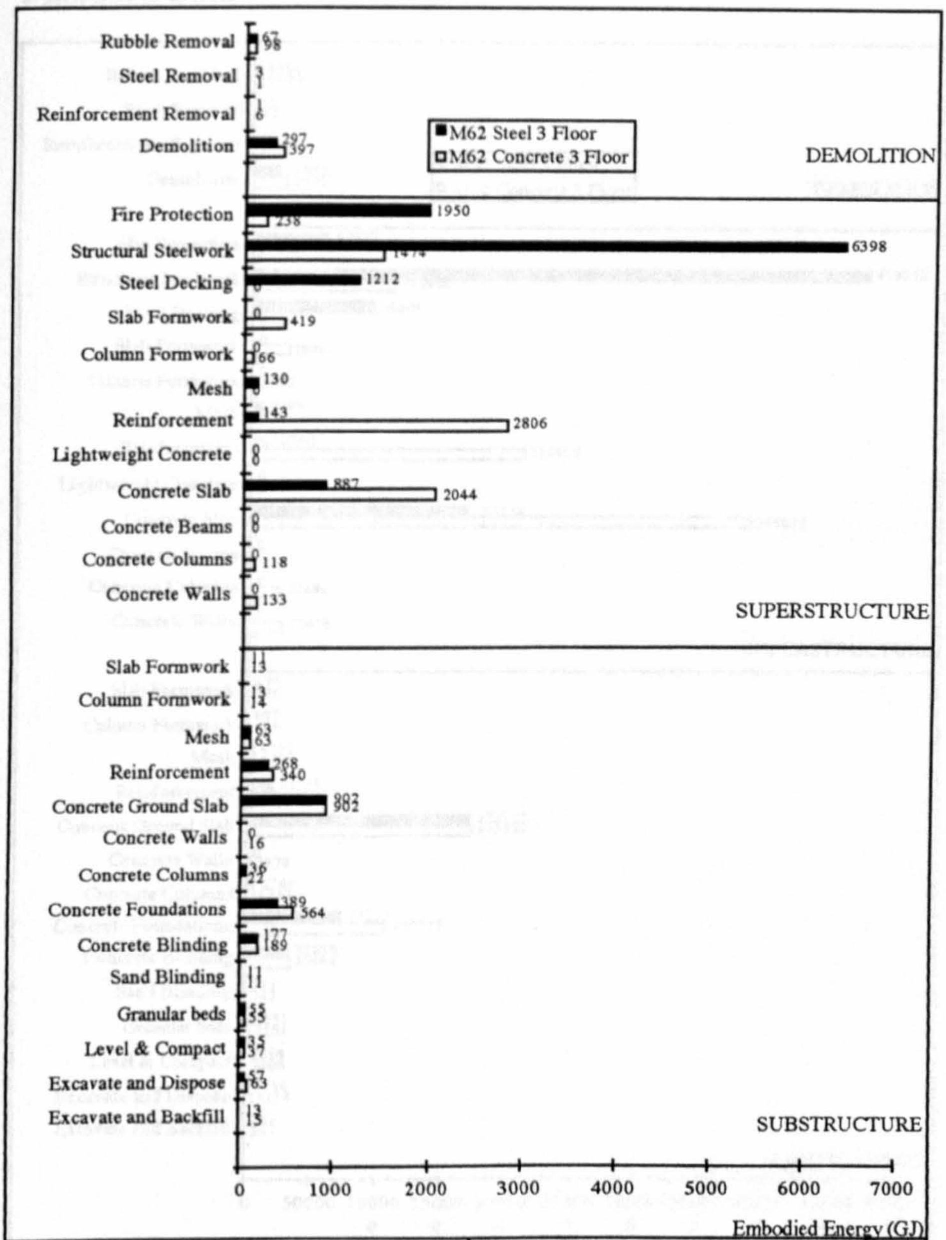
Element	Unit	No.	Rate Selected	Unit Rates				Total Values			
				Energy	CO2	Transportation		Energy	CO2	Transportation	
				GJ/unit	kg/unit	mile/unit	hr/unit	GJ	kg	miles	hours
Substructure											
Excavate and Backfill	m3	255.0	Excavation and Backfill (SEEAM)	0.058	1.16	0.02	0.001	15	297	4	0
Excavate and Dispose	m3	839.0	Excavation and Disposal (SEEAM)	0.075	4.93	1.80	0.120	63	4138	1514	101
Level & Compact	m2	2013.0	Level & Compact (SEEAM)	0.018	1.20	0.02	0.002	37	2408	40	4
Granular beds	t	588.0	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	55	3551	1384	69
Sand Blinding	t	117.8	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	11	711	277	14
Concrete Blinding	m3	111.7	C20 (SEEAM)	1.695	313.64	6.89	0.377	189	35041	770	42
Concrete Foundations	m3	254.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	564	107772	1706	91
Concrete Columns	m3	10.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	22	4243	67	4
Concrete Walls	m3	7.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	16	2970	47	3
Concrete Ground Slab	m3	386.0	C40 Pump (SEEAM)	2.338	448.50	7.01	0.370	902	173122	2705	143
Reinforcement	t	19.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	340	25527	431	12
Mesh	t	3.5	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	63	4737	93	3
Column Formwork	m2	275.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	14	764	71	2
Slab Formwork	m2	301.0	Formwork (Flat Slab)(SEEAM/OB)	0.043	1.95	0.26	0.007	13	586	79	2
Superstructure											
Concrete Walls	m3	60.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	133	25458	403	22
Concrete Columns	m3	53.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	118	22488	356	19
Concrete Slab	m3	968.0	C30 Pump (SEEAM)	2.112	400.84	7.08	0.377	2044	388015	6858	365
Reinforcement	t	157.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	2806	210930	3562	98
Column Formwork	m2	1262.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	66	3505	324	9
Slab Formwork	m2	3227.0	Formwork (Shaped Soffit)(SEEAM/OB)	0.130	8.94	0.28	0.008	419	28861	902	27
Steelwork	t	53.0	Structural Steel (Short) (SEEAM/OB)	27.816	2083.12	10.10	0.401	1474	110406	535	21
Fire Protection	m2	431.0	Fire Protection (18mm Vicuclad) (SEEA	0.553	16.43	0.49	0.013	238	7083	213	5
Demolition											
Demolition	m2	4355	Demolition (Concrete)(SEEAM)	0.091	5.98	0.01	0.001	397	26057	65	6
ReBar Removal	t	179	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	6	424	308	12
Steel Removal	t	53	Steel Transport (Demolished)(SEEAM)	0.012	0.79	0.55	0.022	1	42	29	1
Rubble Removal	t	2724	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	98	6439	4681	187
Base Data											
Cement	t			5.800	1193.00	3.29	0.088				
GGBS	t			1.450	78.09	8.40	0.224				
PFA	t			0.339	20.86	8.40	0.224				
Lytag	t			0.920	58.27	12.35	0.329				
Aggregates	t			0.093	6.04	2.35	0.118				

Table 2: M62 Steel 3 Floor Structure using Standard Data

Summary		M62 Steel 3 Floor	Notes	STANDARD DATA SET			
Structure Gross Area	m2	4355					
Materials Weight	t	2941	Total	Substructure	Superstructure	Demolition	Total
Embodied Energy	GJ/m2	3.01	GJ	2029	10720	368	13116
Embodied CO2	kg/m2	268.30	kg	323583	820700	24151	1168435
Transportation Distance	miles/m2	4.61	miles	8332	8325	3427	20085
Transportation Time	hr/m2	0.21	hr	444	329	140	913
Transportation Speed	MPH	22.01					

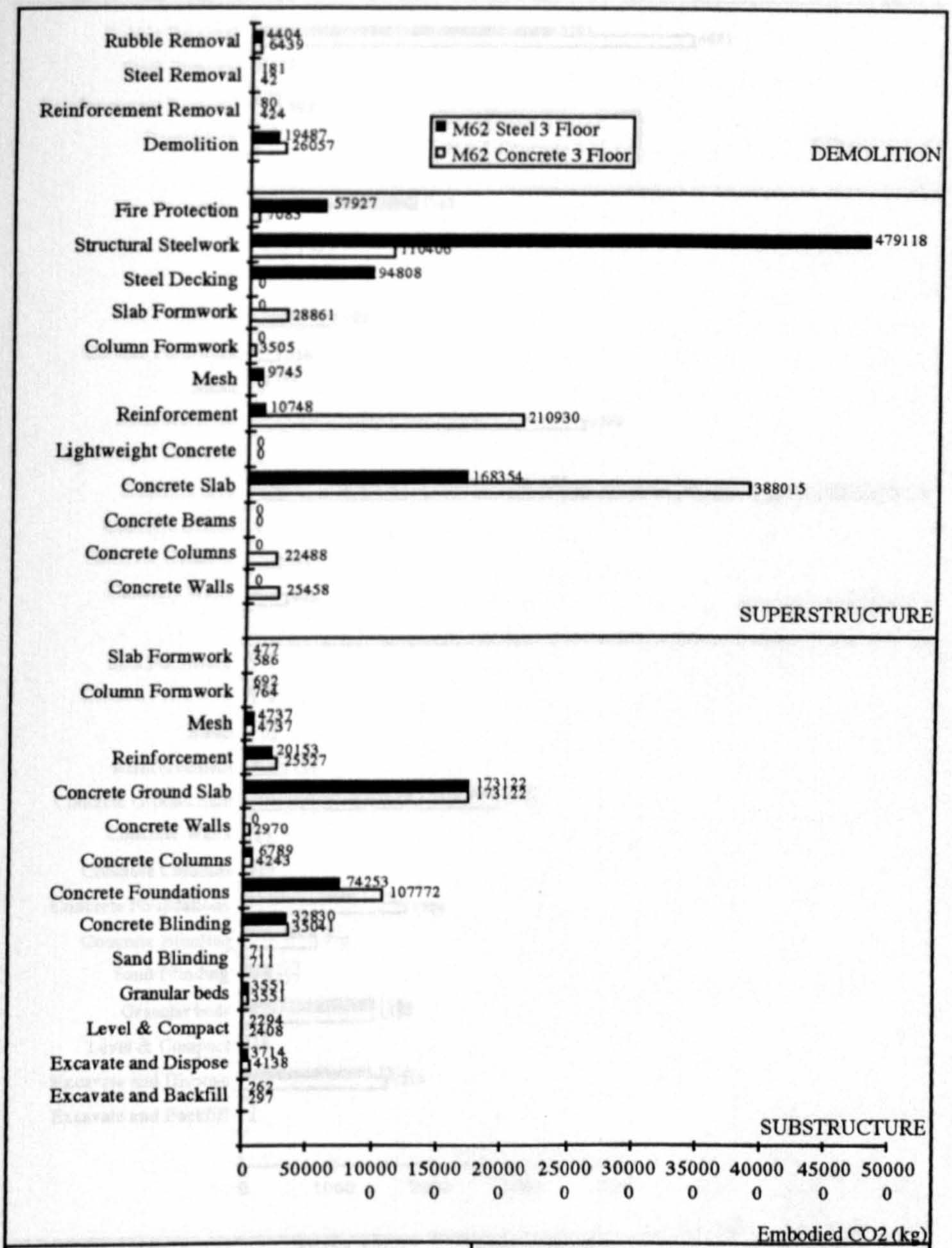
Element	Unit	No.	Rate Selected	Unit Rates				Total Values			
				Energy	CO2	Transportation		Energy	CO2	Transportation	
				GJ/unit	kg/unit	mile/unit	hr/unit	GJ	kg	miles	hours
Substructure											
Excavate and Backfill	m3	225.0	Excavation and Backfill (SEEAM)	0.058	1.16	0.02	0.001	13	262	3	0
Excavate and Dispose	m3	753.0	Excavation and Disposal (SEEAM)	0.075	4.93	1.80	0.120	57	3714	1359	91
Level & Compact	m2	1918.0	Level & Compact (SEEAM)	0.018	1.20	0.02	0.002	35	2294	38	4
Granular beds	t	588.0	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	55	3551	1384	69
Sand Blinding	t	117.8	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	11	711	277	14
Concrete Blinding	m3	104.7	C20 (SEEAM)	1.695	313.64	6.89	0.377	177	32830	721	40
Concrete Foundations	m3	175.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	389	74253	1175	63
Concrete Columns	m3	16.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	36	6789	107	6
Concrete Ground Slab	m3	386.0	C40 Pump (SEEAM)	2.338	448.50	7.01	0.370	902	173122	2705	143
Reinforcement	t	15.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	268	20153	340	9
Mesh	t	3.5	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	63	4737	93	3
Column Formwork	m2	249.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	13	692	64	2
Slab Formwork	m2	245.0	Formwork (Flat Slab)(SEEAM/OB)	0.043	1.95	0.26	0.007	11	477	64	2
Superstructure											
Concrete Slab	m3	420.0	C30 Pump (SEEAM)	2.112	400.84	7.08	0.377	887	168354	2975	158
Reinforcement	t	8.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	143	10748	182	5
Mesh	t	7.2	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	130	9745	191	5
Steel Decking	m2	3230.0	Steel Decking (SEEAM/OB)	0.375	29.35	0.28	0.007	1212	94808	910	23
Steelwork	t	230.0	Structural Steel (Short) (SEEAM/OB)	27.816	2083.12	10.10	0.401	6398	479118	2324	92
Fire Protection	m2	3525.0	Fire Protection (18mm Vicuclad) (SEEA	0.553	16.43	0.49	0.013	1950	57927	1743	45
Demolition											
Demolition	m2	4355	Demolition (Steel)(SEEAM)	0.068	4.47	0.01	0.001	297	19487	43	4
ReBar Removal	t	34	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	1	80	58	2
Steel Removal	t	230	Steel Transport (Demolished)(SEEAM)	0.012	0.79	0.55	0.022	3	181	125	5
Rubble Removal	t	1863	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	67	4404	3201	128
Base Data											
Cement	t			5.800	1193.00	3.29	0.088				
GGBS	t			1.450	78.09	8.40	0.224				
PFA	t			0.339	20.86	8.40	0.224				
Lytag	t			0.920	58.27	12.35	0.329				
Aggregates	t			0.093	6.04	2.35	0.118				

Figure 1: M62 3 Floor Steel and Concrete Embodied Energy Comparison, Standard Data



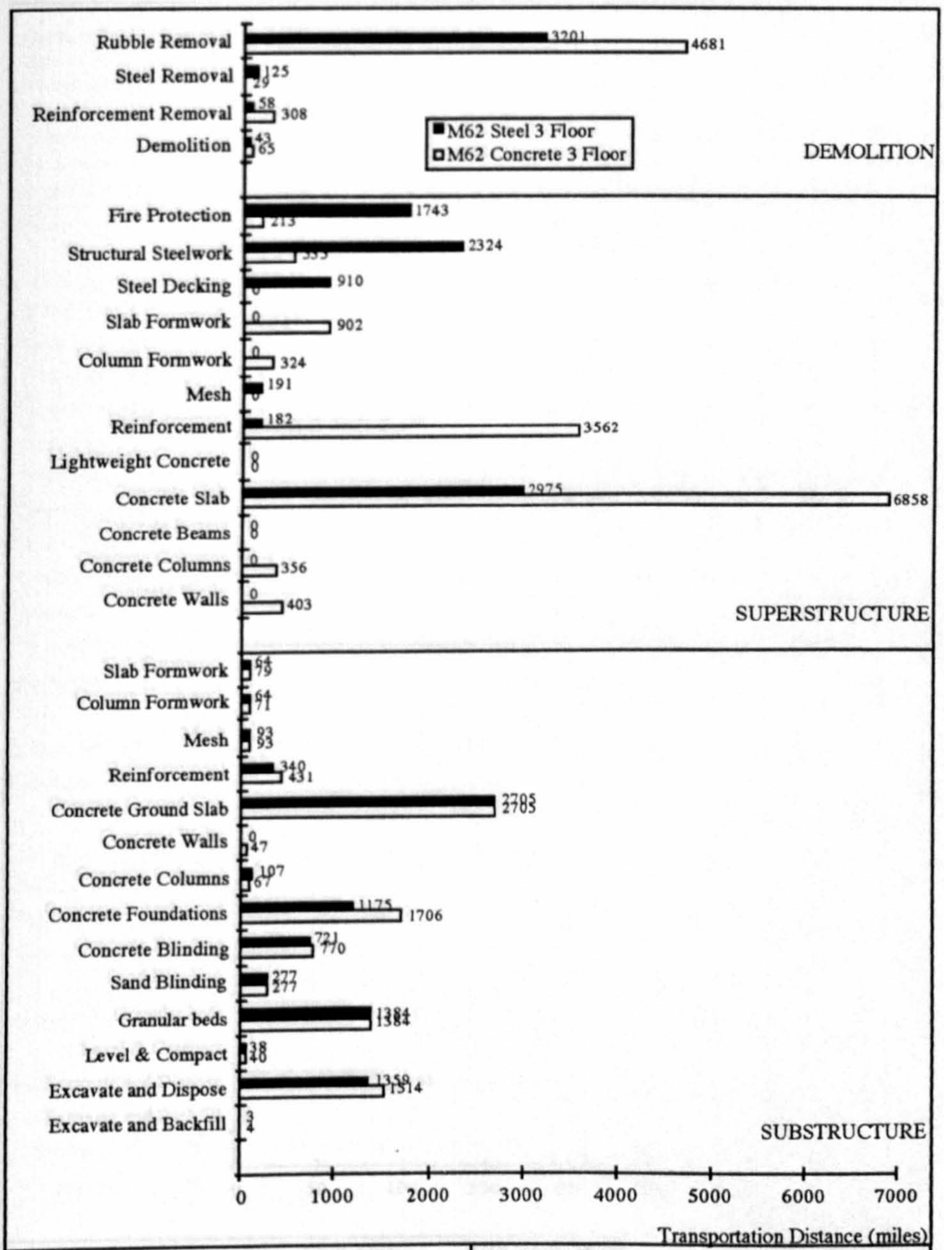
M62 Concrete 3 Floor	10104 GJ		M62 Steel 3 Floor	13116 GJ	
	2.32 GJ/m2			3.01 GJ/m2	
Section Total	GJ		Section Total	GJ	
Substructure	2304	22.8%	Substructure	2029	15.5%
Superstructure	7298	72.2%	Superstructure	10720	81.7%
Demolition	502	5.0%	Demolition	368	2.8%
Item Total	GJ		Item Total	GJ	
Standard Concrete	3988	39.5%	Standard Concrete	2391	18.2%
Lightweight Concrete			Lightweight Concrete		
Reinforcement	3146	31.1%	Reinforcement	411	3.1%
Mesh	63	0.6%	Mesh	193	1.5%
Formwork	512	5.1%	Formwork	24	0.2%
Structural Steelwork	1474	14.6%	Structural Steelwork	6398	48.8%
Steel Decking			Steel Decking	1212	9.2%
Fire Protection	238	2.4%	Fire Protection	1950	14.9%

Figure 2: M62 3 Floor Steel and Concrete Embodied CO_2 Comparison, Standard Data



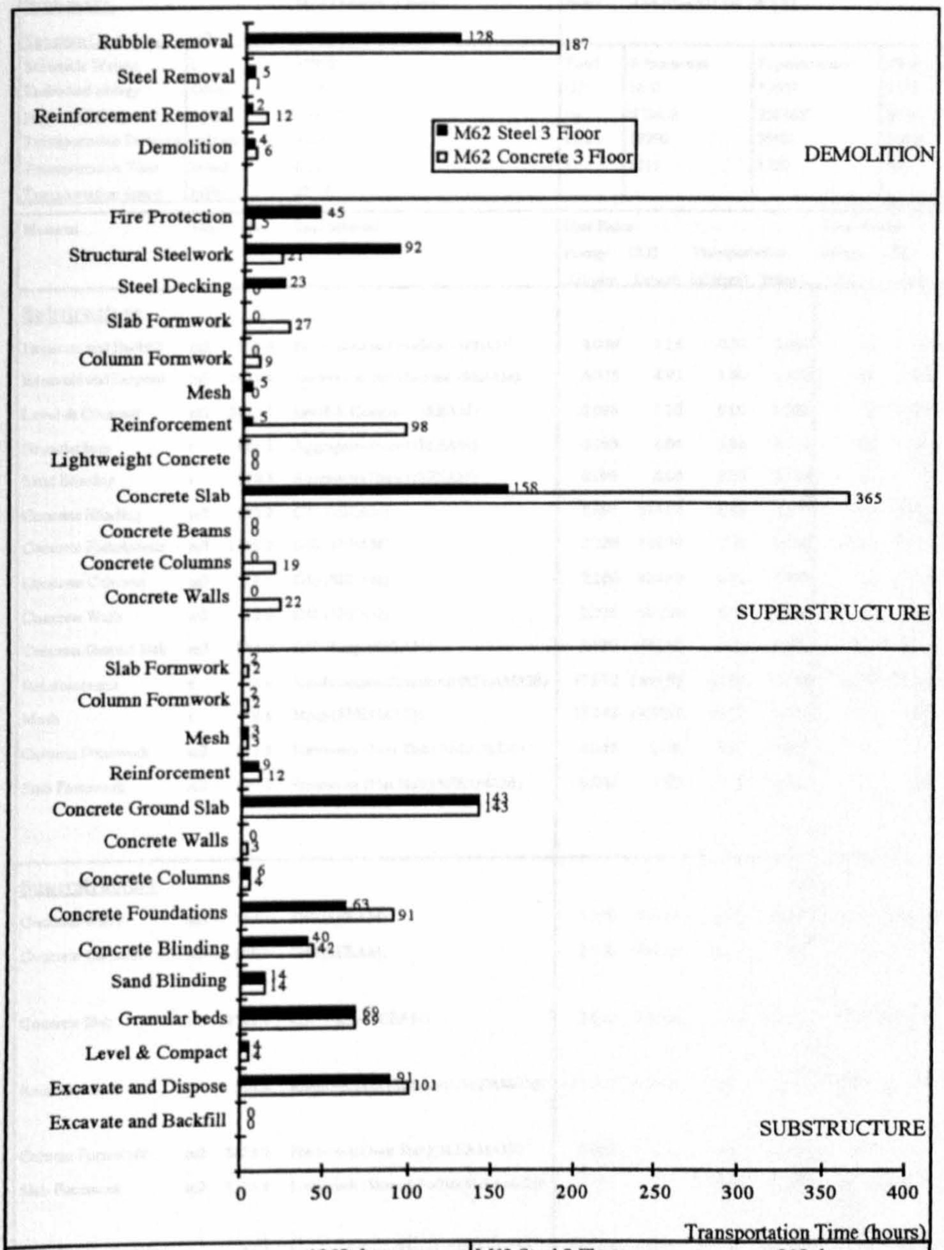
M62 Concrete 3 Floor	1195575 kg		M62 Steel 3 Floor	1168435 kg	
	274.53 kg/m2			268.30 kg/m2	
Section Total	kg		Section Total	kg	
Substructure	365866	30.6%	Substructure	323583	27.7%
Superstructure	796746	66.6%	Superstructure	820700	70.2%
Demolition	32963	2.8%	Demolition	24151	2.1%
Item Total	kg		Item Total	kg	
Standard Concrete	759110	63.5%	Standard Concrete	455347	39.0%
Lightweight Concrete			Lightweight Concrete		
Reinforcement	236457	19.8%	Reinforcement	30901	2.6%
Mesh	4737	0.4%	Mesh	14482	1.2%
Formwork	33716	2.8%	Formwork	1168	0.1%
Structural Steelwork	110406	9.2%	Structural Steelwork	479118	41.0%
Steel Decking			Steel Decking	94808	8.1%
Fire Protection	7083	0.6%	Fire Protection	57927	5.0%

Figure 3: M62 3 Floor Steel and Concrete Transportation Distance Comparison, Standard Data



M62 Concrete 3 Floor	27424 miles 6.30 miles/m2		M62 Steel 3 Floor	20085 miles 4.61 miles/m2	
Section Total	miles		Section Total	miles	
Substructure	9187	33.5%	Substructure	8332	41.5%
Superstructure	13153	48.0%	Superstructure	8325	41.5%
Demolition	5083	18.5%	Demolition	3427	17.1%
Item Total	miles		Item Total	miles	
Standard Concrete	12912	47.1%	Standard Concrete	7685	38.3%
Lightweight Concrete			Lightweight Concrete		
Reinforcement	3993	14.6%	Reinforcement	522	2.6%
Mesh	93	0.3%	Mesh	285	1.4%
Formwork	1375	5.0%	Formwork	128	0.6%
Structural Steelwork	535	2.0%	Structural Steelwork	2324	11.6%
Steel Decking			Steel Decking	910	4.5%
Fire Protection	213	0.8%	Fire Protection	1743	8.7%

Figure 4: M62 3 Floor Steel and Concrete Transportation Time Comparison, Standard Data



M62 Concrete 3 Floor	1263 hours		M62 Steel 3 Floor	913 hours	
	0.29 hours/m2			0.21 hours/m2	
Section Total	hours		Section Total	hours	
Substructure	489	38.7%	Substructure	444	48.7%
Superstructure	567	44.9%	Superstructure	329	36.0%
Demolition	207	16.4%	Demolition	140	15.3%
Item Total	hours		Item Total	hours	
Standard Concrete	688	54.5%	Standard Concrete	410	44.9%
Lightweight Concrete			Lightweight Concrete		
Reinforcement	110	8.7%	Reinforcement	14	1.6%
Mesh	3	0.2%	Mesh	8	0.9%
Formwork	40	3.2%	Formwork	4	0.4%
Structural Steelwork	21	1.7%	Structural Steelwork	92	10.1%
Steel Decking			Steel Decking	23	2.5%
Fire Protection	5	0.4%	Fire Protection	45	4.9%

Table 3: M62 Concrete 7 Floor Structure using Standard Data

Summary		M62 Concrete 7 Floor	Notes	STANDARD DATA SET			
Structure Gross Area	m2	10399					
Materials Weight	t	12992	Total	Substructure	Superstructure	Demolition	Total
Embodied Energy	GJ/m2	2.54	GJ	5653	19507	1235	26394
Embodied CO2	kg/m2	309.38	kg	872468	2263657	81112	3217237
Transportation Distance	miles/m2	7.03	miles	19290	39881	13886	73057
Transportation Time	hr/m2	0.32	hr	1019	1720	565	3304
Transportation Speed	MPH	22.11					

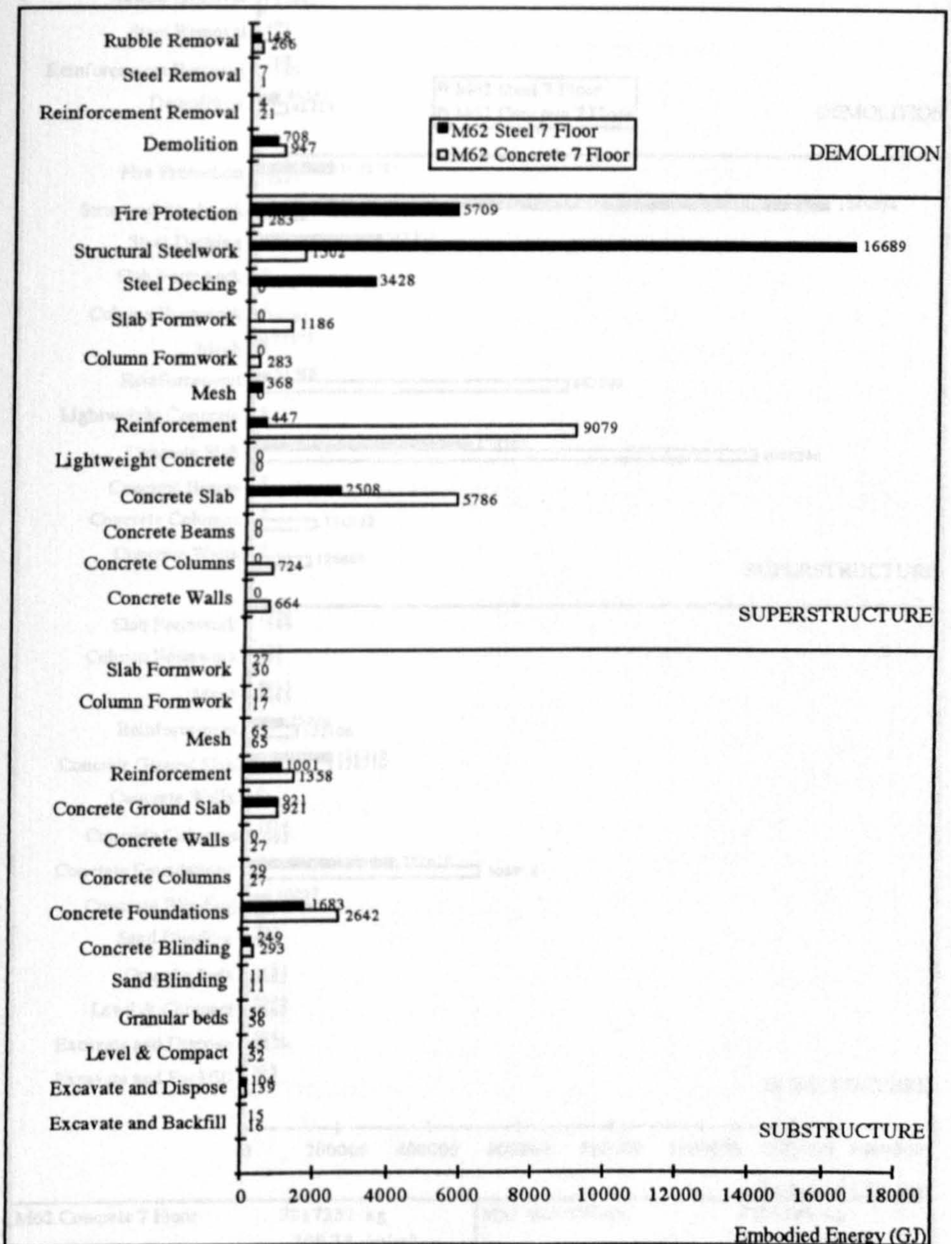
Element	Unit	No.	Rate Selected	Unit Rates				Total Values			
				Energy	CO2	Transportation		Energy	CO2	Transportation	
				GJ/unit	kg/unit	mile/unit	hr/unit	GJ	kg	miles	hours
Substructure											
Excavate and Backfill	m3	273.0	Excavation and Backfill (SEEAM)	0.058	1.16	0.02	0.001	16	318	4	0
Excavate and Dispose	m3	1851.0	Excavation and Disposal (SEEAM)	0.075	4.93	1.80	0.120	139	9129	3340	223
Level & Compact	m2	2842.0	Level & Compact (SEEAM)	0.018	1.20	0.02	0.002	52	3399	57	6
Granular beds	t	601.5	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	56	3632	1415	71
Sand Blinding	t	120.5	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	11	727	283	14
Concrete Blinding	m3	173.0	C20 (SEEAM)	1.695	313.64	6.89	0.377	293	54260	1192	65
Concrete Foundations	m3	1190.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	2642	504918	7993	428
Concrete Columns	m3	12.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	27	5092	81	4
Concrete Walls	m3	12.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	27	5092	81	4
Concrete Ground Slab	m3	394.0	C40 Pump (SEEAM)	2.338	448.50	7.01	0.370	921	176710	2761	146
Reinforcement	t	76.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	1358	102106	1724	47
Mesh	t	3.6	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	65	4845	95	3
Column Formwork	m2	321.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	17	891	82	2
Slab Formwork	m2	693.0	Formwork (Flat Slab)(SEEAM/OB)	0.043	1.95	0.26	0.007	30	1349	182	5
Superstructure											
Concrete Walls	m3	299.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	664	126866	2008	108
Concrete Columns	m3	326.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	724	138322	2190	117
Concrete Slab	m3	2740.0	C30 Pump (SEEAM)	2.112	400.84	7.08	0.377	5786	1098308	19411	1033
Reinforcement	t	508.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	9079	682500	11526	317
Column Formwork	m2	5434.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	283	15091	1395	41
Slab Formwork	m2	9133.0	Formwork (Shaped Soffit)(SEEAM/OB)	0.130	8.94	0.28	0.008	1186	81683	2552	75
Steelwork	t	54.0	Structural Steel (Short) (SEEAM/OB)	27.816	2083.12	10.10	0.401	1502	112489	546	22
Fire Protection	m2	511.0	Fire Protection (18mm Vicuclad) (SEEA	0.553	16.43	0.49	0.013	283	8397	253	7
Demolition											
Demolition	m2	10399	Demolition (Concrete)(SEEAM)	0.091	5.98	0.01	0.001	947	62219	154	15
ReBar Removal	t	588	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	21	1389	1010	40
Steel Removal	t	54	Steel Transport (Demolished)(SEEAM)	0.012	0.79	0.55	0.022	1	43	29	1
Rubble Removal	t	7385	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	266	17461	12693	508
Base Data											
Cement	t			5.800	1193.00	3.29	0.088				
GGBS	t			1.450	78.09	8.40	0.224				
PFA	t			0.339	20.86	8.40	0.224				
Lytag	t			0.920	58.27	12.35	0.329				
Aggregates	t			0.093	6.04	2.35	0.118				

Table 4: M62 Steel 7 Floor Structure using Standard Data

Summary		M62 Steel 7 Floor	Notes	STANDARD DATA SET			
Structure Gross Area	m2	10399					
Materials Weight	t	6800	Total	Substructure	Superstructure	Demolition	Total
Embodied Energy	GJ/m2	3.29	GJ	4218	29150	867	34235
Embodied CO2	kg/m2	281.59	kg	646311	2225028	56947	2928286
Transportation Distance	miles/m2	4.40	miles	14802	23264	7658	45724
Transportation Time	hr/m2	0.19	hr	780	915	312	2008
Transportation Speed	MPH	22.78					

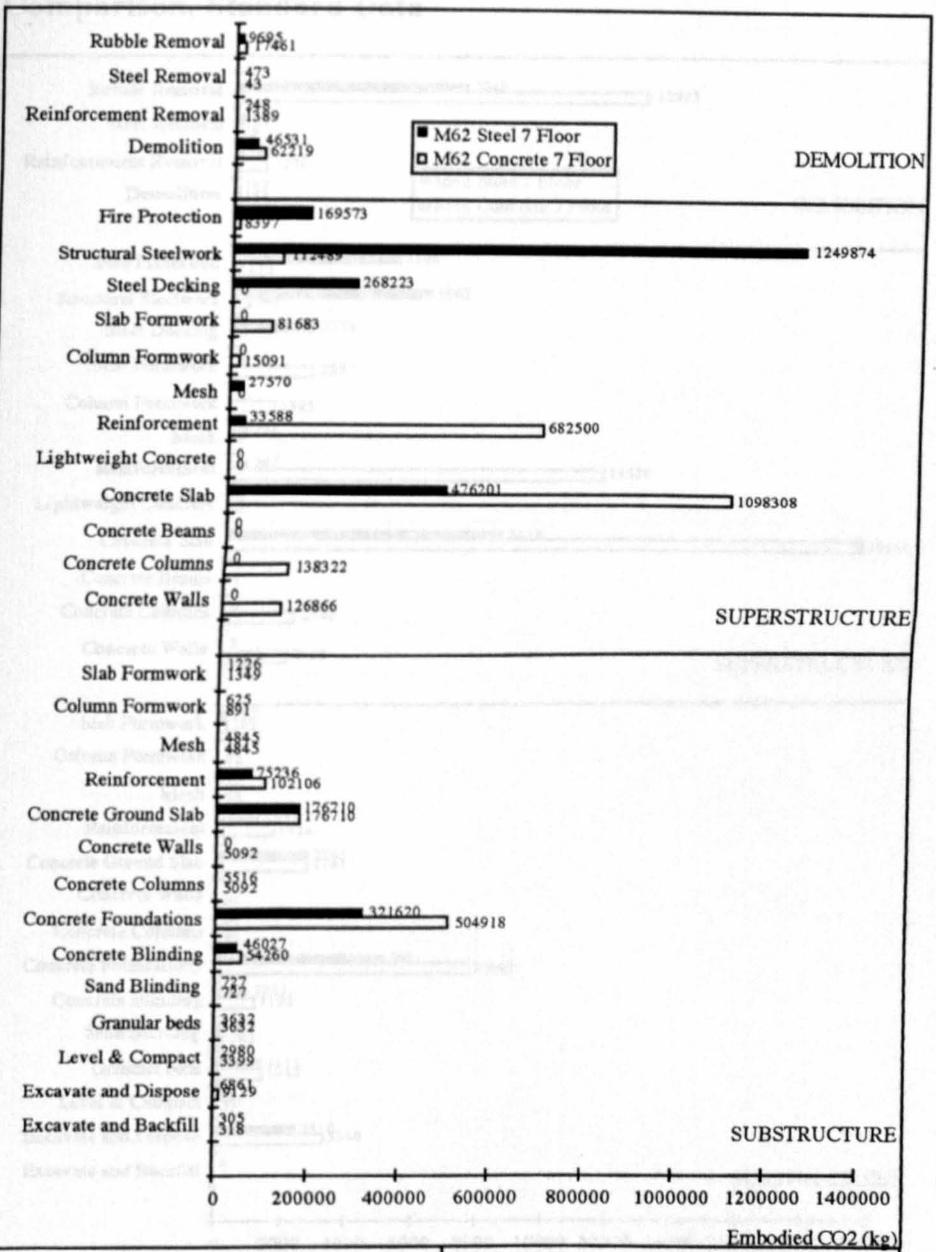
Element	Unit	No.	Rate Selected	Unit Rates				Total Values			
				Energy	CO2	Transportation		Energy	CO2	Transportation	
				GJ/unit	kg/unit	mile/unit	hr/unit	GJ	kg	miles	hours
Substructure											
Excavate and Backfill	m3	262.0	Excavation and Backfill (SEEAM)	0.058	1.16	0.02	0.001	15	305	4	0
Excavate and Dispose	m3	1391.0	Excavation and Disposal (SEEAM)	0.075	4.93	1.80	0.120	104	6861	2510	167
Level & Compact	m2	2492.0	Level & Compact (SEEAM)	0.018	1.20	0.02	0.002	45	2980	50	5
Granular beds	t	601.5	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	56	3632	1415	71
Sand Blinding	t	120.5	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	11	727	283	14
Concrete Blinding	m3	146.8	C20 (SEEAM)	1.695	313.64	6.89	0.377	249	46027	1011	55
Concrete Foundations	m3	758.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	1683	321620	5091	273
Concrete Columns	m3	13.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	29	5516	87	5
Concrete Ground Slab	m3	394.0	C40 Pump (SEEAM)	2.338	448.50	7.01	0.370	921	176710	2761	146
Reinforcement	t	56.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	1001	75236	1271	35
Mesh	t	3.6	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	65	4845	95	3
Column Formwork	m2	225.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	12	625	58	2
Slab Formwork	m2	630.0	Formwork (Flat Slab)(SEEAM/OB)	0.043	1.95	0.26	0.007	27	1226	165	4
Superstructure											
Concrete Slab	m3	1188.0	C30 Pump (SEEAM)	2.112	400.84	7.08	0.377	2508	476201	8416	448
Reinforcement	t	25.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	447	33588	567	16
Mesh	t	20.3	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	368	27570	542	15
Steel Decking	m2	9138.0	Steel Decking (SEEAM/OB)	0.375	29.35	0.28	0.007	3428	268223	2573	65
Steelwork	t	600.0	Structural Steel (Short) (SEEAM/OB)	27.816	2083.12	10.10	0.401	16689	1249874	6062	241
Fire Protection	m2	#####	Fire Protection (18mm Vicuclad) (SEEA	0.553	16.43	0.49	0.013	5709	169573	5104	131
Demolition											
Demolition	m2	10399	Demolition (Steel)(SEEAM)	0.068	4.47	0.01	0.001	708	46531	103	10
ReBar Removal	t	105	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	4	248	180	7
Steel Removal	t	600	Steel Transport (Demolished)(SEEAM)	0.012	0.79	0.55	0.022	7	473	327	13
Rubble Removal	t	4101	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	148	9695	7048	282
Base Data											
Cement	t			5.800	1193.00	3.29	0.088				
GGBS	t			1.450	78.09	8.40	0.224				
PFA	t			0.339	20.86	8.40	0.224				
Lytag	t			0.920	58.27	12.35	0.329				
Aggregates	t			0.093	6.04	2.35	0.118				

Figure 5: M62 7 Floor Steel and Concrete Embodied Energy Comparison, Standard Data



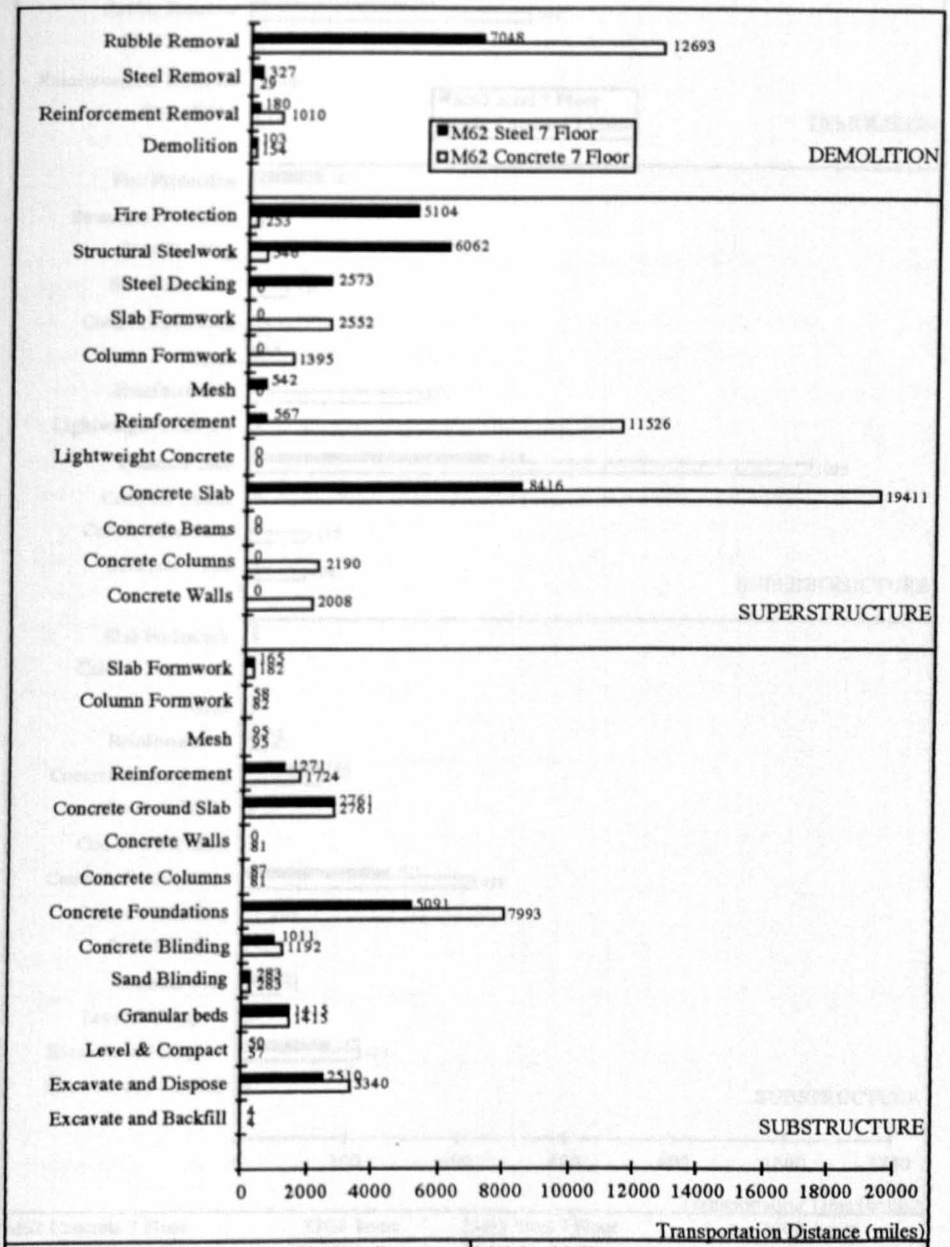
M62 Concrete 7 Floor	26394 GJ		M62 Steel 7 Floor	34235 GJ	
	2.54 GJ/m2			3.29 GJ/m2	
Section Total	GJ		Section Total	GJ	
Substructure	5653	21.4%	Substructure	4218	12.3%
Superstructure	19507	73.9%	Superstructure	29150	85.1%
Demolition	1235	4.7%	Demolition	867	2.5%
Item Total	GJ		Item Total	GJ	
Standard Concrete	11083	42.0%	Standard Concrete	5390	15.7%
Lightweight Concrete			Lightweight Concrete		
Reinforcement	10437	39.5%	Reinforcement	1448	4.2%
Mesh	65	0.2%	Mesh	433	1.3%
Formwork	1516	5.7%	Formwork	39	0.1%
Structural Steelwork	1502	5.7%	Structural Steelwork	16689	48.7%
Steel Decking			Steel Decking	3428	10.0%
Fire Protection	283	1.1%	Fire Protection	5709	16.7%

Figure 6: M62 7 Steel and Concrete Embodied CO_2 Comparison, Standard Data



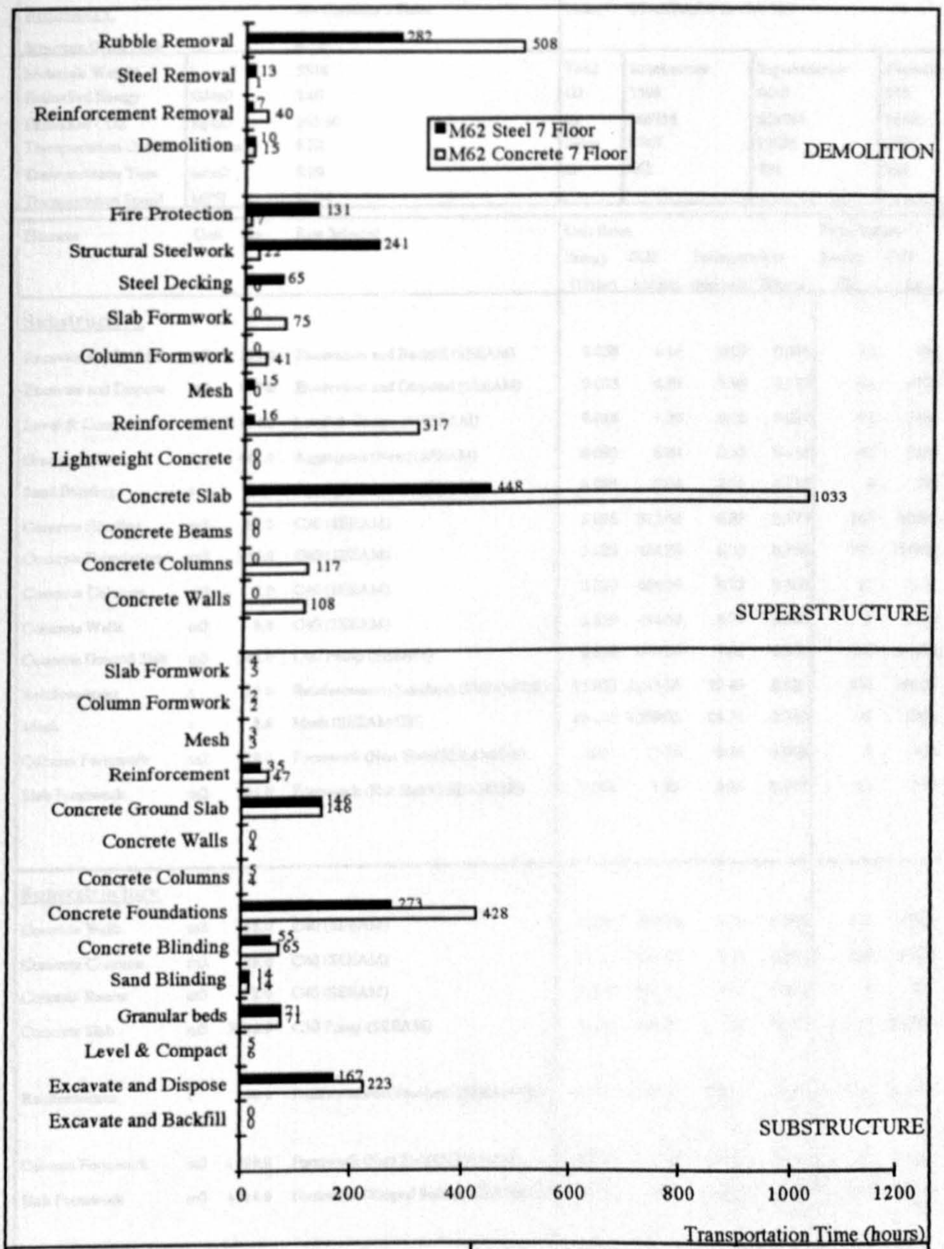
M62 Concrete 7 Floor	3217237 kg		M62 Steel 7 Floor	2928286 kg	
	309.38 kg/m2			281.59 kg/m2	
Section Total	kg		Section Total	kg	
Substructure	872468	27.1%	Substructure	646311	22.1%
Superstructure	2263657	70.4%	Superstructure	2225028	76.0%
Demolition	81112	2.5%	Demolition	56947	1.9%
Item Total	kg		Item Total	kg	
Standard Concrete	2109566	65.6%	Standard Concrete	1026073	35.0%
Lightweight Concrete			Lightweight Concrete		
Reinforcement	784607	24.4%	Reinforcement	108824	3.7%
Mesh	4845	0.2%	Mesh	32415	1.1%
Formwork	99015	3.1%	Formwork	1851	0.1%
Structural Steelwork	112489	3.5%	Structural Steelwork	1249874	42.7%
Steel Decking			Steel Decking	268223	9.2%
Fire Protection	8397	0.3%	Fire Protection	169573	5.8%

Figure 7: M62 7 Floor Steel and Concrete Transportation Distance Comparison, Standard Data



M62 Concrete 7 Floor	73057	miles	M62 Steel 7 Floor	45724	miles
	7.03	miles/m2		4.40	miles/m2
Section Total	miles		Section Total	miles	
Substructure	19290	26.4%	Substructure	14802	32.4%
Superstructure	39881	54.6%	Superstructure	23264	50.9%
Demolition	13886	19.0%	Demolition	7658	16.7%
Item Total	miles		Item Total	miles	
Standard Concrete	35716	48.9%	Standard Concrete	17367	38.0%
Lightweight Concrete			Lightweight Concrete		
Reinforcement	13251	18.1%	Reinforcement	1838	4.0%
Mesh	95	0.1%	Mesh	637	1.4%
Formwork	4211	5.8%	Formwork	223	0.5%
Structural Steelwork	546	0.7%	Structural Steelwork	6062	13.3%
Steel Decking			Steel Decking	2573	5.6%
Fire Protection	253	0.3%	Fire Protection	5104	11.2%

Figure 8: M62 7 Floor Steel and Concrete Transportation Time Comparison, Standard Data



M62 Concrete 7 Floor	3304 hours 0.32 hours/m2		M62 Steel 7 Floor	2008 hours 0.19 hours/m2	
Section Total	hours		Section Total	hours	
Substructure	1019	30.8%	Substructure	780	38.9%
Superstructure	1720	52.1%	Superstructure	915	45.6%
Demolition	565	17.1%	Demolition	312	15.6%
Item Total	hours		Item Total	hours	
Standard Concrete	1906	57.7%	Standard Concrete	927	46.2%
Lightweight Concrete			Lightweight Concrete		
Reinforcement	365	11.0%	Reinforcement	51	2.5%
Mesh	3	0.1%	Mesh	17	0.9%
Formwork	124	3.7%	Formwork	6	0.3%
Structural Steelwork	22	0.7%	Structural Steelwork	241	12.0%
Steel Decking			Steel Decking	65	3.2%
Fire Protection	7	0.2%	Fire Protection	131	6.5%

Table 5: M4 Concrete 3 Floor Structure using Standard Data

Summary		M4 Concrete 3 Floor	Notes	STANDARD DATA SET			
Structure Gross Area	m2	4768					
Materials Weight	t	5548	Total	Substructure	Superstructure	Demolition	Total
Embodied Energy	GJ/m2	2.00	GJ	2395	6610	553	9558
Embodied CO2	kg/m2	263.60	kg	366735	853764	36325	1256824
Transportation Distance	miles/m2	6.32	miles	8745	15656	5738	30139
Transportation Time	hr/m2	0.29	hr	462	704	234	1399
Transportation Speed	MPH	21.54					

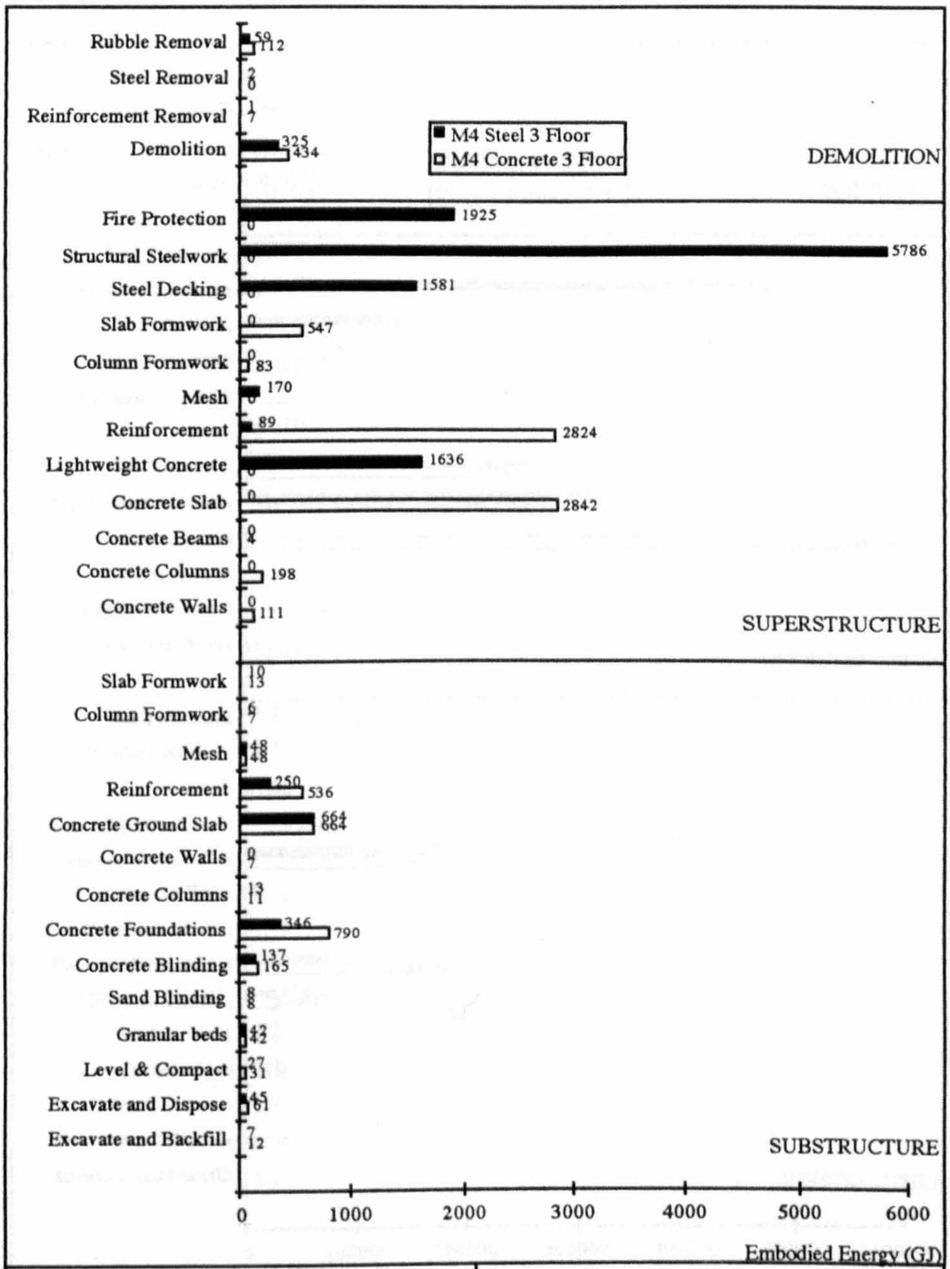
Element	Unit	No.	Rate Selected	Unit Rates				Total Values			
				Energy	CO2	Transportation		Energy	CO2	Transportation	
				GJ/unit	kg/unit	mile/unit	hr/unit	GJ	kg	miles	hours
Substructure											
Excavate and Backfill	m3	199.0	Excavation and Backfill (SEEAM)	0.058	1.16	0.02	0.001	12	232	3	0
Excavate and Dispose	m3	817.0	Excavation and Disposal (SEEAM)	0.075	4.93	1.80	0.120	61	4030	1474	98
Level & Compact	m2	1694.0	Level & Compact (SEEAM)	0.018	1.20	0.02	0.002	31	2026	34	3
Granular beds	t	447.0	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	42	2699	1052	53
Sand Blinding	t	89.3	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	8	539	210	11
Concrete Blinding	m3	97.3	C20 (SEEAM)	1.695	313.64	6.89	0.377	165	30517	670	37
Concrete Foundations	m3	356.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	790	151051	2391	128
Concrete Columns	m3	5.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	11	2122	34	2
Concrete Walls	m3	3.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	7	1273	20	1
Concrete Ground Slab	m3	284.0	C40 Pump (SEEAM)	2.338	448.50	7.01	0.370	664	127375	1990	105
Reinforcement	t	30.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	536	40305	681	19
Mesh	t	2.6	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	48	3590	71	2
Column Formwork	m2	138.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	7	383	35	1
Slab Formwork	m2	305.0	Formwork (Flat Slab)(SEEAM/OB)	0.043	1.95	0.26	0.007	13	594	80	2
Superstructure											
Concrete Walls	m3	50.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	111	21215	336	18
Concrete Columns	m3	89.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	198	37763	598	32
Concrete Beams	m3	2.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	4	849	13	1
Concrete Slab	m3	1346.0	C30 Pump (SEEAM)	2.112	400.84	7.08	0.377	2842	539534	9536	508
Reinforcement	t	158.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	2824	212274	3585	99
Column Formwork	m2	1599.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	83	4441	411	12
Slab Formwork	m2	4214.0	Formwork (Shaped Soffit)(SEEAM/OB)	0.130	8.94	0.28	0.008	547	37689	1177	35
Demolition											
Demolition	m2	4768	Demolition (Concrete)(SEEAM)	0.091	5.98	0.01	0.001	434	28528	71	7
ReBar Removal	t	191	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	7	451	328	13
Rubble Removal	t	3107	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	112	7346	5340	214
Base Data											
Cement	t			5.800	1193.00	3.29	0.088				
GGBS	t			1.450	78.09	8.40	0.224				
PFA	t			0.339	20.86	8.40	0.224				
Lytag	t			0.920	58.27	12.35	0.329				
Aggregates	t			0.093	6.04	2.35	0.118				

Table 6: M4 Steel 3 Floor Structure using Standard Data

Summary		M4 Steel 3 Floor	Notes	STANDARD DATA SET			
Structure Gross Area	m2	4768					
Materials Weight	t	2549	Total	Substructure	Superstructure	Demolition	Total
Embodied Energy	GJ/m2	2.76	GJ	1602	11187	387	13177
Embodied CO2	kg/m2	250.94	kg	252676	918337	25454	1196467
Transportation Distance	miles/m2	4.47	miles	6479	11818	3036	21333
Transportation Time	hr/m2	0.18	hr	345	405	124	874
Transportation Speed	MPH	24.40					

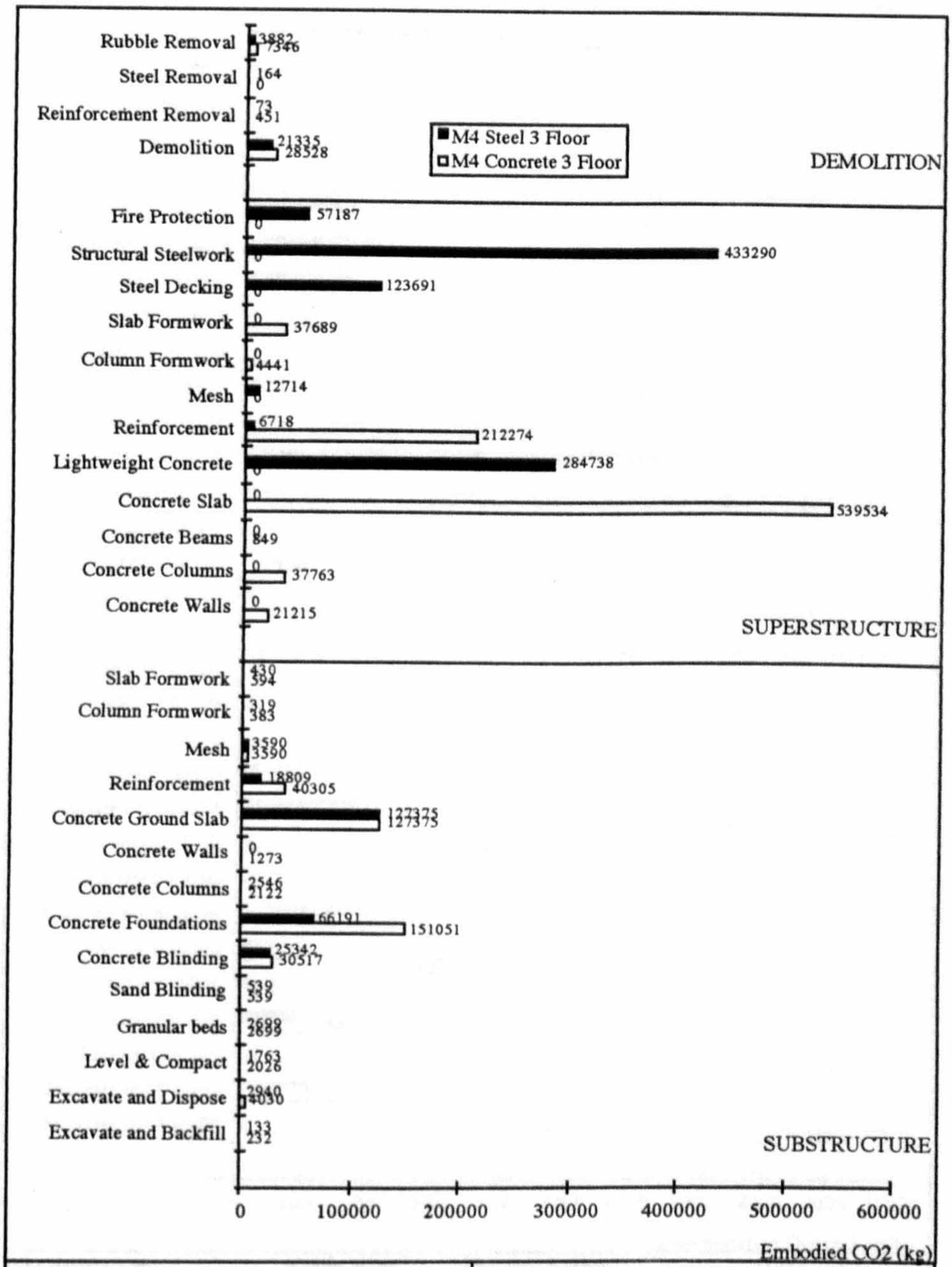
Element	Unit	No.	Rate Selected	Unit Rates				Total Values			
				Energy	CO2	Transportation		Energy	CO2	Transportation	
				GJ/unit	kg/unit	mile/unit	hr/unit	GJ	kg	miles	hours
Substructure											
Excavate and Backfill	m3	114.0	Excavation and Backfill (SEEAM)	0.058	1.16	0.02	0.001	7	133	2	0
Excavate and Dispose	m3	596.0	Excavation and Disposal (SEEAM)	0.075	4.93	1.80	0.120	45	2940	1075	72
Level & Compact	m2	1474.0	Level & Compact (SEEAM)	0.018	1.20	0.02	0.002	27	1763	29	3
Granular beds	t	447.0	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	42	2699	1052	53
Sand Blinding	t	89.3	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	8	539	210	11
Concrete Blinding	m3	80.8	C20 (SEEAM)	1.695	313.64	6.89	0.377	137	25342	557	30
Concrete Foundations	m3	156.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	346	66191	1048	56
Concrete Columns	m3	6.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	13	2546	40	2
Concrete Ground Slab	m3	284.0	C40 Pump (SEEAM)	2.338	448.50	7.01	0.370	664	127375	1990	105
Reinforcement	t	14.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	250	18809	318	9
Mesh	t	2.6	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	48	3590	71	2
Column Formwork	m2	115.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	6	319	30	1
Slab Formwork	m2	221.0	Formwork (Flat Slab)(SEEAM/OB)	0.043	1.95	0.26	0.007	10	430	58	2
Superstructure											
Lightweight Concrete	m3	527.0	C30 Lytag Pump (SEEAM)	3.104	540.30	12.23	0.451	1636	284738	6445	238
Reinforcement	t	5.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	89	6718	113	3
Mesh	t	9.4	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	170	12714	250	7
Steel Decking	m2	4214.0	Steel Decking (SEEAM/OB)	0.375	29.35	0.28	0.007	1581	123691	1187	30
Steelwork	t	208.0	Structural Steel (Short) (SEEAM/OB)	27.816	2083.12	10.10	0.401	5786	433290	2102	83
Fire Protection	m2	3480.0	Fire Protection (18mm Vicuclad) (SEEA	0.553	16.43	0.49	0.013	1925	57187	1721	44
Demolition											
Demolition	m2	4768	Demolition (Steel)(SEEAM)	0.068	4.47	0.01	0.001	325	21335	47	5
ReBar Removal	t	31	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	1	73	53	2
Steel Removal	t	208	Steel Transport (Demolished)(SEEAM)	0.012	0.79	0.55	0.022	2	164	113	5
Rubble Removal	t	1642	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	59	3882	2822	113
Base Data											
Cement	t			5.800	1193.00	3.29	0.088				
GGBS	t			1.450	78.09	8.40	0.224				
PFA	t			0.339	20.86	8.40	0.224				
Lytag	t			0.920	58.27	12.35	0.329				
Aggregates	t			0.093	6.04	2.35	0.118				

Figure 9: M4 3 Floor Steel and Concrete Embodied Energy Comparison, Standard Data



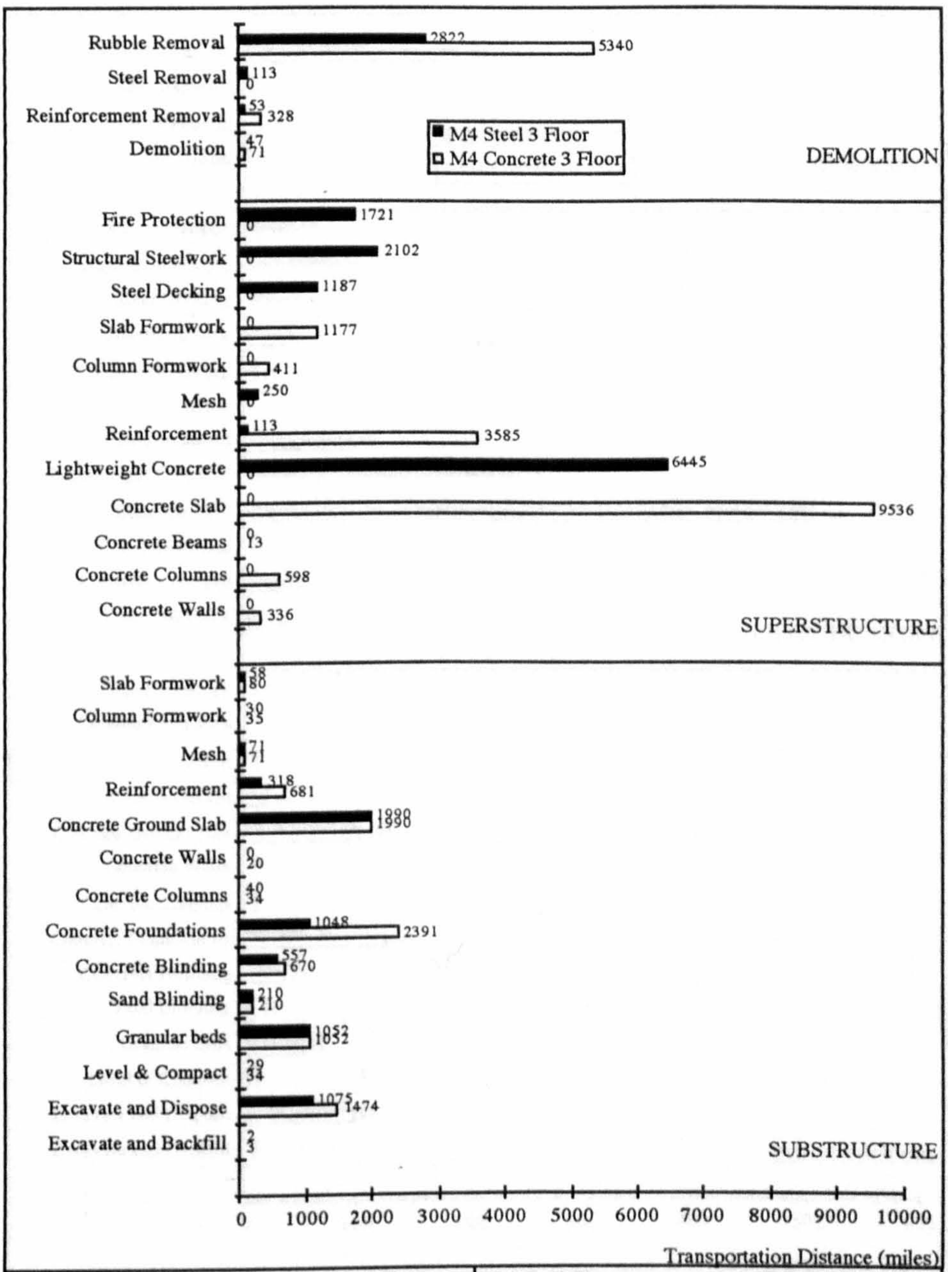
M4 Concrete 3 Floor	9558 GJ 2.00 GJ/m2		M4 Steel 3 Floor	13177 GJ 2.76 GJ/m2	
Section Total	GJ		Section Total	GJ	
Substructure	2395	25.1%	Substructure	1602	12.2%
Superstructure	6610	69.2%	Superstructure	11187	84.9%
Demolition	553	5.8%	Demolition	387	2.9%
Item Total	GJ		Item Total	GJ	
Standard Concrete	4792	50.1%	Standard Concrete	1161	8.8%
Lightweight Concrete			Lightweight Concrete	1636	12.4%
Reinforcement	3360	35.2%	Reinforcement	340	2.6%
Mesh	48	0.5%	Mesh	218	1.7%
Formwork	651	6.8%	Formwork	16	0.1%
Structural Steelwork			Structural Steelwork	5786	43.9%
Steel Decking			Steel Decking	1581	12.0%
Fire Protection			Fire Protection	1925	14.6%

Figure 10: M4 3 Steel and Concrete Embodied CO$_2$ Comparison, Standard Data



M4 Concrete 3 Floor	1256824 kg		M4 Steel 3 Floor	1196467 kg	
	263.60 kg/m2			250.94 kg/m2	
Section Total	kg		Section Total	kg	
Substructure	366735	29.2%	Substructure	252676	21.1%
Superstructure	853764	67.9%	Superstructure	918337	76.8%
Demolition	36325	2.9%	Demolition	25454	2.1%
Item Total	kg		Item Total	kg	
Standard Concrete	911697	72.5%	Standard Concrete	221454	18.5%
Lightweight Concrete			Lightweight Concrete	284738	23.8%
Reinforcement	252579	20.1%	Reinforcement	25527	2.1%
Mesh	3590	0.3%	Mesh	16304	1.4%
Formwork	43107	3.4%	Formwork	750	0.1%
Structural Steelwork			Structural Steelwork	433290	36.2%
Steel Decking			Steel Decking	123691	10.3%
Fire Protection			Fire Protection	57187	4.8%

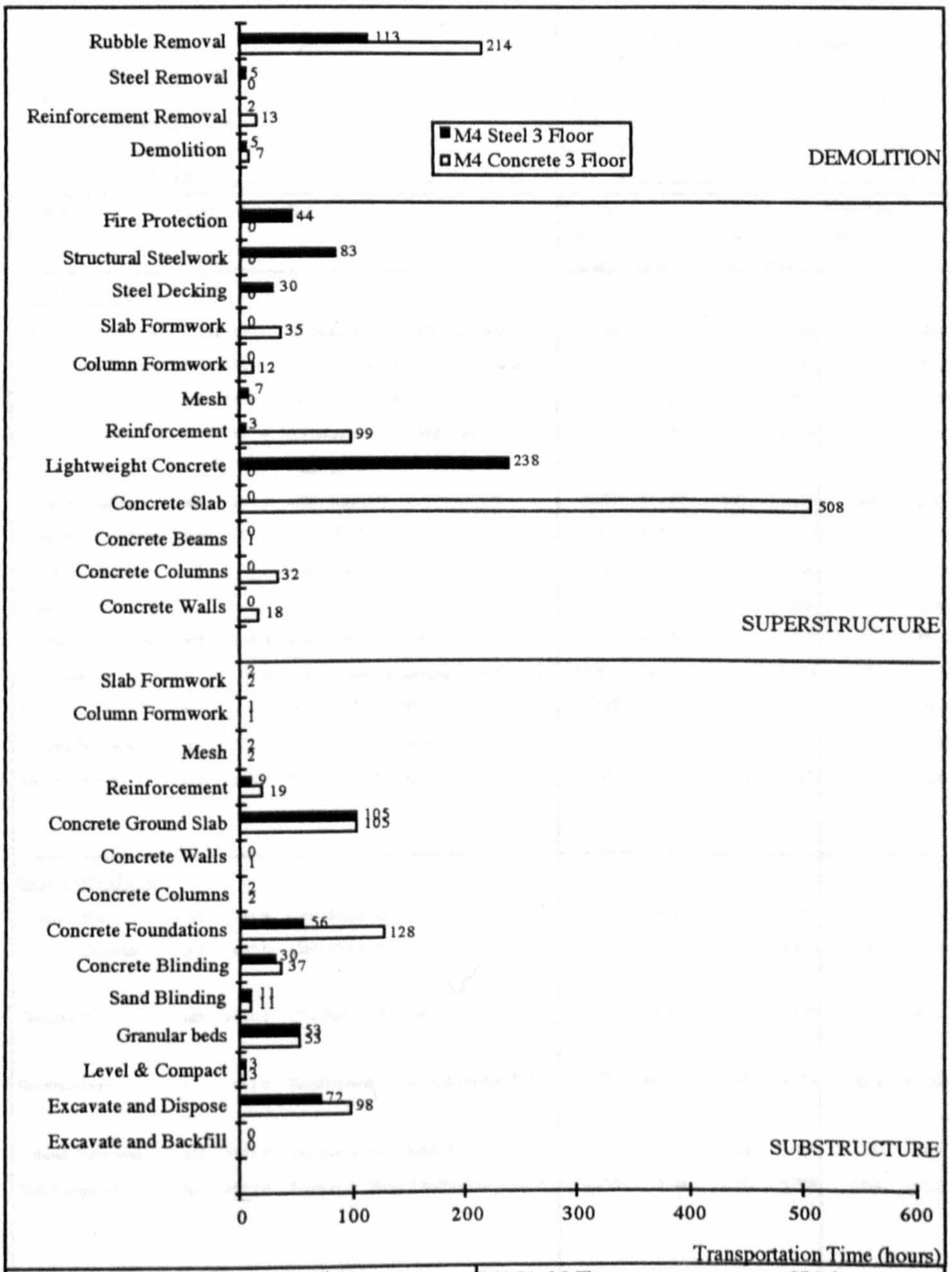
Figure 11: M4 3 Floor Steel and Concrete Transportation Distance Comparison, Standard Data



M4 Concrete 3 Floor	30139 miles 6.32 miles/m2	
Section Total	**miles**	
Substructure	8745	29.0%
Superstructure	15656	51.9%
Demolition	5738	19.0%
Item Total	**miles**	
Standard Concrete	15588	51.7%
Lightweight Concrete		
Reinforcement	4266	14.2%
Mesh	71	0.2%
Formwork	1703	5.7%
Structural Steelwork		
Steel Decking		
Fire Protection		

M4 Steel 3 Floor	21333 miles 4.47 miles/m2	
Section Total	**miles**	
Substructure	6479	30.4%
Superstructure	11818	55.4%
Demolition	3036	14.2%
Item Total	**miles**	
Standard Concrete	3635	17.0%
Lightweight Concrete	6445	30.2%
Reinforcement	431	2.0%
Mesh	320	1.5%
Formwork	87	0.4%
Structural Steelwork	2102	9.9%
Steel Decking	1187	5.6%
Fire Protection	1721	8.1%

Figure 12: M4 3 Floor Steel and Concrete Transportation Time Comparison, Standard Data



M4 Concrete 3 Floor	1399 hours		M4 Steel 3 Floor	874 hours	
	0.29 hours/m2			0.18 hours/m2	
Section Total	hours		Section Total	hours	
Substructure	462	33.0%	Substructure	345	39.4%
Superstructure	704	50.3%	Superstructure	405	46.3%
Demolition	234	16.7%	Demolition	124	14.2%
Item Total	hours		Item Total	hours	
Standard Concrete	831	59.4%	Standard Concrete	194	22.2%
Lightweight Concrete			Lightweight Concrete	238	27.2%
Reinforcement	117	8.4%	Reinforcement	12	1.4%
Mesh	2	0.1%	Mesh	9	1.0%
Formwork	50	3.6%	Formwork	2	0.3%
Structural Steelwork			Structural Steelwork	83	9.5%
Steel Decking			Steel Decking	30	3.4%
Fire Protection			Fire Protection	44	5.1%

Table 7: M4 Concrete 7 Floor Structure using Standard Data

Summary		M4 Concrete 7 Floor	Notes	STANDARD DATA SET			
Structure Gross Area	m2	11275					
Materials Weight	t	12614	Total	Substructure	Superstructure	Demolition	Total
Embodied Energy	GJ/m2	2.08	GJ	4651	17484	1288	23424
Embodied CO2	kg/m2	263.81	kg	689141	2200660	84634	2974435
Transportation Distance	miles/m2	6.03	miles	15122	40231	12651	68004
Transportation Time	hr/m2	0.27	hr	789	1781	516	3086
Transportation Speed	MPH	22.04					

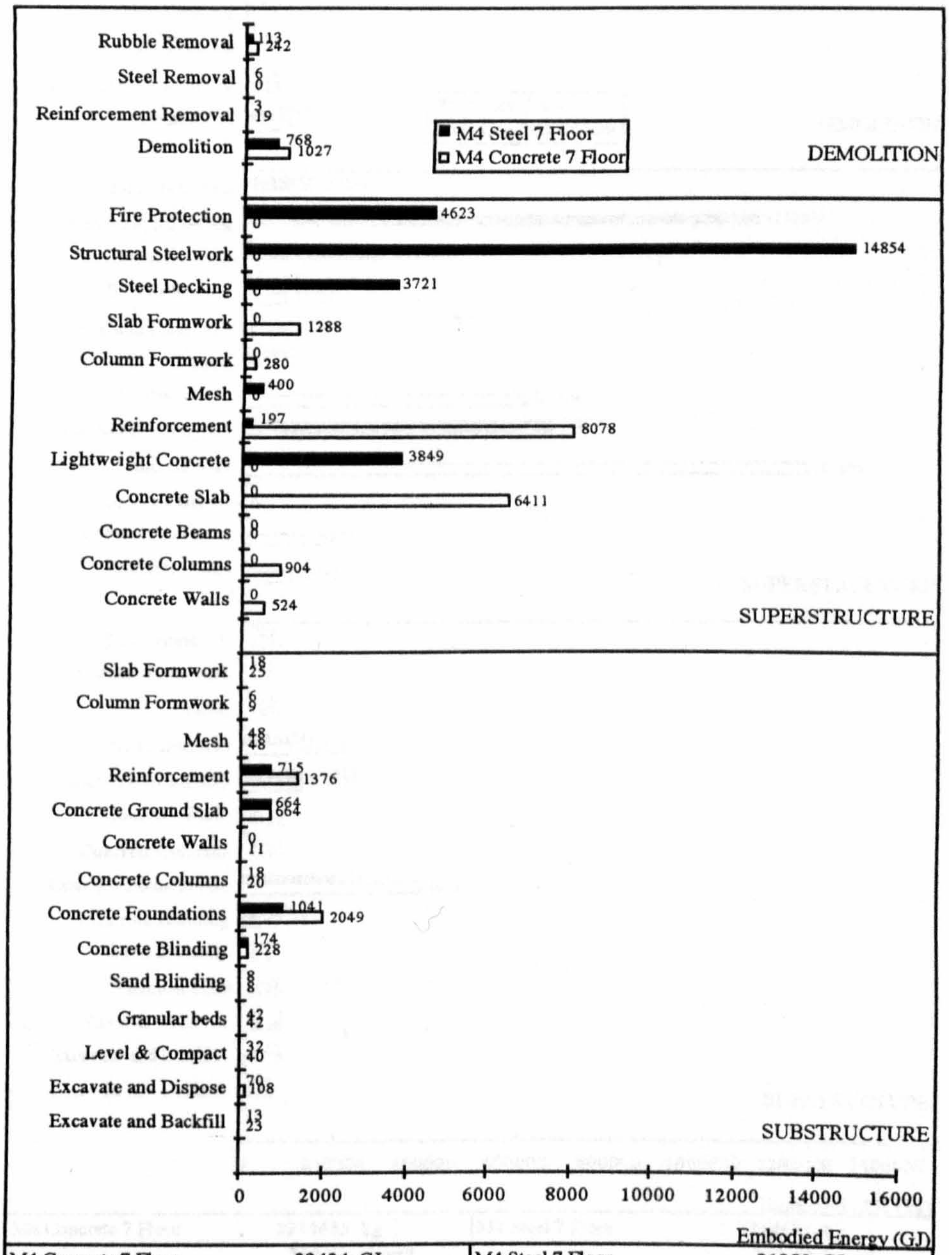
Element	Unit	No.	Rate Selected	Unit Rates Energy GJ/unit	CO2 kg/unit	Transportation mile/unit	hr/unit	Total Values Energy GJ	CO2 kg	Transportation miles	hours
Substructure											
Excavate and Backfill	m3	400.0	Excavation and Backfill (SEEAM)	0.058	1.16	0.02	0.001	23	466	6	0
Excavate and Dispose	m3	1434.0	Excavation and Disposal (SEEAM)	0.075	4.93	1.80	0.120	108	7073	2588	173
Level & Compact	m2	2189.0	Level & Compact (SEEAM)	0.018	1.20	0.02	0.002	40	2618	44	4
Granular beds	t	447.0	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	42	2699	1052	53
Sand Blinding	t	89.3	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	8	539	210	11
Concrete Blinding	m3	134.4	C20 (SEEAM)	1.695	313.64	6.89	0.377	228	42161	926	51
Concrete Foundations	m3	923.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	2049	391629	6199	332
Concrete Columns	m3	9.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	20	3819	60	3
Concrete Walls	m3	5.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	11	2122	34	2
Concrete Ground Slab	m3	284.0	C40 Pump (SEEAM)	2.338	448.50	7.01	0.370	664	127375	1990	105
Reinforcement	t	77.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	1376	103450	1747	48
Mesh	t	2.6	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	48	3590	71	2
Column Formwork	m2	170.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	9	472	44	1
Slab Formwork	m2	580.0	Formwork (Flat Slab)(SEEAM/OB)	0.043	1.95	0.26	0.007	25	1129	152	4
Superstructure											
Concrete Walls	m3	236.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	524	100135	1585	85
Concrete Columns	m3	407.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	904	172690	2734	146
Concrete Slab	m3	3036.0	C30 Pump (SEEAM)	2.112	400.84	7.08	0.377	6411	1216957	21508	1145
Reinforcement	t	452.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	8078	607264	10256	282
Column Formwork	m2	5362.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	280	14891	1377	40
Slab Formwork	m2	9920.0	Formwork (Shaped Soffit)(SEEAM/OB)	0.130	8.94	0.28	0.008	1288	88722	2772	82
Demolition											
Demolition	m2	11275	Demolition (Concrete)(SEEAM)	0.091	5.98	0.01	0.001	1027	67461	167	17
ReBar Removal	t	532	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	19	1257	914	37
Rubble Removal	t	6732	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	242	15916	11570	463
Base Data											
Cement	t			5.800	1193.00	3.29	0.088				
GGBS	t			1.450	78.09	8.40	0.224				
PFA	t			0.339	20.86	8.40	0.224				
Lytag	t			0.920	58.27	12.35	0.329				
Aggregates	t			0.093	6.04	2.35	0.118				

Table 8: M4 Steel 7 Floor Structure using Standard Data

Summary		M4 Steel 7 Floor	Notes	STANDARD DATA SET			
Structure Gross Area	m2	11275					
Materials Weight	t	5142	Total	Substructure	Superstructure	Demolition	Total
Embodied Energy	GJ/m2	2.78	GJ	2849	27643	890	31382
Embodied CO2	kg/m2	243.43	kg	430610	2255542	58481	2744632
Transportation Distance	miles/m2	3.93	miles	10003	28323	5934	44260
Transportation Time	hr/m2	0.15	hr	525	973	244	1743
Transportation Speed	MPH	25.40					

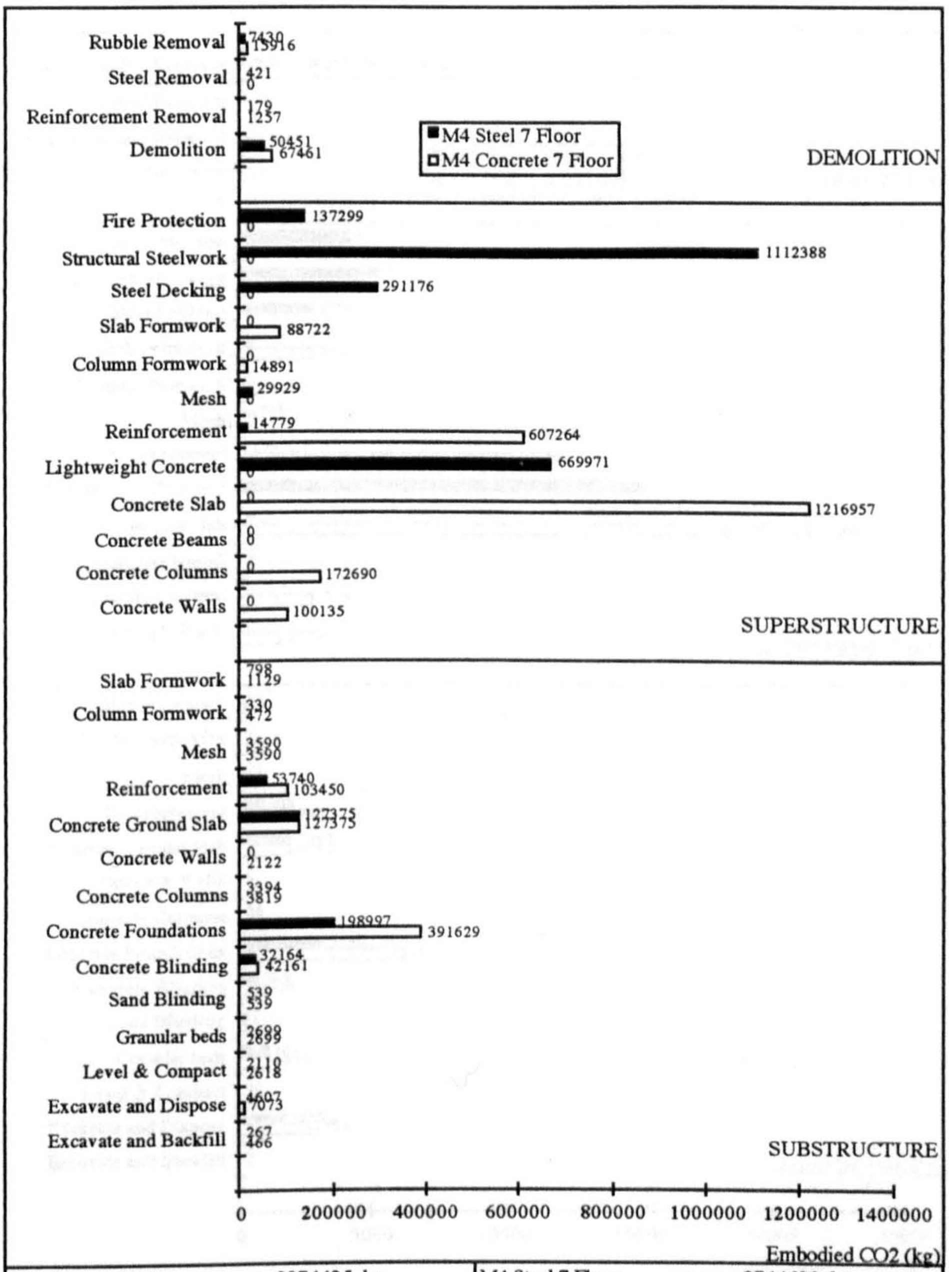
Element	Unit	No.	Rate Selected	Unit Rates				Total Values			
				Energy	CO2	Transportation		Energy	CO2	Transportation	
				GJ/unit	kg/unit	mile/unit	hr/unit	GJ	kg	miles	hours
Substructure											
Excavate and Backfill	m3	229.0	Excavation and Backfill (SEEAM)	0.058	1.16	0.02	0.001	13	267	4	0
Excavate and Dispose	m3	934.0	Excavation and Disposal (SEEAM)	0.075	4.93	1.80	0.120	70	4607	1685	112
Level & Compact	m2	1764.0	Level & Compact (SEEAM)	0.018	1.20	0.02	0.002	32	2110	35	4
Granular beds	t	447.0	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	42	2699	1052	53
Sand Blinding	t	89.3	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	8	539	210	11
Concrete Blinding	m3	102.6	C20 (SEEAM)	1.695	313.64	6.89	0.377	174	32164	706	39
Concrete Foundations	m3	469.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	1041	198997	3150	169
Concrete Columns	m3	8.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	18	3394	54	3
Concrete Ground Slab	m3	284.0	C40 Pump (SEEAM)	2.338	448.50	7.01	0.370	664	127375	1990	105
Reinforcement	t	40.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	715	53740	908	25
Mesh	t	2.6	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	48	3590	71	2
Column Formwork	m2	119.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	6	330	31	1
Slab Formwork	m2	410.0	Formwork (Flat Slab)(SEEAM/OB)	0.043	1.95	0.26	0.007	18	798	107	3
Superstructure											
Lightweight Concrete	m3	1240.0	C30 Lytag Pump (SEEAM)	3.104	540.30	12.23	0.451	3849	669971	15164	559
Reinforcement	t	11.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	197	14779	250	7
Mesh	t	22.0	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	400	29929	588	16
Steel Decking	m2	9920.0	Steel Decking (SEEAM/OB)	0.375	29.35	0.28	0.007	3721	291176	2794	70
Steelwork	t	534.0	Structural Steel (Short) (SEEAM/OB)	27.816	2083.12	10.10	0.401	14854	1112388	5395	214
Fire Protection	m2	8355.0	Fire Protection (18mm Vicuclad) (SEEA	0.553	16.43	0.49	0.013	4623	137299	4132	106
Demolition											
Demolition	m2	11275	Demolition (Steel)(SEEAM)	0.068	4.47	0.01	0.001	768	50451	111	11
ReBar Removal	t	76	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	3	179	130	5
Steel Removal	t	534	Steel Transport (Demolished)(SEEAM)	0.012	0.79	0.55	0.022	6	421	291	12
Rubble Removal	t	3143	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	113	7430	5401	216
Base Data											
Cement	t			5.800	1193.00	3.29	0.088				
GGBS	t			1.450	78.09	8.40	0.224				
PFA	t			0.339	20.86	8.40	0.224				
Lytag	t			0.920	58.27	12.35	0.329				
Aggregates	t			0.093	6.04	2.35	0.118				

Figure 13: M4 7 Floor Steel and Concrete Embodied Energy Comparison, Standard Data



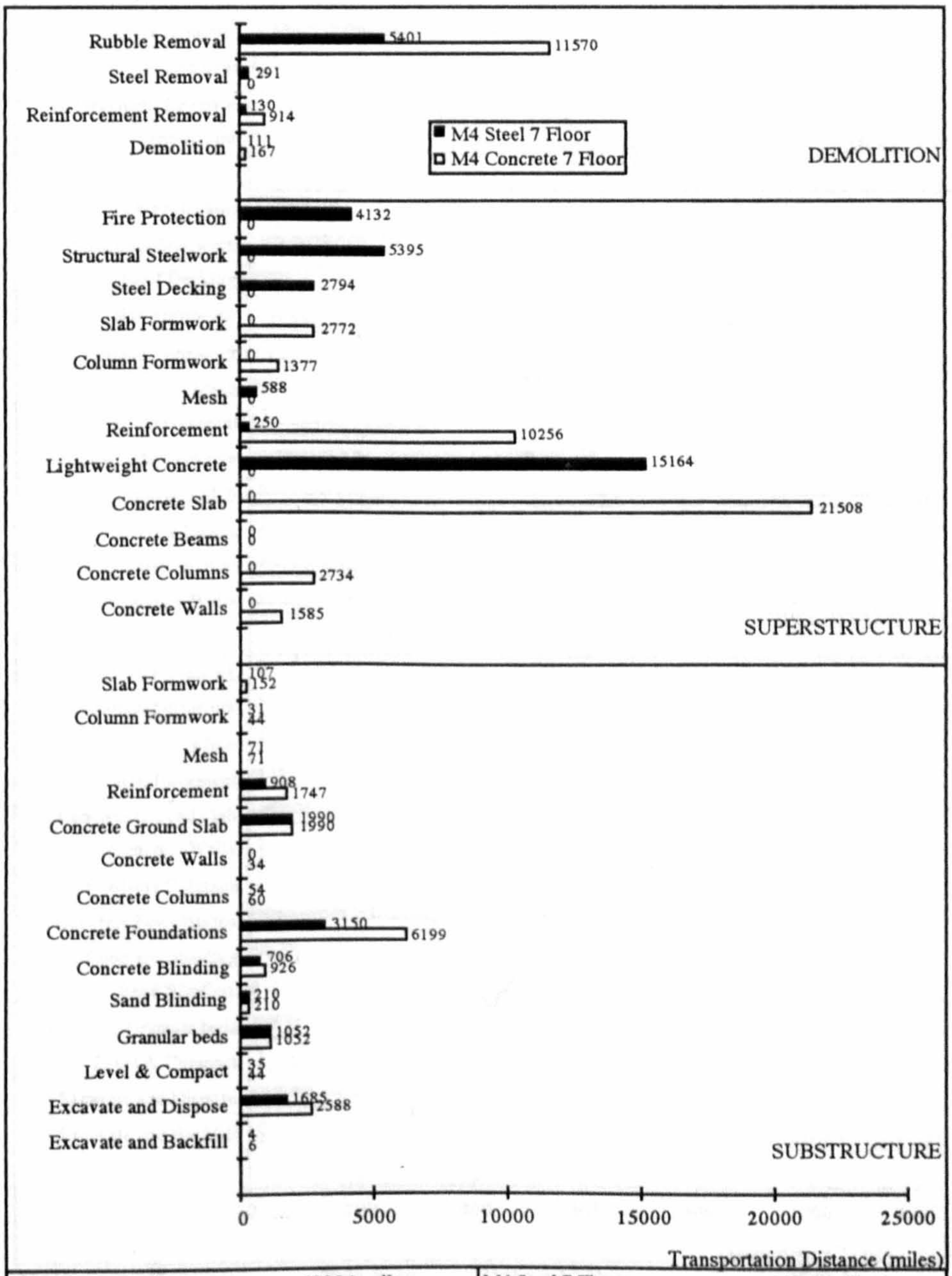
M4 Concrete 7 Floor	23424 GJ 2.08 GJ/m2		M4 Steel 7 Floor	31382 GJ 2.78 GJ/m2	
Section Total	**GJ**		**Section Total**	**GJ**	
Substructure	4651	19.9%	Substructure	2849	9.1%
Superstructure	17484	74.6%	Superstructure	27643	88.1%
Demolition	1288	5.5%	Demolition	890	2.8%
Item Total	**GJ**		**Item Total**	**GJ**	
Standard Concrete	10810	46.2%	Standard Concrete	1897	6.0%
Lightweight Concrete			Lightweight Concrete	3849	12.3%
Reinforcement	9454	40.4%	Reinforcement	911	2.9%
Mesh	48	0.2%	Mesh	448	1.4%
Formwork	1602	6.8%	Formwork	24	0.1%
Structural Steelwork			Structural Steelwork	14854	47.3%
Steel Decking			Steel Decking	3721	11.9%
Fire Protection			Fire Protection	4623	14.7%

Figure 14: M4 7 Steel and Concrete Embodied CO_2 Comparison, Standard Data



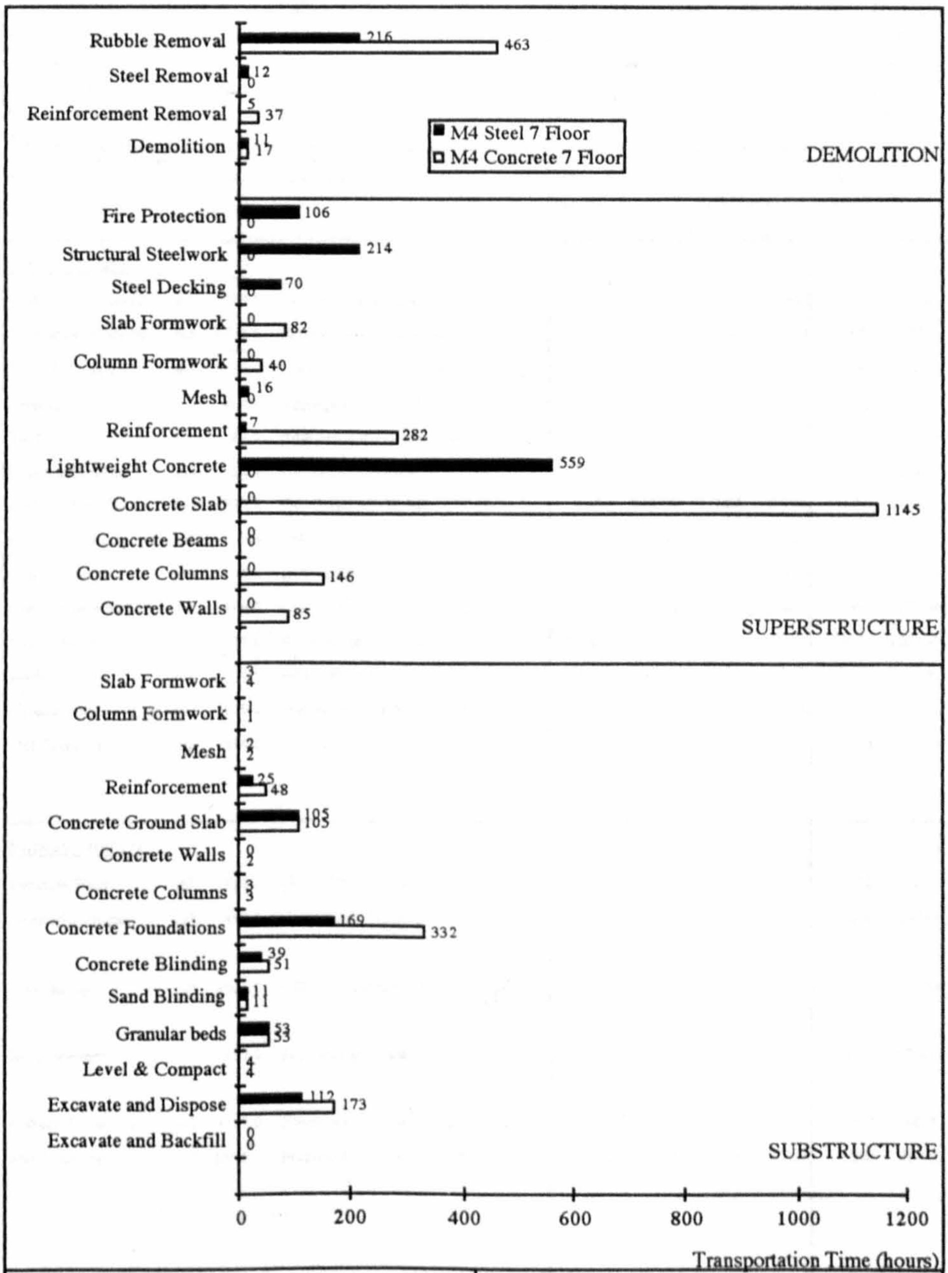
M4 Concrete 7 Floor	2974435 kg		M4 Steel 7 Floor	2744632 kg	
	263.81 kg/m2			243.43 kg/m2	
Section Total	kg		Section Total	kg	
Substructure	689141	23.2%	Substructure	430610	15.7%
Superstructure	2200660	74.0%	Superstructure	2255542	82.2%
Demolition	84634	2.8%	Demolition	58481	2.1%
Item Total	kg		Item Total	kg	
Standard Concrete	2056888	69.2%	Standard Concrete	361930	13.2%
Lightweight Concrete			Lightweight Concrete	669971	24.4%
Reinforcement	710714	23.9%	Reinforcement	68519	2.5%
Mesh	3590	0.1%	Mesh	33519	1.2%
Formwork	105214	3.5%	Formwork	1129	0.0%
Structural Steelwork			Structural Steelwork	1112388	40.5%
Steel Decking			Steel Decking	291176	10.6%
Fire Protection			Fire Protection	137299	5.0%

Figure 15: M4 7 Floor Steel and Concrete Transportation Distance Comparison, Standard Data



M4 Concrete 7 Floor	68004 miles 6.03 miles/m2		M4 Steel 7 Floor	44260 miles 3.93 miles/m2	
Section Total	miles		Section Total	miles	
Substructure	15122	22.2%	Substructure	10003	22.6%
Superstructure	40231	59.2%	Superstructure	28323	64.0%
Demolition	12651	18.6%	Demolition	5934	13.4%
Item Total	miles		Item Total	miles	
Standard Concrete	35037	51.5%	Standard Concrete	5901	13.3%
Lightweight Concrete			Lightweight Concrete	15164	34.3%
Reinforcement	12003	17.6%	Reinforcement	1157	2.6%
Mesh	71	0.1%	Mesh	659	1.5%
Formwork	4344	6.4%	Formwork	138	0.3%
Structural Steelwork			Structural Steelwork	5395	12.2%
Steel Decking			Steel Decking	2794	6.3%
Fire Protection			Fire Protection	4132	9.3%

Figure 16: M4 7 Floor Steel and Concrete Transportation Time Comparison, Standard Data



M4 Concrete 7 Floor	3086 hours 0.27 hours/m2		M4 Steel 7 Floor	1743 hours 0.15 hours/m2	
Section Total	hours		Section Total	hours	
Substructure	789	25.6%	Substructure	525	30.2%
Superstructure	1781	57.7%	Superstructure	973	55.8%
Demolition	516	16.7%	Demolition	244	14.0%
Item Total	hours		Item Total	hours	
Standard Concrete	1870	60.6%	Standard Concrete	316	18.1%
Lightweight Concrete			Lightweight Concrete	559	32.1%
Reinforcement	330	10.7%	Reinforcement	32	1.8%
Mesh	2	0.1%	Mesh	18	1.0%
Formwork	128	4.1%	Formwork	4	0.2%
Structural Steelwork			Structural Steelwork	214	12.3%
Steel Decking			Steel Decking	70	4.0%
Fire Protection			Fire Protection	106	6.1%

Table 9: M4 Concrete 7 Floor Structure using GGBS Concrete

Summary		M4 Concrete 7 Floor	Notes	GGBS CONCRETE			
Structure Gross Area	m2	11275					
Materials Weight	t	12614	Total	Substructure	Superstructure	Demolition	Total
Embodied Energy	GJ/m2	1.78	GJ	3833	14967	1288	20089
Embodied CO2	kg/m2	186.17	kg	464937	1549474	84634	2099045
Transportation Distance	miles/m2	6.46	miles	16615	43549	12651	72815
Transportation Time	hr/m2	0.29	hr	830	1875	516	3220
Transportation Speed	MPH	22.61					

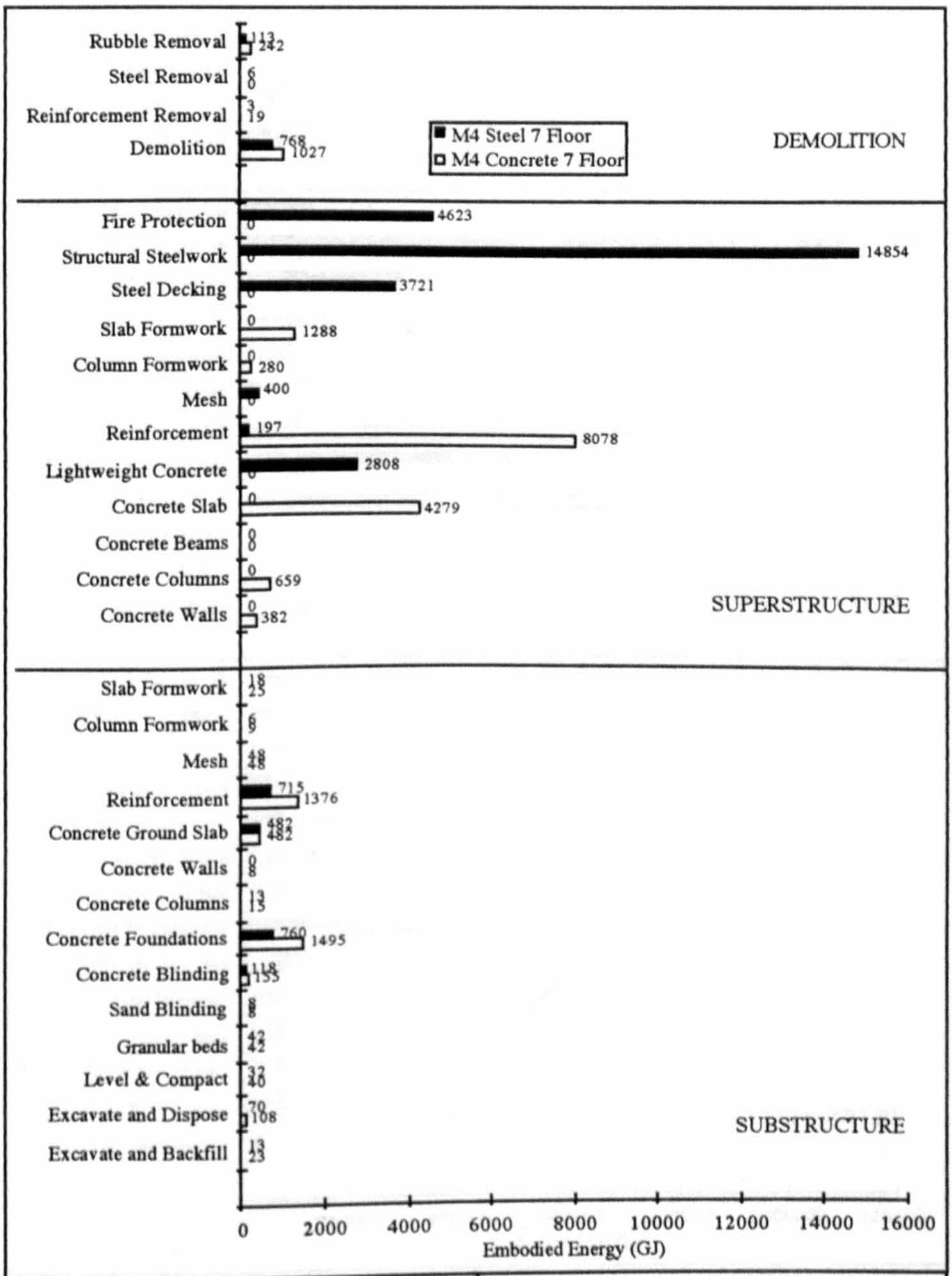
Element	Unit	No.	Rate Selected	Unit Rates				Total Values			
				Energy	CO2	Transportation		Energy	CO2	Transportation	
				GJ/unit	kg/unit	mile/unit	hr/unit	GJ	kg	miles	hours
Substructure											
Excavate and Backfill	m3	400.0	Excavation and Backfill (SEEAM)	0.058	1.16	0.02	0.001	23	466	6	0
Excavate and Dispose	m3	1434.0	Excavation and Disposal (SEEAM)	0.075	4.93	1.80	0.120	108	7073	2588	173
Level & Compact	m2	2189.0	Level & Compact (SEEAM)	0.018	1.20	0.02	0.002	40	2618	44	4
Granular beds	t	447.0	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	42	2699	1052	53
Sand Blinding	t	89.3	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	8	539	210	11
Concrete Blinding	m3	134.4	C20 GGBS (SEEAM)	1.153	174.54	7.54	0.395	155	23463	1014	53
Concrete Foundations	m3	923.0	C40 GGBS (SEEAM)	1.620	258.56	7.84	0.390	1495	238650	7232	360
Concrete Columns	m3	9.0	C40 GGBS (SEEAM)	1.620	258.56	7.84	0.390	15	2327	71	4
Concrete Walls	m3	5.0	C40 GGBS (SEEAM)	1.620	258.56	7.84	0.390	8	1293	39	2
Concrete Ground Slab	m3	284.0	C40 GGBS Pump (SEEAM)	1.697	271.72	8.26	0.406	482	77169	2347	115
Reinforcement	t	77.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	1376	103450	1747	48
Mesh	t	2.6	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	48	3590	71	2
Column Formwork	m2	170.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	9	472	44	1
Slab Formwork	m2	580.0	Formwork (Flat Slab)(SEEAM/OB)	0.043	1.95	0.26	0.007	25	1129	152	4
Superstructure											
Concrete Walls	m3	236.0	C40 GGBS (SEEAM)	1.620	258.56	7.84	0.390	382	61020	1849	92
Concrete Columns	m3	407.0	C40 GGBS (SEEAM)	1.620	258.56	7.84	0.390	659	105233	3189	159
Concrete Slab	m3	3036.0	C30 GGBS Pump (SEEAM)	1.409	221.46	7.94	0.402	4279	672344	24107	1219
Reinforcement	t	452.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	8078	607264	10256	282
Column Formwork	m2	5362.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	280	14891	1377	40
Slab Formwork	m2	9920.0	Formwork (Shaped Soffit)(SEEAM/OB)	0.130	8.94	0.28	0.008	1288	88722	2772	82
Demolition											
Demolition	m2	11275	Demolition (Concrete)(SEEAM)	0.091	5.98	0.01	0.001	1027	67461	167	17
ReBar Removal	t	532	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	19	1257	914	37
Rubble Removal	t	6732	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	242	15916	11570	463
Base Data											
Cement	t			5.800	1193.00	3.29	0.088				
GGBS	t			1.450	78.09	8.40	0.224				
PFA	t			0.339	20.86	8.40	0.224				
Lytag	t			0.920	58.27	12.35	0.329				
Aggregates	t			0.093	6.04	2.35	0.118				

Table 10: M4 Steel 7 Floor Structure using GGBS Concrete

Summary		M4 Steel 7 Floor	Notes	GGBS CONCRETE			
Structure Gross Area	m2	11275					
Materials Weight	t	5142	Total	Substructure	Superstructure	Demolition	Total
Embodied Energy	GJ/m2	2.64	GJ	2325	26602	890	29817
Embodied CO2	kg/m2	205.64	kg	287081	1973015	58481	2318576
Transportation Distance	miles/m2	4.22	miles	10960	30731	5934	47624
Transportation Time	hr/m2	0.16	hr	552	1037	244	1833
Transportation Speed	MPH	25.98					

Element	Unit	No.	Rate Selected	Unit Rates				Total Values			
				Energy	CO2	Transportation		Energy	CO2	Transportation	
				GJ/unit	kg/unit	mile/unit	hr/unit	GJ	kg	miles	hours
Substructure											
Excavate and Backfill	m3	229.0	Excavation and Backfill (SEEAM)	0.058	1.16	0.02	0.001	13	267	4	0
Excavate and Dispose	m3	934.0	Excavation and Disposal (SEEAM)	0.075	4.93	1.80	0.120	70	4607	1685	112
Level & Compact	m2	1764.0	Level & Compact (SEEAM)	0.018	1.20	0.02	0.002	32	2110	35	4
Granular beds	t	447.0	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	42	2699	1052	53
Sand Blinding	t	89.3	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	8	539	210	11
Concrete Blinding	m3	102.6	C20 GGBS (SEEAM)	1.153	174.54	7.54	0.395	118	17899	774	41
Concrete Foundations	m3	469.0	C40 GGBS (SEEAM)	1.620	258.56	7.84	0.390	760	121264	3675	183
Concrete Columns	m3	8.0	C40 GGBS (SEEAM)	1.620	258.56	7.84	0.390	13	2068	63	3
Concrete Ground Slab	m3	284.0	C40 GGBS Pump (SEEAM)	1.697	271.72	8.26	0.406	482	77169	2347	115
Reinforcement	t	40.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	715	53740	908	25
Mesh	t	2.6	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	48	3590	71	2
Column Formwork	m2	119.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	6	330	31	1
Slab Formwork	m2	410.0	Formwork (Flat Slab)(SEEAM/OB)	0.043	1.95	0.26	0.007	18	798	107	3
Superstructure											
Lightweight Concrete	m3	1240.0	C30 Lytag GGBS Pump (SEEAM)	2.264	312.46	14.17	0.503	2808	387444	17572	624
Reinforcement	t	11.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	197	14779	250	7
Mesh	t	22.0	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	400	29929	588	16
Steel Decking	m2	9920.0	Steel Decking (SEEAM/OB)	0.375	29.35	0.28	0.007	3721	291176	2794	70
Steelwork	t	534.0	Structural Steel (Short) (SEEAM/OB)	27.816	2083.12	10.10	0.401	14854	1112388	5395	214
Fire Protection	m2	8355.0	Fire Protection (18mm Vicuclad) (SEEA	0.553	16.43	0.49	0.013	4623	137299	4132	106
Demolition											
Demolition	m2	11275	Demolition (Steel)(SEEAM)	0.068	4.47	0.01	0.001	768	50451	111	11
ReBar Removal	t	76	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	3	179	130	5
Steel Removal	t	534	Steel Transport (Demolished)(SEEAM)	0.012	0.79	0.55	0.022	6	421	291	12
Rubble Removal	t	3143	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	113	7430	5401	216
Base Data											
Cement	t			5.800	1193.00	3.29	0.088				
GGBS	t			1.450	78.09	8.40	0.224				
PFA	t			0.339	20.86	8.40	0.224				
Lytag	t			0.920	58.27	12.35	0.329				
Aggregates	t			0.093	6.04	2.35	0.118				

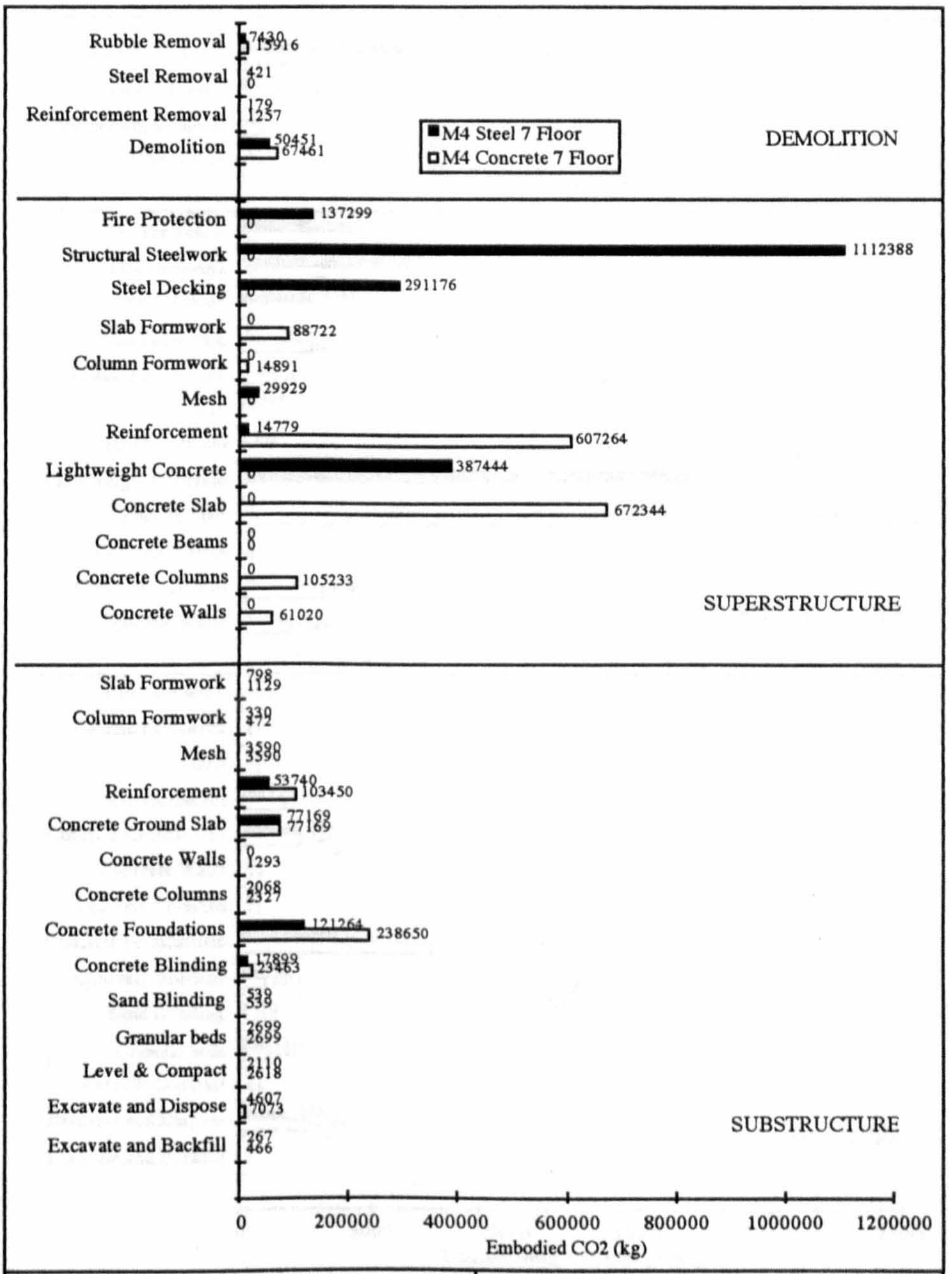
Figure 17: M4 7 Floor Steel and Concrete Embodied Energy Comparison, GGBS Concrete



M4 Concrete 7 Floor	20089 GJ 1.78 GJ/m2	
Section Total	GJ	
Substructure	3833	19.1%
Superstructure	14967	74.5%
Demolition	1288	6.4%
Item Total	GJ	
Standard Concrete	7476	37.2%
Lightweight Concrete	0	0.0%
Reinforcement	9454	47.1%
Mesh	48	0.2%
Formwork	1602	8.0%
Structural Steelwork	0	0.0%
Steel Decking	0	0.0%
Fire Protection	0	0.0%

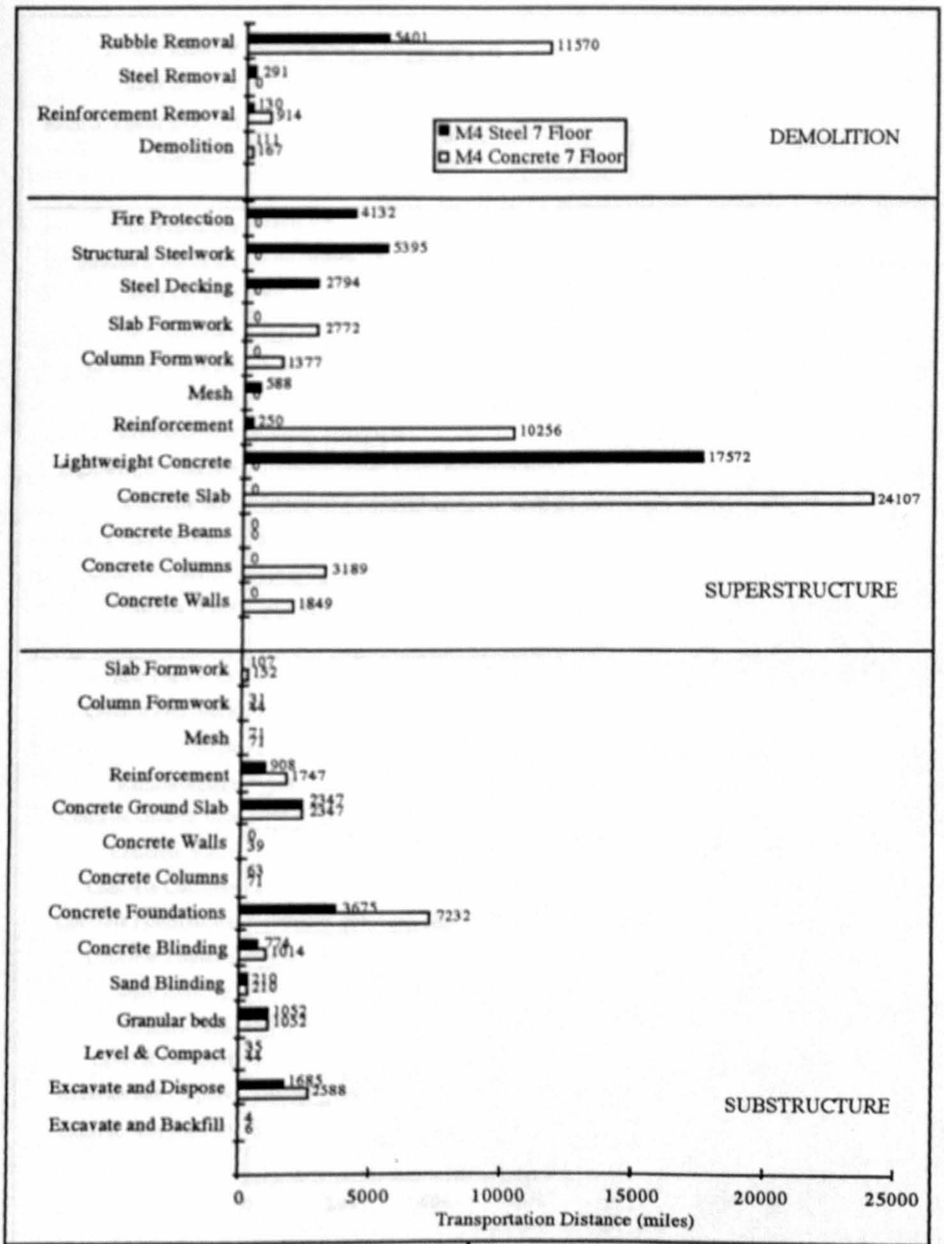
M4 Steel 7 Floor	29817 GJ 2.64 GJ/m2	
Section Total	GJ	
Substructure	2325	7.8%
Superstructure	26602	89.2%
Demolition	890	3.0%
Item Total	GJ	
Standard Concrete	1373	4.6%
Lightweight Concrete	2808	9.4%
Reinforcement	911	3.1%
Mesh	448	1.5%
Formwork	24	0.1%
Structural Steelwork	14854	49.8%
Steel Decking	3721	12.5%
Fire Protection	4623	15.5%

Figure 18: M4 7 Steel and Concrete Embodied CO_2 Comparison, GGBS Concrete



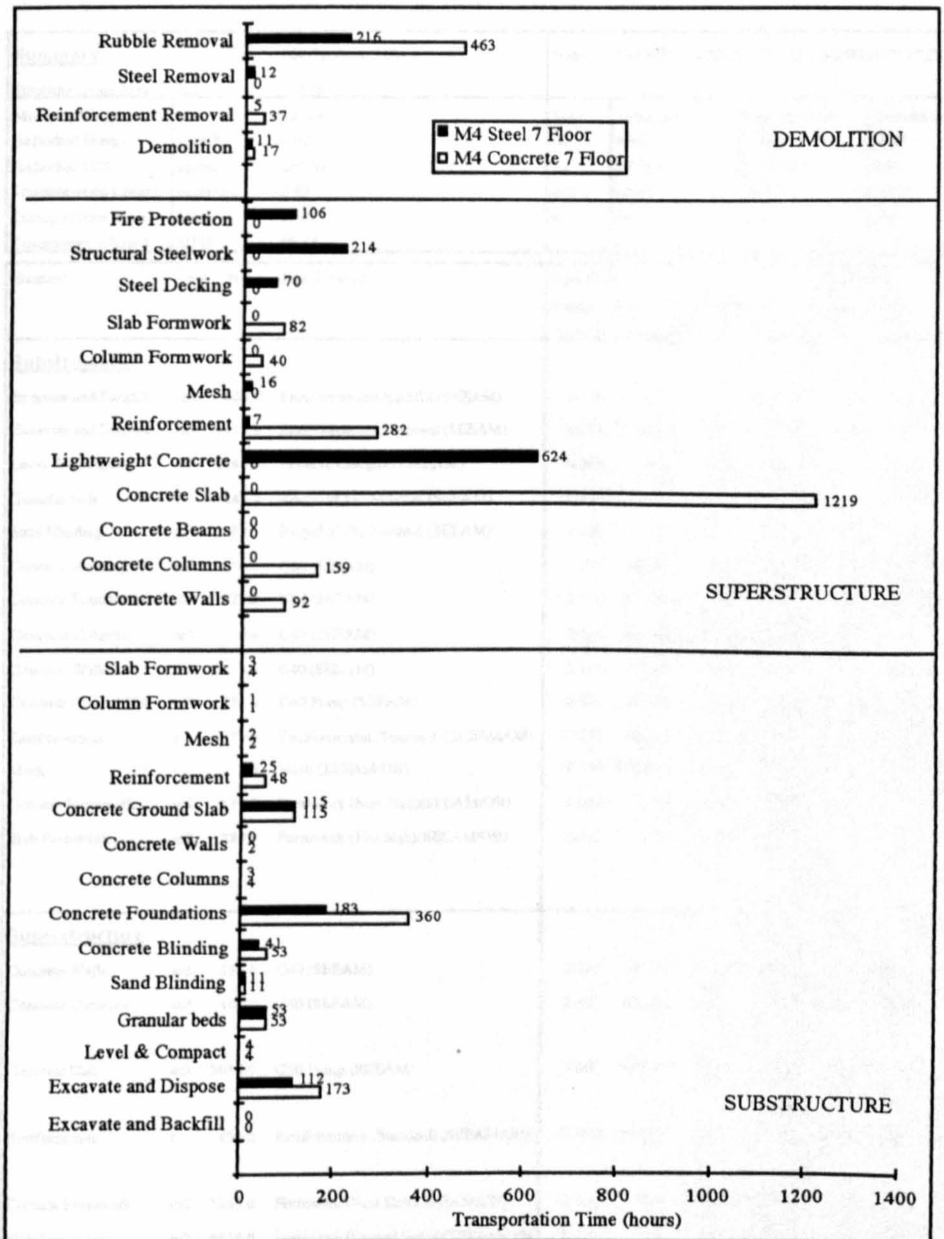
M4 Concrete 7 Floor	2099045 kg 186.17 kg/m2		M4 Steel 7 Floor	2318576 kg 205.64 kg/m2	
Section Total	kg		Section Total	kg	
Substructure	464937	22.1%	Substructure	287081	12.4%
Superstructure	1549474	73.8%	Superstructure	1973015	85.1%
Demolition	84634	4.0%	Demolition	58481	2.5%
Item Total	kg		Item Total	kg	
Standard Concrete	1181498	56.3%	Standard Concrete	218400	9.4%
Lightweight Concrete	0	0.0%	Lightweight Concrete	387444	16.7%
Reinforcement	710714	33.9%	Reinforcement	68519	3.0%
Mesh	3590	0.2%	Mesh	33519	1.4%
Formwork	105214	5.0%	Formwork	1129	0.0%
Structural Steelwork	0	0.0%	Structural Steelwork	1112388	48.0%
Steel Decking	0	0.0%	Steel Decking	291176	12.6%
Fire Protection	0	0.0%	Fire Protection	137299	5.9%

Figure 19: M4 7 Floor Steel and Concrete Transportation Distance Comparison, GGBS Concrete



M4 Concrete 7 Floor	72815 miles 6.46 miles/m2		M4 Steel 7 Floor	47624 miles 4.22 miles/m2	
Section Total	miles		Section Total	miles	
Substructure	16615	22.8%	Substructure	10960	23.0%
Superstructure	43549	59.8%	Superstructure	30731	64.5%
Demolition	12651	17.4%	Demolition	5934	12.5%
Item Total	miles		Item Total	miles	
Standard Concrete	39847	54.7%	Standard Concrete	6858	14.4%
Lightweight Concrete	0	0.0%	Lightweight Concrete	17572	36.9%
Reinforcement	12003	16.5%	Reinforcement	1157	2.4%
Mesh	71	0.1%	Mesh	659	1.4%
Formwork	4344	6.0%	Formwork	138	0.3%
Structural Steelwork	0	0.0%	Structural Steelwork	5395	11.3%
Steel Decking	0	0.0%	Steel Decking	2794	5.9%
Fire Protection	0	0.0%	Fire Protection	4132	8.7%

Figure 20: M4 7 Floor Steel and Concrete Transportation Time Comparison, GGBS Concrete



M4 Concrete 7 Floor	3220 hours 0.29 hours/m2		M4 Steel 7 Floor	1833 hours 0.16 hours/m2	
Section Total	hours		Section Total	hours	
Substructure	830	25.8%	Substructure	552	30.1%
Superstructure	1875	58.2%	Superstructure	1037	56.6%
Demolition	516	16.0%	Demolition	244	13.3%
Item Total	hours		Item Total	hours	
Standard Concrete	2004	62.2%	Standard Concrete	342	18.6%
Lightweight Concrete	0	0.0%	Lightweight Concrete	624	34.0%
Reinforcement	330	10.3%	Reinforcement	32	1.7%
Mesh	2	0.1%	Mesh	18	1.0%
Formwork	128	4.0%	Formwork	4	0.2%
Structural Steelwork	0	0.0%	Structural Steelwork	214	11.7%
Steel Decking	0	0.0%	Steel Decking	70	3.8%
Fire Protection	0	0.0%	Fire Protection	106	5.8%

Table 11: M4 Concrete 7 Floor Structure using On Site Batching and Recycling

Summary		M4 Concrete 7 Floor	Notes	ON SITE BATCHING AND AGGREGATE PRODUCTION			
Structure Gross Area	m2	11275					
Materials Weight	t	12614	Total	Substructure	Superstructure	Demolition	Total
Embodied Energy	GJ/m2	2.02	GJ	4466	17077	1288	22831
Embodied CO2	kg/m2	260.42	kg	677218	2174355	84634	2936206
Transportation Distance	miles/m2	3.49	miles	6552	20151	12651	39354
Transportation Time	hr/m2	0.12	hr	285	578	516	1379
Transportation Speed	MPH	28.54					

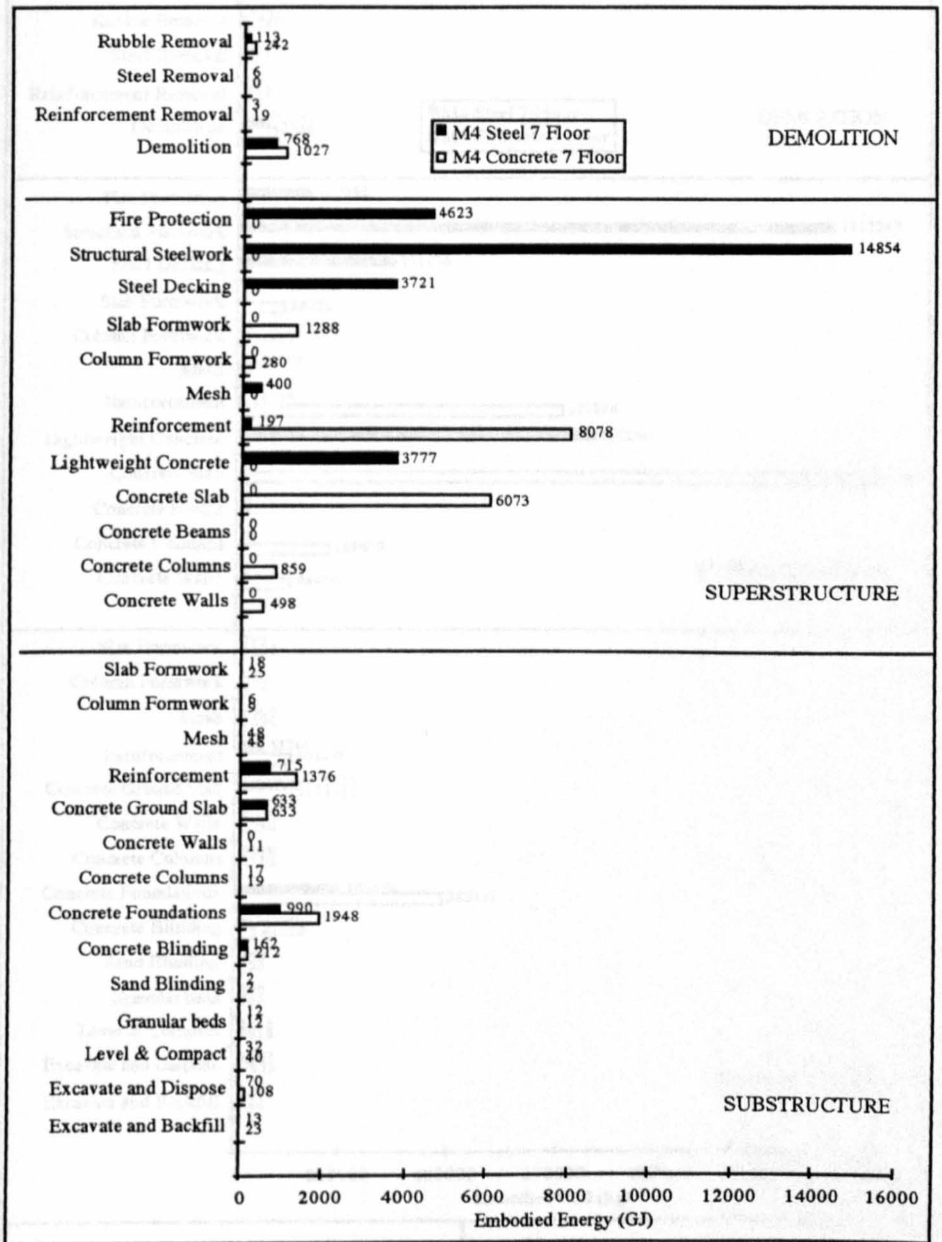
Element	Unit	No.	Rate Selected	Unit Rates				Total Values			
				Energy	CO2	Transportation		Energy	CO2	Transportation	
				GJ/unit	kg/unit	mile/unit	hr/unit	GJ	kg	miles	hours
Substructure											
Excavate and Backfill	m3	400.0	Excavation and Backfill (SEEAM)	0.058	1.16	0.02	0.001	23	466	6	0
Excavate and Dispose	m3	1434.0	Excavation and Disposal (SEEAM)	0.075	4.93	1.80	0.120	108	7073	2588	173
Level & Compact	m2	2189.0	Level & Compact (SEEAM)	0.018	1.20	0.02	0.002	40	2618	44	4
Granular beds	t	447.0	Recycled Fill Material (SEEAM)	0.026	1.71			12	766		
Sand Blinding	t	89.3	Recycled Fill Material (SEEAM)	0.026	1.71			2	153		
Concrete Blinding	m3	134.4	C20 (SEEAM)	1.577	305.97	1.05	0.027	212	41130	140	4
Concrete Foundations	m3	923.0	C40 (SEEAM)	2.111	417.24	1.35	0.036	1948	385117	1248	33
Concrete Columns	m3	9.0	C40 (SEEAM)	2.111	417.24	1.35	0.036	19	3755	12	0
Concrete Walls	m3	5.0	C40 (SEEAM)	2.111	417.24	1.35	0.036	11	2086	7	0
Concrete Ground Slab	m3	284.0	C40 Pump (SEEAM)	2.231	441.60	1.74	0.053	633	125413	494	15
Reinforcement	t	77.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	1376	103450	1747	48
Mesh	t	2.6	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	48	3590	71	2
Column Formwork	m2	170.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	9	472	44	1
Slab Formwork	m2	580.0	Formwork (Flat Slab)(SEEAM/OB)	0.043	1.95	0.26	0.007	25	1129	152	4
Superstructure											
Concrete Walls	m3	236.0	C40 (SEEAM)	2.111	417.24	1.35	0.036	498	98470	319	8
Concrete Columns	m3	407.0	C40 (SEEAM)	2.111	417.24	1.35	0.036	859	169819	550	14
Concrete Slab	m3	3036.0	C30 Pump (SEEAM)	2.000	393.67	1.61	0.050	6073	1195190	4877	150
Reinforcement	t	452.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	8078	607264	10256	282
Column Formwork	m2	5362.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	280	14891	1377	40
Slab Formwork	m2	9920.0	Formwork (Shaped Soffit)(SEEAM/OB)	0.130	8.94	0.28	0.008	1288	88722	2772	82
Demolition											
Demolition	m2	11275	Demolition (Concrete)(SEEAM)	0.091	5.98	0.01	0.001	1027	67461	167	17
ReBar Removal	t	532	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	19	1257	914	37
Rubble Removal	t	6732	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	242	15916	11570	463
Base Data											
Cement	t			5.800	1193.00	3.29	0.088				
GGBS	t			1.450	78.09	8.40	0.224				
PFA	t			0.339	20.86	8.40	0.224				
Lytag	t			0.920	58.27	12.35	0.329				
Aggregates	t			0.047	3.08						

Table 12: M4 Steel 7 Floor Structure using On Site Batching and Recycling

Summary		M4 Steel 7 Floor	Notes	ON SITE BATCHING AND AGGREGATE PRODUCTION			
Structure Gross Area	m2	11275					
Materials Weight	t	5142	Total	Substructure	Superstructure	Demolition	Total
Embodied Energy	GJ/m2	2.77	GJ	2718	27571	890	31180
Embodied CO2	kg/m2	242.27	kg	422177	2250887	58481	2731544
Transportation Distance	miles/m2	3.10	miles	4086	24903	5934	34923
Transportation Time	hr/m2	0.10	hr	182	735	244	1161
Transportation Speed	MPH	30.08					

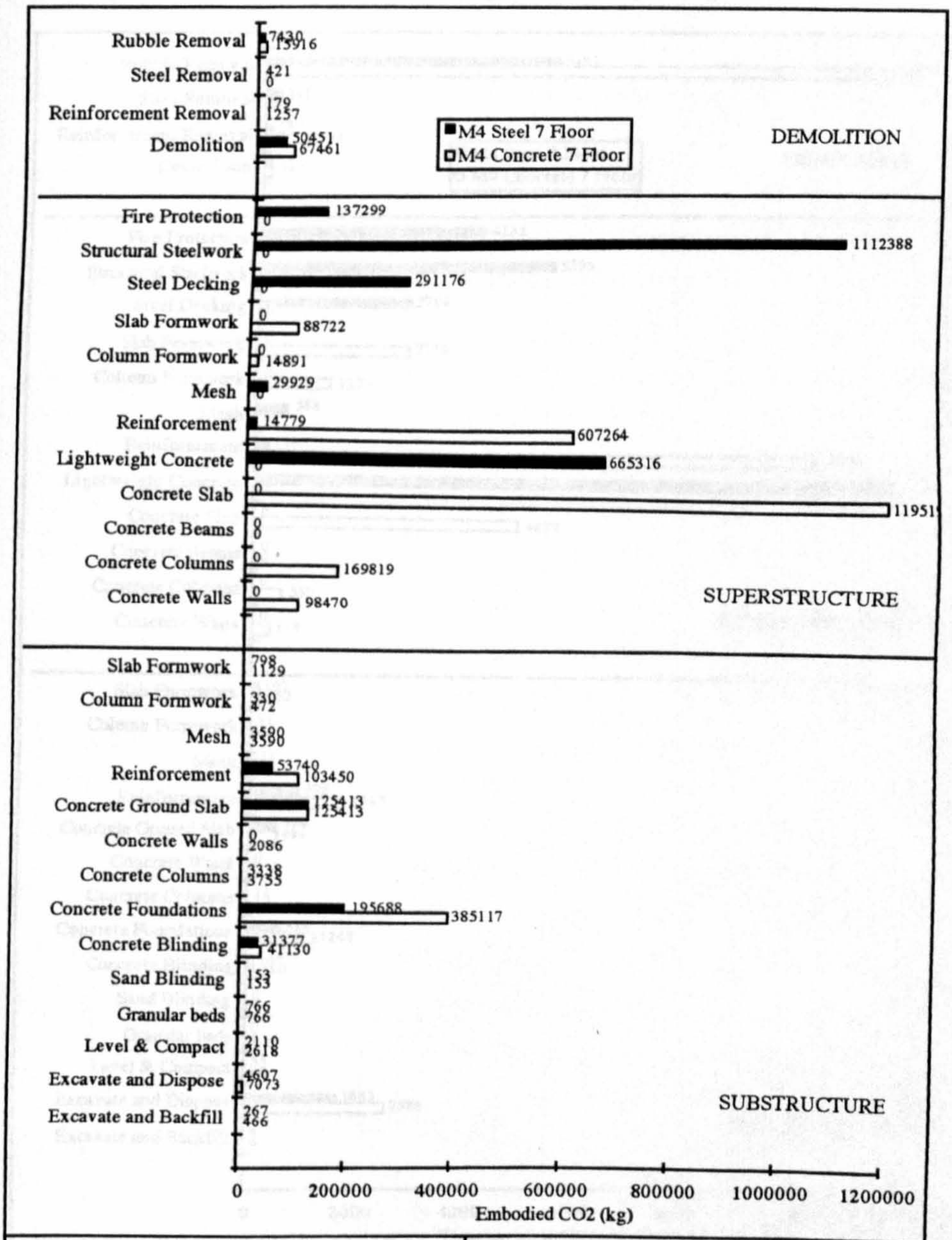
Element	Unit	No.	Rate Selected	Unit Rates				Total Values			
				Energy	CO2	Transportation		Energy	CO2	Transportation	
				GJ/unit	kg/unit	mile/unit	hr/unit	GJ	kg	miles	hours
Substructure											
Excavate and Backfill	m3	229.0	Excavation and Backfill (SEEAM)	0.058	1.16	0.02	0.001	13	267	4	0
Excavate and Dispose	m3	934.0	Excavation and Disposal (SEEAM)	0.075	4.93	1.80	0.120	70	4607	1685	112
Level & Compact	m2	1764.0	Level & Compact (SEEAM)	0.018	1.20	0.02	0.002	32	2110	35	4
Granular beds	t	447.0	Recycled Fill Material (SEEAM)	0.026	1.71			12	766		
Sand Blinding	t	89.3	Recycled Fill Material (SEEAM)	0.026	1.71			2	153		
Concrete Blinding	m3	102.6	C20 (SEEAM)	1.577	305.97	1.05	0.027	162	31377	107	3
Concrete Foundations	m3	469.0	C40 (SEEAM)	2.111	417.24	1.35	0.036	990	195688	634	17
Concrete Columns	m3	8.0	C40 (SEEAM)	2.111	417.24	1.35	0.036	17	3338	11	0
Concrete Ground Slab	m3	284.0	C40 Pump (SEEAM)	2.231	441.60	1.74	0.053	633	125413	494	15
Reinforcement	t	40.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	715	53740	908	25
Mesh	t	2.6	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	48	3590	71	2
Column Formwork	m2	119.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	6	330	31	1
Slab Formwork	m2	410.0	Formwork (Flat Slab)(SEEAM/OB)	0.043	1.95	0.26	0.007	18	798	107	3
Superstructure											
Lightweight Concrete	m3	1240.0	C30 Lytag Pump (SEEAM)	3.046	536.55	9.47	0.259	3777	665316	11744	321
Reinforcement	t	11.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	197	14779	250	7
Mesh	t	22.0	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	400	29929	588	16
Steel Decking	m2	9920.0	Steel Decking (SEEAM/OB)	0.375	29.35	0.28	0.007	3721	291176	2794	70
Steelwork	t	534.0	Structural Steel (Short) (SEEAM/OB)	27.816	2083.12	10.10	0.401	14854	1112388	5395	214
Fire Protection	m2	8355.0	Fire Protection (18mm Vicuclad) (SEEA	0.553	16.43	0.49	0.013	4623	137299	4132	106
Demolition											
Demolition	m2	11275	Demolition (Steel)(SEEAM)	0.068	4.47	0.01	0.001	768	50451	111	11
ReBar Removal	t	76	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	3	179	130	5
Steel Removal	t	534	Steel Transport (Demolished)(SEEAM)	0.012	0.79	0.55	0.022	6	421	291	12
Rubble Removal	t	3143	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	113	7430	5401	216
Base Data											
Cement	t			5.800	1193.00	3.29	0.088				
GGBS	t			1.450	78.09	8.40	0.224				
PFA	t			0.339	20.86	8.40	0.224				
Lytag	t			0.920	58.27	12.35	0.329				
Aggregates	t			0.047	3.08						

Figure 21: M4 7 Floor Steel and Concrete Embodied Energy Comparison, On Site Batching and Recycling



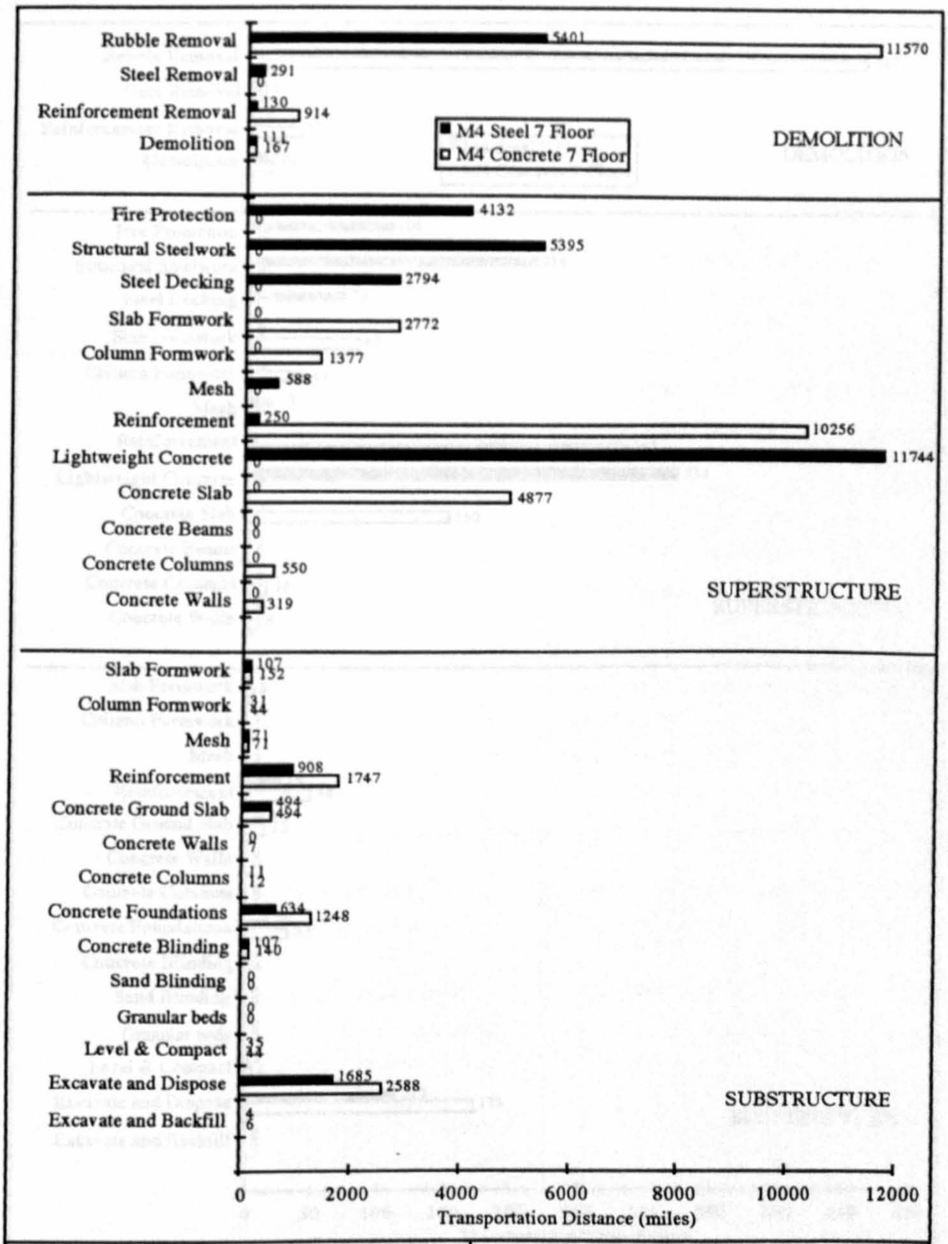
M4 Concrete 7 Floor	22831 GJ		M4 Steel 7 Floor	31180 GJ	
	2.02 GJ/m2			2.77 GJ/m2	
Section Total	GJ		Section Total	GJ	
Substructure	4466	19.6%	Substructure	2718	8.7%
Superstructure	17077	74.8%	Superstructure	27571	88.4%
Demolition	1288	5.6%	Demolition	890	2.9%
Item Total	GJ		Item Total	GJ	
Standard Concrete	10254	44.9%	Standard Concrete	1802	5.8%
Lightweight Concrete	0	0.0%	Lightweight Concrete	3777	12.1%
Reinforcement	9454	41.4%	Reinforcement	911	2.9%
Mesh	48	0.2%	Mesh	448	1.4%
Formwork	1602	7.0%	Formwork	24	0.1%
Structural Steelwork	0	0.0%	Structural Steelwork	14854	47.6%
Steel Decking	0	0.0%	Steel Decking	3721	11.9%
Fire Protection	0	0.0%	Fire Protection	4623	14.8%

Figure 22: M4 7 Steel and Concrete Embodied CO_2 Comparison, On Site Batching and Recycling



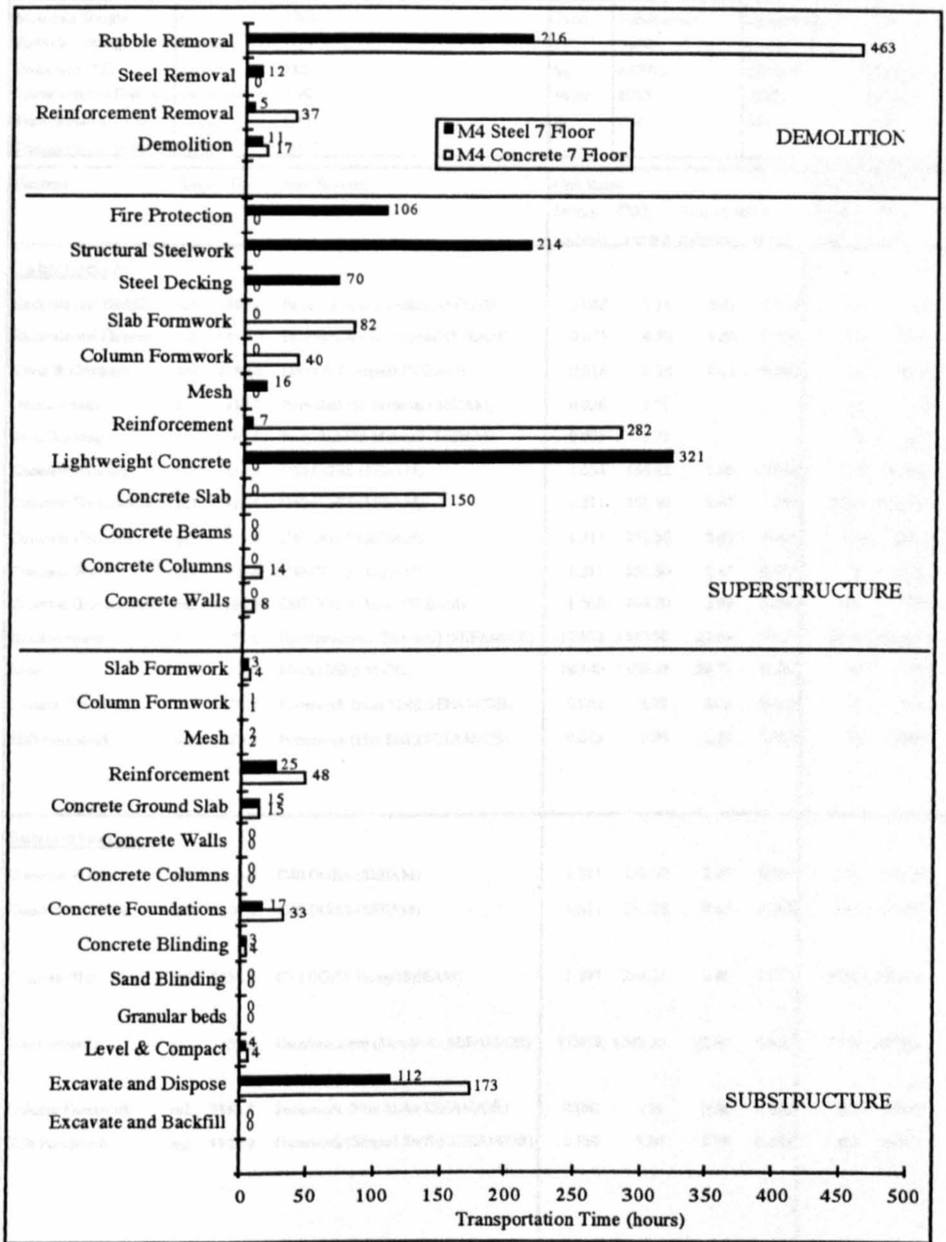
M4 Concrete 7 Floor	2936206 kg 260.42 kg/m2		M4 Steel 7 Floor	2731544 kg 242.27 kg/m2	
Section Total	kg		Section Total	kg	
Substructure	677218	23.1%	Substructure	422177	15.5%
Superstructure	2174355	74.1%	Superstructure	2250887	82.4%
Demolition	84634	2.9%	Demolition	58481	2.1%
Item Total	kg		Item Total	kg	
Standard Concrete	2020979	68.8%	Standard Concrete	355816	13.0%
Lightweight Concrete	0	0.0%	Lightweight Concrete	665316	24.4%
Reinforcement	710714	24.2%	Reinforcement	68519	2.5%
Mesh	3590	0.1%	Mesh	33519	1.2%
Formwork	105214	3.6%	Formwork	1129	0.0%
Structural Steelwork	0	0.0%	Structural Steelwork	1112388	40.7%
Steel Decking	0	0.0%	Steel Decking	291176	10.7%
Fire Protection	0	0.0%	Fire Protection	137299	5.0%

Figure 23: M4 7 Floor Steel and Concrete Transportation Distance Comparison, On Site Batching and Recycling



M4 Concrete 7 Floor	39354 miles		M4 Steel 7 Floor	34923 miles	
	3.49 miles/m2			3.10 miles/m2	
Section Total	miles		Section Total	miles	
Substructure	6552	16.6%	Substructure	4086	11.7%
Superstructure	20151	51.2%	Superstructure	24903	71.3%
Demolition	12651	32.1%	Demolition	5934	17.0%
Item Total	miles		Item Total	miles	
Standard Concrete	7648	19.4%	Standard Concrete	1246	3.6%
Lightweight Concrete	0	0.0%	Lightweight Concrete	11744	33.6%
Reinforcement	12003	30.5%	Reinforcement	1157	3.3%
Mesh	71	0.2%	Mesh	659	1.9%
Formwork	4344	11.0%	Formwork	138	0.4%
Structural Steelwork	0	0.0%	Structural Steelwork	5395	15.4%
Steel Decking	0	0.0%	Steel Decking	2794	8.0%
Fire Protection	0	0.0%	Fire Protection	4132	11.8%

Figure 24: M4 7 Floor Steel and Concrete Transportation Time Comparison, On Site Batching and Recycling



M4 Concrete 7 Floor	1379 hours 0.12 hours/m2		M4 Steel 7 Floor	1161 hours 0.10 hours/m2	
Section Total	hours		Section Total	hours	
Substructure	285	20.7%	Substructure	182	15.7%
Superstructure	578	41.9%	Superstructure	735	63.3%
Demolition	516	37.4%	Demolition	244	21.0%
Item Total	hours		Item Total	hours	
Standard Concrete	225	16.3%	Standard Concrete	35	3.0%
Lightweight Concrete	0	0.0%	Lightweight Concrete	321	27.7%
Reinforcement	330	24.0%	Reinforcement	32	2.7%
Mesh	2	0.1%	Mesh	18	1.6%
Formwork	128	9.3%	Formwork	4	0.3%
Structural Steelwork	0	0.0%	Structural Steelwork	214	18.5%
Steel Decking	0	0.0%	Steel Decking	70	6.0%
Fire Protection	0	0.0%	Fire Protection	106	9.2%

Table 13: M4 Concrete 7 Floor Structure using Lowest Reasonable Values

Summary		M4 Concrete 7 Floor	Notes	ON SITE BATCHING AND AGGREGATE PRODUCTION, GGBS CONCRETE				
Structure Gross Area	m2	11275						
Materials Weight	t	12614	Total	Substructure	Superstructure	Demolition	Total	
Embodied Energy	GJ/m2	1.73	GJ	3648	14556	1288	19492	
Embodied CO2	kg/m2	182.75	kg	452973	1522921	84634	2060528	
Transportation Distance	miles/m2	3.90	miles	8013	23275	12651	43938	
Transportation Time	hr/m2	0.13	hr	324	661	516	1501	
Transportation Speed	MPH	29.27						

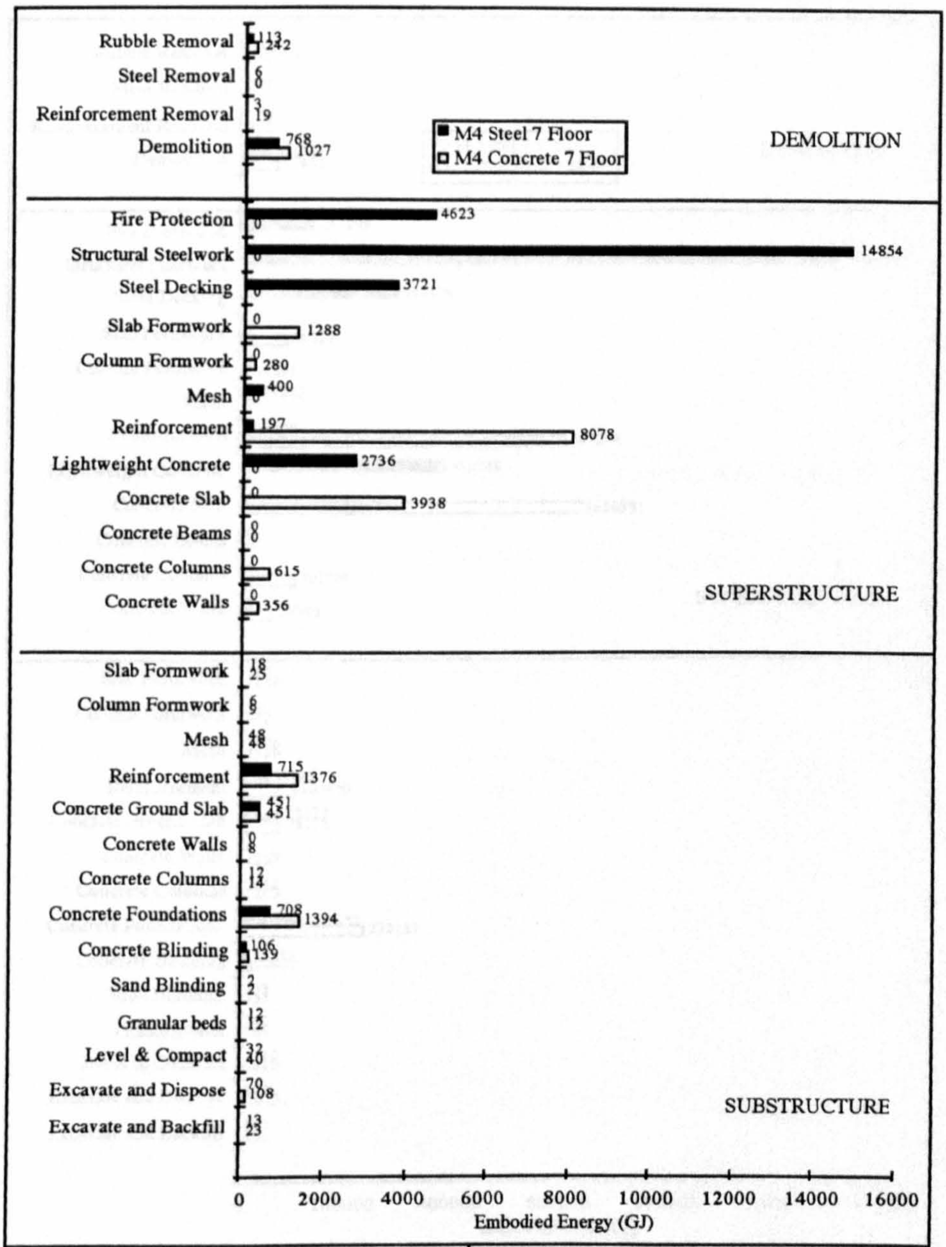
Element	Unit	No.	Rate Selected	Unit Rates				Total Values			
				Energy	CO2	Transportation		Energy	CO2	Transportation	
				GJ/unit	kg/unit	mile/unit	hr/unit	GJ	kg	miles	hours
Substructure											
Excavate and Backfill	m3	400.0	Excavation and Backfill (SEEAM)	0.058	1.16	0.02	0.001	23	466	6	0
Excavate and Dispose	m3	1434.0	Excavation and Disposal (SEEAM)	0.075	4.93	1.80	0.120	108	7073	2588	173
Level & Compact	m2	2189.0	Level & Compact (SEEAM)	0.018	1.20	0.02	0.002	40	2618	44	4
Granular beds	t	447.0	Recycled Fill Material (SEEAM)	0.026	1.71			12	766		
Sand Blinding	t	89.3	Recycled Fill Material (SEEAM)	0.026	1.71			2	153		
Concrete Blinding	m3	134.4	C20 GGBS (SEEAM)	1.034	166.85	1.68	0.044	139	22429	226	6
Concrete Foundations	m3	923.0	C40 GGBS (SEEAM)	1.511	251.50	2.47	0.065	1394	232132	2276	60
Concrete Columns	m3	9.0	C40 GGBS (SEEAM)	1.511	251.50	2.47	0.065	14	2263	22	1
Concrete Walls	m3	5.0	C40 GGBS (SEEAM)	1.511	251.50	2.47	0.065	8	1257	12	0
Concrete Ground Slab	m3	284.0	C40 GGBS Pump (SEEAM)	1.588	264.70	2.90	0.084	451	75175	825	24
Reinforcement	t	77.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	1376	103450	1747	48
Mesh	t	2.6	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	48	3590	71	2
Column Formwork	m2	170.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	9	472	44	1
Slab Formwork	m2	580.0	Formwork (Flat Slab)(SEEAM/OB)	0.043	1.95	0.26	0.007	25	1129	152	4
Superstructure											
Concrete Walls	m3	236.0	C40 GGBS (SEEAM)	1.511	251.50	2.47	0.065	356	59353	582	15
Concrete Columns	m3	407.0	C40 GGBS (SEEAM)	1.511	251.50	2.47	0.065	615	102359	1004	27
Concrete Slab	m3	3036.0	C30 GGBS Pump (SEEAM)	1.297	214.21	2.40	0.071	3938	650331	7285	215
Reinforcement	t	452.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	8078	607264	10256	282
Column Formwork	m2	5362.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	280	14891	1377	40
Slab Formwork	m2	9920.0	Formwork (Shaped Soffit)(SEEAM/OB)	0.130	8.94	0.28	0.008	1288	88722	2772	82
Demolition											
Demolition	m2	11275	Demolition (Concrete)(SEEAM)	0.091	5.98	0.01	0.001	1027	67461	167	17
ReBar Removal	t	532	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	19	1257	914	37
Rubble Removal	t	6732	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	242	15916	11570	463
Base Data											
Cement	t			5.800	1193.00	3.29	0.088				
GGBS	t			1.450	78.09	8.40	0.224				
PFA	t			0.339	20.86	8.40	0.224				
Lytag	t			0.920	58.27	12.35	0.329				
Aggregates	t			0.047	3.08						

Table 14: M4 Steel 7 Floor Structure using Lowest Reasonable Values

Summary		M4 Steel 7 Floor	Notes	ON SITE BATCHING AND AGGREGATE PRODUCTION, GGBS CONCRETE			
Structure Gross Area	m2	11275					
Materials Weight	t	5142	Total	Substructure	Superstructure	Demolition	Total
Embodied Energy	GJ/m2	2.63	GJ	2194	26530	890	29614
Embodied CO2	kg/m2	204.47	kg	278610	1968360	58481	2305451
Transportation Distance	miles/m2	3.39	miles	5014	27310	5934	38258
Transportation Time	hr/m2	0.11	hr	206	799	244	1250
Transportation Speed	MPH	30.61					

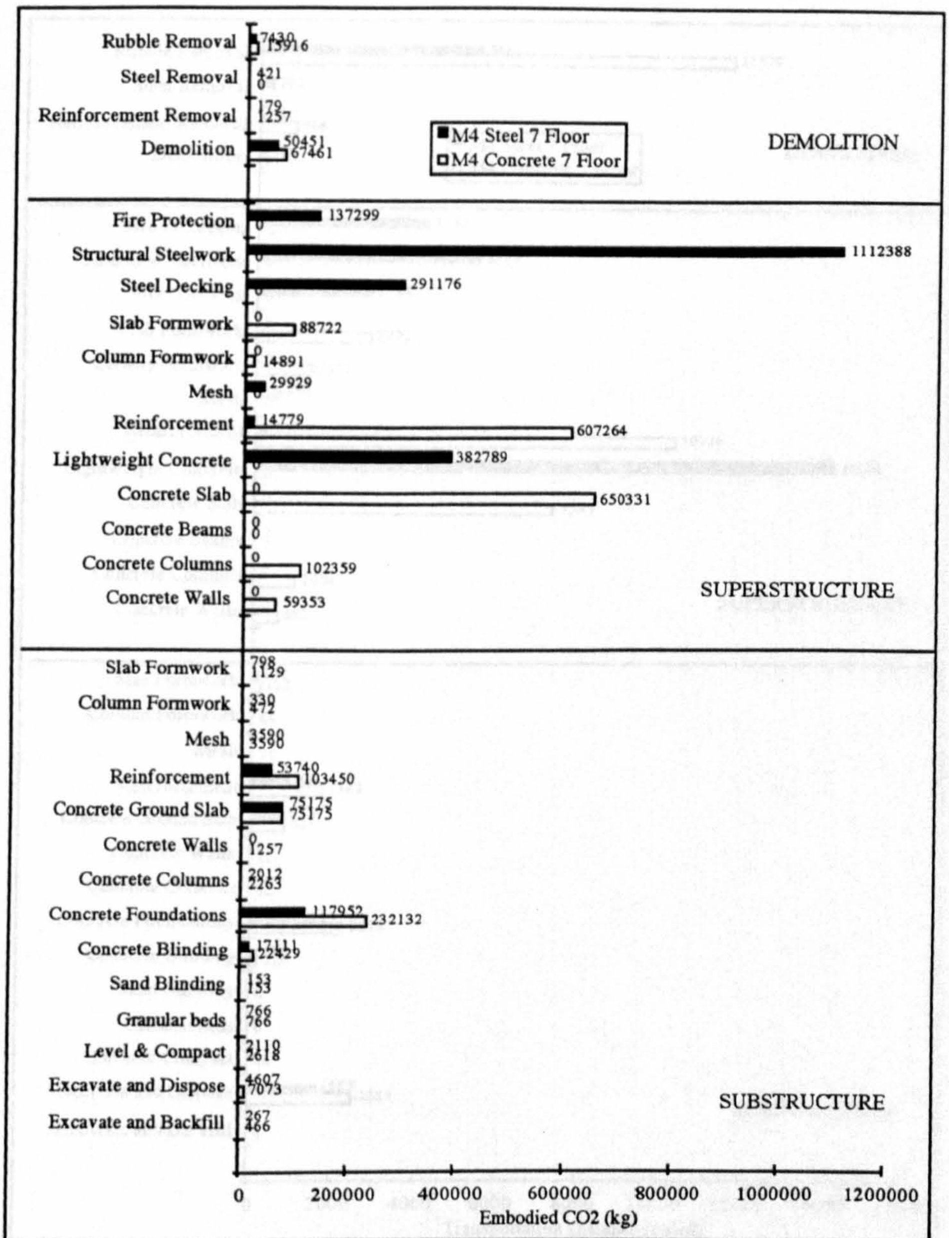
Element	Unit	No.	Rate Selected	Unit Rates				Total Values			
				Energy	CO2	Transportation		Energy	CO2	Transportation	
				GJ/unit	kg/unit	mile/unit	hr/unit	GJ	kg	miles	hours
Substructure											
Excavate and Backfill	m3	229.0	Excavation and Backfill (SEEAM)	0.058	1.16	0.02	0.001	13	267	4	0
Excavate and Dispose	m3	934.0	Excavation and Disposal (SEEAM)	0.075	4.93	1.80	0.120	70	4607	1685	112
Level & Compact	m2	1764.0	Level & Compact (SEEAM)	0.018	1.20	0.02	0.002	32	2110	35	4
Granular beds	t	447.0	Recycled Fill Material (SEEAM)	0.026	1.71			12	766		
Sand Blinding	t	89.3	Recycled Fill Material (SEEAM)	0.026	1.71			2	153		
Concrete Blinding	m3	102.6	C20 GGBS (SEEAM)	1.034	166.85	1.68	0.044	106	17111	173	5
Concrete Foundations	m3	469.0	C40 GGBS (SEEAM)	1.511	251.50	2.47	0.065	708	117952	1157	31
Concrete Columns	m3	8.0	C40 GGBS (SEEAM)	1.511	251.50	2.47	0.065	12	2012	20	1
Concrete Ground Slab	m3	284.0	C40 GGBS Pump (SEEAM)	1.588	264.70	2.90	0.084	451	75175	825	24
Reinforcement	t	40.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	715	53740	908	25
Mesh	t	2.6	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	48	3590	71	2
Column Formwork	m2	119.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	6	330	31	1
Slab Formwork	m2	410.0	Formwork (Flat Slab)(SEEAM/OB)	0.043	1.95	0.26	0.007	18	798	107	3
Superstructure											
Lightweight Concrete	m3	1240.0	C30 Lytag GGBS Pump (SEEAM)	2.206	308.70	11.41	0.311	2736	382789	14151	386
Reinforcement	t	11.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	197	14779	250	7
Mesh	t	22.0	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	400	29929	588	16
Steel Decking	m2	9920.0	Steel Decking (SEEAM/OB)	0.375	29.35	0.28	0.007	3721	291176	2794	70
Steelwork	t	534.0	Structural Steel (Short) (SEEAM/OB)	27.816	2083.12	10.10	0.401	14854	1112388	5395	214
Fire Protection	m2	8355.0	Fire Protection (18mm Vicuclad) (SEEA	0.553	16.43	0.49	0.013	4623	137299	4132	106
Demolition											
Demolition	m2	11275	Demolition (Steel)(SEEAM)	0.068	4.47	0.01	0.001	768	50451	111	11
ReBar Removal	t	76	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	3	179	130	5
Steel Removal	t	534	Steel Transport (Demolished)(SEEAM)	0.012	0.79	0.55	0.022	6	421	291	12
Rubble Removal	t	3143	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	113	7430	5401	216
Base Data											
Cement	t			5.800	1193.00	3.29	0.088				
GGBS	t			1.450	78.09	8.40	0.224				
PFA	t			0.339	20.86	8.40	0.224				
Lytag	t			0.920	58.27	12.35	0.329				
Aggregates	t			0.047	3.08						

Figure 25: M4 7 Floor Steel and Concrete Embodied Energy Comparison, Lowest Reasonable Values



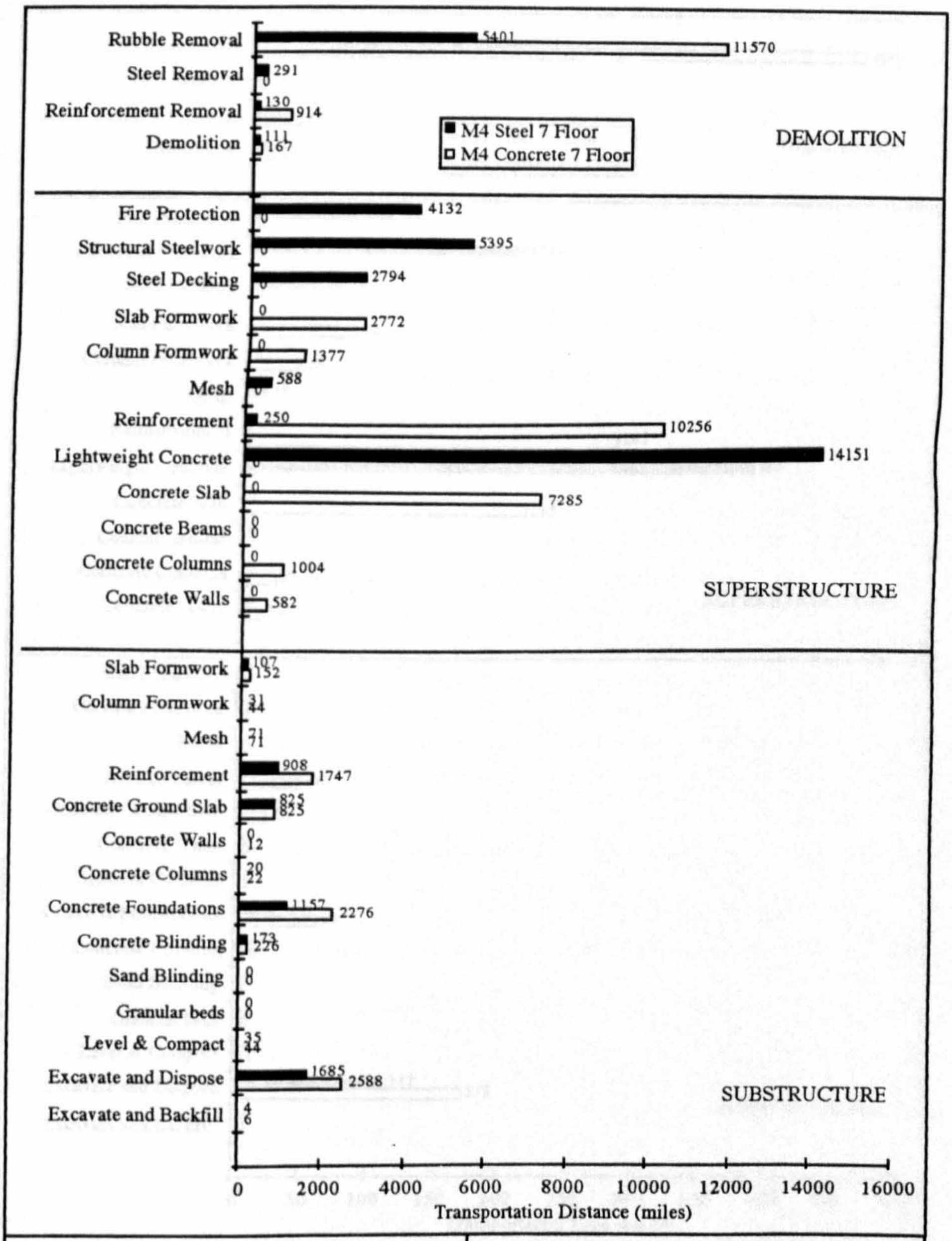
M4 Concrete 7 Floor	19492 GJ 1.73 GJ/m2		M4 Steel 7 Floor	29614 GJ 2.63 GJ/m2	
Section Total	GJ		Section Total	GJ	
Substructure	3648	18.7%	Substructure	2194	7.4%
Superstructure	14556	74.7%	Superstructure	26530	89.6%
Demolition	1288	6.6%	Demolition	890	3.0%
Item Total	GJ		Item Total	GJ	
Standard Concrete	6915	35.5%	Standard Concrete	1278	4.3%
Lightweight Concrete	0	0.0%	Lightweight Concrete	2736	9.2%
Reinforcement	9454	48.5%	Reinforcement	911	3.1%
Mesh	48	0.2%	Mesh	448	1.5%
Formwork	1602	8.2%	Formwork	24	0.1%
Structural Steelwork	0	0.0%	Structural Steelwork	14854	50.2%
Steel Decking	0	0.0%	Steel Decking	3721	12.6%
Fire Protection	0	0.0%	Fire Protection	4623	15.6%

Figure 26: M4 7 Steel and Concrete Embodied CO_2 Comparison, Lowest Reasonable Values



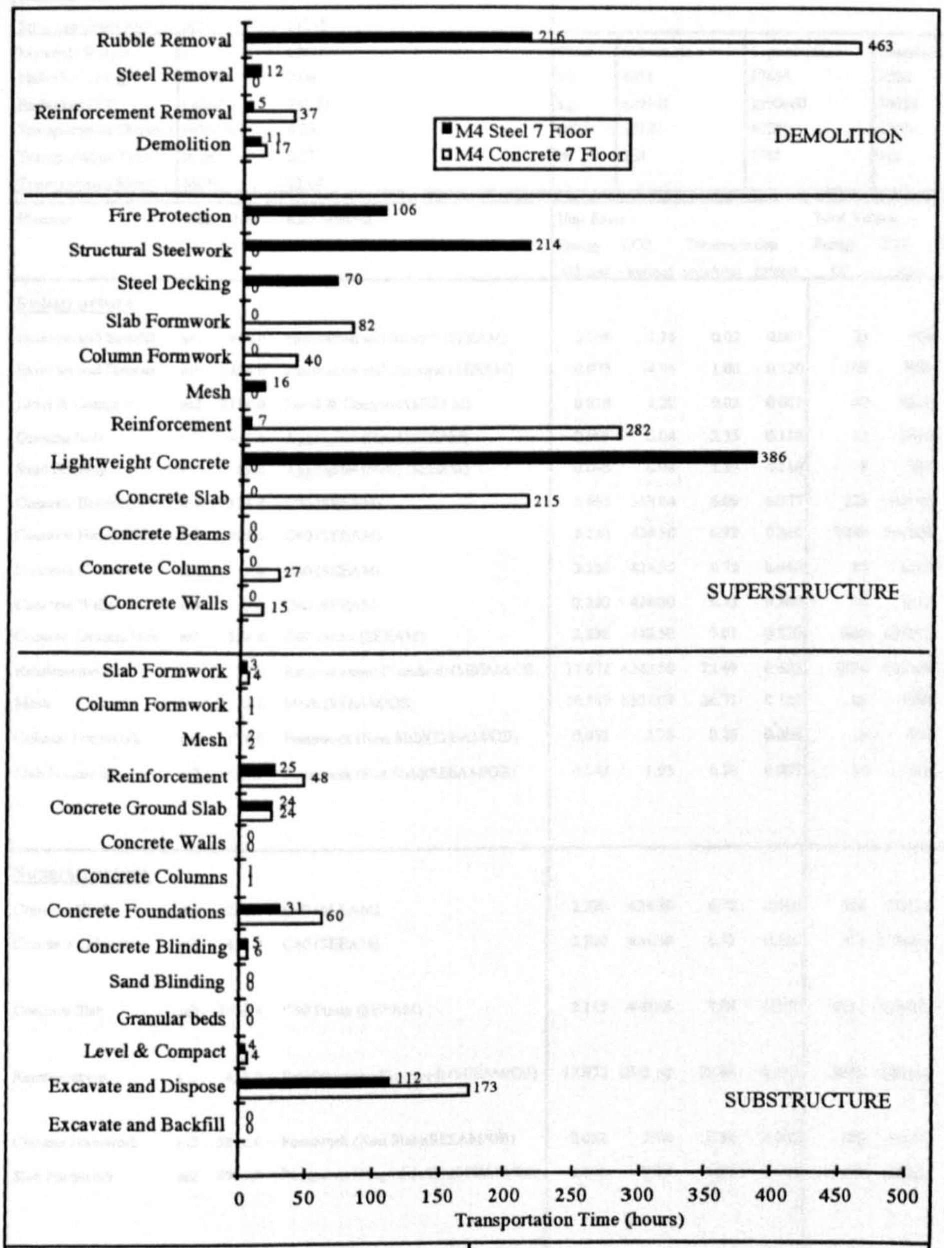
M4 Concrete 7 Floor	2060528 kg 182.75 kg/m2		M4 Steel 7 Floor	2305451 kg 204.47 kg/m2	
Section Total	kg		Section Total	kg	
Substructure	452973	22.0%	Substructure	278610	12.1%
Superstructure	1522921	73.9%	Superstructure	1968360	85.4%
Demolition	84634	4.1%	Demolition	58481	2.5%
Item Total	kg		Item Total	kg	
Standard Concrete	1145301	55.6%	Standard Concrete	212250	9.2%
Lightweight Concrete	0	0.0%	Lightweight Concrete	382789	16.6%
Reinforcement	710714	34.5%	Reinforcement	68519	3.0%
Mesh	3590	0.2%	Mesh	33519	1.5%
Formwork	105214	5.1%	Formwork	1129	0.0%
Structural Steelwork	0	0.0%	Structural Steelwork	1112388	48.3%
Steel Decking	0	0.0%	Steel Decking	291176	12.6%
Fire Protection	0	0.0%	Fire Protection	137299	6.0%

Figure 27: M4 7 Floor Steel and Concrete Transportation Distance Comparison, Lowest Reasonable Values



M4 Concrete 7 Floor	43938 miles		M4 Steel 7 Floor	38258 miles	
	3.90 miles/m2			3.39 miles/m2	
Section Total	miles		Section Total	miles	
Substructure	8013	18.2%	Substructure	5014	13.1%
Superstructure	23275	53.0%	Superstructure	27310	71.4%
Demolition	12651	28.8%	Demolition	5934	15.5%
Item Total	miles		Item Total	miles	
Standard Concrete	12233	27.8%	Standard Concrete	2174	5.7%
Lightweight Concrete	0	0.0%	Lightweight Concrete	14151	37.0%
Reinforcement	12003	27.3%	Reinforcement	1157	3.0%
Mesh	71	0.2%	Mesh	659	1.7%
Formwork	4344	9.9%	Formwork	138	0.4%
Structural Steelwork	0	0.0%	Structural Steelwork	5395	14.1%
Steel Decking	0	0.0%	Steel Decking	2794	7.3%
Fire Protection	0	0.0%	Fire Protection	4132	10.8%

Figure 28: M4 7 Floor Steel and Concrete Transportation Time Comparison, Lowest Reasonable Values



M4 Concrete 7 Floor	1501 hours 0.13 hours/m2		M4 Steel 7 Floor	1250 hours 0.11 hours/m2	
Section Total	hours		Section Total	hours	
Substructure	324	21.6%	Substructure	206	16.5%
Superstructure	661	44.0%	Superstructure	799	64.0%
Demolition	516	34.4%	Demolition	244	19.5%
Item Total	hours		Item Total	hours	
Standard Concrete	348	23.2%	Standard Concrete	60	4.8%
Lightweight Concrete	0	0.0%	Lightweight Concrete	386	30.9%
Reinforcement	330	22.0%	Reinforcement	32	2.5%
Mesh	2	0.1%	Mesh	18	1.4%
Formwork	128	8.5%	Formwork	4	0.3%
Structural Steelwork	0	0.0%	Structural Steelwork	214	17.1%
Steel Decking	0	0.0%	Steel Decking	70	5.6%
Fire Protection	0	0.0%	Fire Protection	106	8.5%

Table 15: M4 Concrete 7 Floor Structure using Increased Fire Protection

Summary		M4 Concrete 7 Floor	Notes	30mm VICUCLAD			
Structure Gross Area	m2	11275					
Materials Weight	t	12614	Total	Substructure	Superstructure	Demolition	Total
Embodied Energy	GJ/m2	2.08	GJ	4651	17484	1288	23424
Embodied CO2	kg/m2	263.81	kg	689141	2200660	84634	2974435
Transportation Distance	miles/m2	6.03	miles	15122	40231	12651	68004
Transportation Time	hr/m2	0.27	hr	789	1781	516	3086
Transportation Speed	MPH	22.04					

Element	Unit	No.	Rate Selected	Unit Rates				Total Values			
				Energy	CO2	Transportation		Energy	CO2	Transportation	
				GJ/unit	kg/unit	mile/unit	hr/unit	GJ	kg	miles	hours
Substructure											
Excavate and Backfill	m3	400.0	Excavation and Backfill (SEEAM)	0.058	1.16	0.02	0.001	23	466	6	0
Excavate and Dispose	m3	1434.0	Excavation and Disposal (SEEAM)	0.075	4.93	1.80	0.120	108	7073	2588	173
Level & Compact	m2	2189.0	Level & Compact (SEEAM)	0.018	1.20	0.02	0.002	40	2618	44	4
Granular beds	t	447.0	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	42	2699	1052	53
Sand Blinding	t	89.3	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	8	539	210	11
Concrete Blinding	m3	134.4	C20 (SEEAM)	1.695	313.64	6.89	0.377	228	42161	926	51
Concrete Foundations	m3	923.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	2049	391629	6199	332
Concrete Columns	m3	9.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	20	3819	60	3
Concrete Walls	m3	5.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	11	2122	34	2
Concrete Ground Slab	m3	284.0	C40 Pump (SEEAM)	2.338	448.50	7.01	0.370	664	127375	1990	105
Reinforcement	t	77.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	1376	103450	1747	48
Mesh	t	2.6	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	48	3590	71	2
Column Formwork	m2	170.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	9	472	44	1
Slab Formwork	m2	580.0	Formwork (Flat Slab)(SEEAM/OB)	0.043	1.95	0.26	0.007	25	1129	152	4
Superstructure											
Concrete Walls	m3	236.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	524	100135	1585	85
Concrete Columns	m3	407.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	904	172690	2734	146
Concrete Slab	m3	3036.0	C30 Pump (SEEAM)	2.112	400.84	7.08	0.377	6411	1216957	21508	1145
Reinforcement	t	452.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	8078	607264	10256	282
Column Formwork	m2	5362.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	280	14891	1377	40
Slab Formwork	m2	9920.0	Formwork (Shaped Soffit)(SEEAM/OB)	0.130	8.94	0.28	0.008	1288	88722	2772	82
Demolition											
Demolition	m2	11275	Demolition (Concrete)(SEEAM)	0.091	5.98	0.01	0.001	1027	67461	167	17
ReBar Removal	t	532	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	19	1257	914	37
Rubble Removal	t	6732	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	242	15916	11570	463
Base Data											
Cement	t			5.800	1193.00	3.29	0.088				
GGBS	t			1.450	78.09	8.40	0.224				
PFA	t			0.339	20.86	8.40	0.224				
Lytag	t			0.920	58.27	12.35	0.329				
Aggregates	t			0.093	6.04	2.35	0.118				

Table 16: M4 Steel 7 Floor Structure using Increased Fire Protection

Summary		M4 Steel 7 Floor	Notes	30mm VICUCLAD			
Structure Gross Area	m2	11275					
Materials Weight	t	5142	Total	Substructure	Superstructure	Demolition	Total
Embodied Energy	GJ/m2	3.06	GJ	2849	30725	890	34464
Embodied CO2	kg/m2	251.54	kg	430610	2347074	58481	2836165
Transportation Distance	miles/m2	4.17	miles	10003	31078	5934	47015
Transportation Time	hr/m2	0.16	hr	525	1044	244	1813
Transportation Speed	MPH	25.93					

Element	Unit	No.	Rate Selected	Unit Rates				Total Values			
				Energy	CO2	Transportation		Energy	CO2	Transportation	
				GJ/unit	kg/unit	mile/unit	hr/unit	GJ	kg	miles	hours
Substructure											
Excavate and Backfill	m3	229.0	Excavation and Backfill (SEEAM)	0.058	1.16	0.02	0.001	13	267	4	0
Excavate and Dispose	m3	934.0	Excavation and Disposal (SEEAM)	0.075	4.93	1.80	0.120	70	4607	1685	112
Level & Compact	m2	1764.0	Level & Compact (SEEAM)	0.018	1.20	0.02	0.002	32	2110	35	4
Granular beds	t	447.0	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	42	2699	1052	53
Sand Blinding	t	89.3	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	8	539	210	11
Concrete Blinding	m3	102.6	C20 (SEEAM)	1.695	313.64	6.89	0.377	174	32164	706	39
Concrete Foundations	m3	469.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	1041	198997	3150	169
Concrete Columns	m3	8.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	18	3394	54	3
Concrete Ground Slab	m3	284.0	C40 Pump (SEEAM)	2.338	448.50	7.01	0.370	664	127375	1990	105
Reinforcement	t	40.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	715	53740	908	25
Mesh	t	2.6	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	48	3590	71	2
Column Formwork	m2	119.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	6	330	31	1
Slab Formwork	m2	410.0	Formwork (Flat Slab)(SEEAM/OB)	0.043	1.95	0.26	0.007	18	798	107	3
Superstructure											
Lightweight Concrete	m3	1240.0	C30 Lytag Pump (SEEAM)	3.104	540.30	12.23	0.451	3849	669971	15164	559
Reinforcement	t	11.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	197	14779	250	7
Mesh	t	22.0	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	400	29929	588	16
Steel Decking	m2	9920.0	Steel Decking (SEEAM/OB)	0.375	29.35	0.28	0.007	3721	291176	2794	70
Steelwork	t	534.0	Structural Steel (Short) (SEEAM/OB)	27.816	2083.12	10.10	0.401	14854	1112388	5395	214
Fire Protection	m2	8355.0	Fire Protection (30mm Vicuclad) (SEEA	0.922	27.39	0.82	0.021	7705	228831	6887	177
Demolition											
Demolition	m2	11275	Demolition (Steel)(SEEAM)	0.068	4.47	0.01	0.001	768	50451	111	11
ReBar Removal	t	76	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	3	179	130	5
Steel Removal	t	534	Steel Transport (Demolished)(SEEAM)	0.012	0.79	0.55	0.022	6	421	291	12
Rubble Removal	t	3143	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	113	7430	5401	216
Base Data											
Cement	t			5.800	1193.00	3.29	0.088				
GGBS	t			1.450	78.09	8.40	0.224				
PFA	t			0.339	20.86	8.40	0.224				
Lytag	t			0.920	58.27	12.35	0.329				
Aggregates	t			0.093	6.04	2.35	0.118				

Table 17: M4 Concrete 7 Floor Structure using Recycled Structural Steel

Summary		M4 Concrete 7 Floor	Notes	RECYCLED STRUCTURAL STEEL			
Structure Gross Area	m2	11275					
Materials Weight	t	12614	Total	Substructure	Superstructure	Demolition	Total
Embodied Energy	GJ/m2	2.08	GJ	4651	17484	1288	23424
Embodied CO2	kg/m2	263.81	kg	689141	2200660	84634	2974435
Transportation Distance	miles/m2	6.03	miles	15122	40231	12651	68004
Transportation Time	hr/m2	0.27	hr	789	1781	516	3086
Transportation Speed	MPH	22.04					

Element	Unit	No.	Rate Selected	Unit Rates				Total Values			
				Energy	CO2	Transportation		Energy	CO2	Transportation	
				GJ/unit	kg/unit	mile/unit	hr/unit	GJ	kg	miles	hours
Substructure											
Excavate and Backfill	m3	400.0	Excavation and Backfill (SEEAM)	0.058	1.16	0.02	0.001	23	466	6	0
Excavate and Dispose	m3	1434.0	Excavation and Disposal (SEEAM)	0.075	4.93	1.80	0.120	108	7073	2588	173
Level & Compact	m2	2189.0	Level & Compact (SEEAM)	0.018	1.20	0.02	0.002	40	2618	44	4
Granular beds	t	447.0	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	42	2699	1052	53
Sand Blinding	t	89.3	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	8	539	210	11
Concrete Blinding	m3	134.4	C20 (SEEAM)	1.695	313.64	6.89	0.377	228	42161	926	51
Concrete Foundations	m3	923.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	2049	391629	6199	332
Concrete Columns	m3	9.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	20	3819	60	3
Concrete Walls	m3	5.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	11	2122	34	2
Concrete Ground Slab	m3	284.0	C40 Pump (SEEAM)	2.338	448.50	7.01	0.370	664	127375	1990	105
Reinforcement	t	77.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	1376	103450	1747	48
Mesh	t	2.6	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	48	3590	71	2
Column Formwork	m2	170.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	9	472	44	1
Slab Formwork	m2	580.0	Formwork (Flat Slab)(SEEAM/OB)	0.043	1.95	0.26	0.007	25	1129	152	4
Superstructure											
Concrete Walls	m3	236.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	524	100135	1585	85
Concrete Columns	m3	407.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	904	172690	2734	146
Concrete Slab	m3	3036.0	C30 Pump (SEEAM)	2.112	400.84	7.08	0.377	6411	1216957	21508	1145
Reinforcement	t	452.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	8078	607264	10256	282
Column Formwork	m2	5362.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	280	14891	1377	40
Slab Formwork	m2	9920.0	Formwork (Shaped Soffit)(SEEAM/OB)	0.130	8.94	0.28	0.008	1288	88722	2772	82
Demolition											
Demolition	m2	11275	Demolition (Concrete)(SEEAM)	0.091	5.98	0.01	0.001	1027	67461	167	17
ReBar Removal	t	532	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	19	1257	914	37
Rubble Removal	t	6732	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	242	15916	11570	463
Base Data											
Cement	t			5.800	1193.00	3.29	0.088				
GGBS	t			1.450	78.09	8.40	0.224				
PFA	t			0.339	20.86	8.40	0.224				
Lytag	t			0.920	58.27	12.35	0.329				
Aggregates	t			0.093	6.04	2.35	0.118				

Table 18: M4 Steel 7 Floor Structure using Recycled Structural Steel

Summary		M4 Steel 7 Floor	Notes	RECYCLED STRUCTURAL STEEL			
Structure Gross Area	m2	11275					
Materials Weight	t	5142	Total	Substructure	Superstructure	Demolition	Total
Embodied Energy	GJ/m2	2.33	GJ	2849	22519	890	26258
Embodied CO2	kg/m2	209.00	kg	430610	1867374	58481	2356465
Transportation Distance	miles/m2	3.93	miles	10003	28323	5934	44260
Transportation Time	hr/m2	0.15	hr	525	973	244	1743
Transportation Speed	MPH	25.40					

Element	Unit	No.	Rate Selected	Unit Rates				Total Values			
				Energy	CO2	Transportation		Energy	CO2	Transportation	
				GJ/unit	kg/unit	mile/unit	hr/unit	GJ	kg	miles	hours
Substructure											
Excavate and Backfill	m3	229.0	Excavation and Backfill (SEEAM)	0.058	1.16	0.02	0.001	13	267	4	0
Excavate and Dispose	m3	934.0	Excavation and Disposal (SEEAM)	0.075	4.93	1.80	0.120	70	4607	1685	112
Level & Compact	m2	1764.0	Level & Compact (SEEAM)	0.018	1.20	0.02	0.002	32	2110	35	4
Granular beds	t	447.0	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	42	2699	1052	53
Sand Blinding	t	89.3	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	8	539	210	11
Concrete Blinding	m3	102.6	C20 (SEEAM)	1.695	313.64	6.89	0.377	174	32164	706	39
Concrete Foundations	m3	469.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	1041	198997	3150	169
Concrete Columns	m3	8.0	C40 (SEEAM)	2.220	424.30	6.72	0.360	18	3394	54	3
Concrete Ground Slab	m3	284.0	C40 Pump (SEEAM)	2.338	448.50	7.01	0.370	664	127375	1990	105
Reinforcement	t	40.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	715	53740	908	25
Mesh	t	2.6	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	48	3590	71	2
Column Formwork	m2	119.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	6	330	31	1
Slab Formwork	m2	410.0	Formwork (Flat Slab)(SEEAM/OB)	0.043	1.95	0.26	0.007	18	798	107	3
Superstructure											
Lightweight Concrete	m3	1240.0	C30 Lytag Pump (SEEAM)	3.104	540.30	12.23	0.451	3849	669971	15164	559
Reinforcement	t	11.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	197	14779	250	7
Mesh	t	22.0	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	400	29929	588	16
Steel Decking	m2	9920.0	Steel Decking (SEEAM/OB)	0.375	29.35	0.28	0.007	3721	291176	2794	70
Steelwork	t	534.0	Structural Steel (Recycled)(SEEAM)	18.221	1356.22	10.10	0.401	9730	724221	5395	214
Fire Protection	m2	8355.0	Fire Protection (18mm Vicuclad) (SEEA	0.553	16.43	0.49	0.013	4623	137299	4132	106
Demolition											
Demolition	m2	11275	Demolition (Steel)(SEEAM)	0.068	4.47	0.01	0.001	768	50451	111	11
ReBar Removal	t	76	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	3	179	130	5
Steel Removal	t	534	Steel Transport (Demolished)(SEEAM)	0.012	0.79	0.55	0.022	6	421	291	12
Rubble Removal	t	3143	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	113	7430	5401	216
Base Data											
Cement	t			5.800	1193.00	3.29	0.088				
GGBS	t			1.450	78.09	8.40	0.224				
PFA	t			0.339	20.86	8.40	0.224				
Lytag	t			0.920	58.27	12.35	0.329				
Aggregates	t			0.093	6.04	2.35	0.118				

Table 19: M4 Concrete 7 Floor Structure using Low Energy Figures For Cement and Aggregate

Summary		M4 Concrete 7 Floor	Notes	LOW VALUES FOR CEMENT AND AGGREGATES			
Structure Gross Area	m2	11275					
Materials Weight	t	12614	Total	Substructure	Superstructure	Demolition	Total
Embodied Energy	GJ/m2	1.91	GJ	4147	16137	1288	21573
Embodied CO2	kg/m2	296.44	kg	786563	2471111	84634	3342308
Transportation Distance	miles/m2	5.32	miles	13006	34355	12651	60011
Transportation Time	hr/m2	0.23	hr	645	1383	516	2544
Transportation Speed	MPH	23.59					

Element	Unit	No.	Rate Selected	Unit Rates				Total Values			
				Energy	CO2	Transportation		Energy	CO2	Transportation	
				GJ/unit	kg/unit	mile/unit	hr/unit	GJ	kg	miles	hours
Substructure											
Excavate and Backfill	m3	400.0	Excavation and Backfill (SEEAM)	0.058	1.16	0.02	0.001	23	466	6	0
Excavate and Dispose	m3	1434.0	Excavation and Disposal (SEEAM)	0.075	4.93	1.80	0.120	108	7073	2588	173
Level & Compact	m2	2189.0	Level & Compact (SEEAM)	0.018	1.20	0.02	0.002	40	2618	44	4
Granular beds	t	447.0	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	42	2699	1052	53
Sand Blinding	t	89.3	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	8	539	210	11
Concrete Blinding	m3	134.4	C20 (SEEAM)	1.373	392.37	5.18	0.261	185	52744	696	35
Concrete Foundations	m3	923.0	C40 (SEEAM)	1.846	495.60	5.17	0.255	1704	457443	4769	235
Concrete Columns	m3	9.0	C40 (SEEAM)	1.846	495.60	5.17	0.255	17	4460	47	2
Concrete Walls	m3	5.0	C40 (SEEAM)	1.846	495.60	5.17	0.255	9	2478	26	1
Concrete Ground Slab	m3	284.0	C40 Pump (SEEAM)	1.951	519.02	5.48	0.266	554	147402	1555	76
Reinforcement	t	77.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	1376	103450	1747	48
Mesh	t	2.6	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	48	3590	71	2
Column Formwork	m2	170.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	9	472	44	1
Slab Formwork	m2	580.0	Formwork (Flat Slab)(SEEAM/OB)	0.043	1.95	0.26	0.007	25	1129	152	4
Superstructure											
Concrete Walls	m3	236.0	C40 (SEEAM)	1.846	495.60	5.17	0.255	436	116963	1219	60
Concrete Columns	m3	407.0	C40 (SEEAM)	1.846	495.60	5.17	0.255	752	201711	2103	104
Concrete Slab	m3	3036.0	C30 Pump (SEEAM)	1.747	474.82	5.48	0.268	5303	1441561	16628	814
Reinforcement	t	452.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	8078	607264	10256	282
Column Formwork	m2	5362.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	280	14891	1377	40
Slab Formwork	m2	9920.0	Formwork (Shaped Soffit)(SEEAM/OB)	0.130	8.94	0.28	0.008	1288	88722	2772	82
Demolition											
Demolition	m2	11275	Demolition (Concrete)(SEEAM)	0.091	5.98	0.01	0.001	1027	67461	167	17
ReBar Removal	t	532	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	19	1257	914	37
Rubble Removal	t	6732	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	242	15916	11570	463
Base Data											
Cement	t			5.100	1193.00	3.29	0.088				
GGBS	t			1.450	78.09	8.40	0.224				
PFA	t			0.339	20.86	8.40	0.224				
Lytag	t			0.920	58.27	12.35	0.329				
Aggregates	t			0.020	45.00	1.51	0.060				

Table 20: M4 Steel 7 Floor Structure using Low Energy Figures For Cement and Aggregate

Summary		M4 Steel 7 Floor	Notes	LOW VALUES FOR CEMENT AND AGGREGATES			
Structure Gross Area	m2	11275					
Materials Weight	t	5142	Total	Substructure	Superstructure	Demolition	Total
Embodied Energy	GJ/m2	2.72	GJ	2528	27215	890	30633
Embodied CO2	kg/m2	252.11	kg	492723	2291339	58481	2842542
Transportation Distance	miles/m2	3.74	miles	8653	27546	5934	42133
Transportation Time	hr/m2	0.14	hr	434	920	244	1598
Transportation Speed	MPH	26.36					

Element	Unit	No.	Rate Selected	Unit Rates				Total Values			
				Energy	CO2	Transportation		Energy	CO2	Transportation	
				GJ/unit	kg/unit	mile/unit	hr/unit	GJ	kg	miles	hours
Substructure											
Excavate and Backfill	m3	229.0	Excavation and Backfill (SEEAM)	0.058	1.16	0.02	0.001	13	267	4	0
Excavate and Dispose	m3	934.0	Excavation and Disposal (SEEAM)	0.075	4.93	1.80	0.120	70	4607	1685	112
Level & Compact	m2	1764.0	Level & Compact (SEEAM)	0.018	1.20	0.02	0.002	32	2110	35	4
Granular beds	t	447.0	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	42	2699	1052	53
Sand Blinding	t	89.3	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	8	539	210	11
Concrete Blinding	m3	102.6	C20 (SEEAM)	1.373	392.37	5.18	0.261	141	40237	531	27
Concrete Foundations	m3	469.0	C40 (SEEAM)	1.846	495.60	5.17	0.255	866	232439	2423	120
Concrete Columns	m3	8.0	C40 (SEEAM)	1.846	495.60	5.17	0.255	15	3965	41	2
Concrete Ground Slab	m3	284.0	C40 Pump (SEEAM)	1.951	519.02	5.48	0.266	554	147402	1555	76
Reinforcement	t	40.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	715	53740	908	25
Mesh	t	2.6	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	48	3590	71	2
Column Formwork	m2	119.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	6	330	31	1
Slab Formwork	m2	410.0	Formwork (Flat Slab)(SEEAM/OB)	0.043	1.95	0.26	0.007	18	798	107	3
Superstructure											
Lightweight Concrete	m3	1240.0	C30 Lytag Pump (SEEAM)	2.759	569.17	11.60	0.409	3421	705768	14387	507
Reinforcement	t	11.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	197	14779	250	7
Mesh	t	22.0	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	400	29929	588	16
Steel Decking	m2	9920.0	Steel Decking (SEEAM/OB)	0.375	29.35	0.28	0.007	3721	291176	2794	70
Steelwork	t	534.0	Structural Steel (Short) (SEEAM/OB)	27.816	2083.12	10.10	0.401	14854	1112388	5395	214
Fire Protection	m2	8355.0	Fire Protection (18mm Vicuclad) (SEEA	0.553	16.43	0.49	0.013	4623	137299	4132	106
Demolition											
Demolition	m2	11275	Demolition (Steel)(SEEAM)	0.068	4.47	0.01	0.001	768	50451	111	11
ReBar Removal	t	76	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	3	179	130	5
Steel Removal	t	534	Steel Transport (Demolished)(SEEAM)	0.012	0.79	0.55	0.022	6	421	291	12
Rubble Removal	t	3143	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	113	7430	5401	216
Base Data											
Cement	t			5.100	1193.00	3.29	0.088				
GGBS	t			1.450	78.09	8.40	0.224				
PFA	t			0.339	20.86	8.40	0.224				
Lytag	t			0.920	58.27	12.35	0.329				
Aggregates	t			0.020	45.00	1.51	0.060				

Table 21: M4 Concrete 7 Floor Structure using High Energy Figures For Cement and Aggregate

Summary		M4 Concrete 7 Floor	Notes	LOW VALUES FOR CEMENT AND AGGREGATES			
Structure Gross Area	m2	11275					
Materials Weight	t	12614	Total	Substructure	Superstructure	Demolition	Total
Embodied Energy	GJ/m2	2.97	GJ	7332	24863	1288	33483
Embodied CO2	kg/m2	296.44	kg	786563	2471111	84634	3342308
Transportation Distance	miles/m2	5.32	miles	13006	34355	12651	60011
Transportation Time	hr/m2	0.23	hr	645	1383	516	2544
Transportation Speed	MPH	23.59					

Element	Unit	No.	Rate Selected	Unit Rates				Total Values			
				Energy	CO2	Transportation		Energy	CO2	Transportation	
				GJ/unit	kg/unit	mile/unit	hr/unit	GJ	kg	miles	hours
Substructure											
Excavate and Backfill	m3	400.0	Excavation and Backfill (SEEAM)	0.058	1.16	0.02	0.001	23	466	6	0
Excavate and Dispose	m3	1434.0	Excavation and Disposal (SEEAM)	0.075	4.93	1.80	0.120	108	7073	2588	173
Level & Compact	m2	2189.0	Level & Compact (SEEAM)	0.018	1.20	0.02	0.002	40	2618	44	4
Granular beds	t	447.0	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	42	2699	1052	53
Sand Blinding	t	89.3	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	8	539	210	11
Concrete Blinding	m3	134.4	C20 (SEEAM)	3.753	392.37	5.18	0.261	504	52744	696	35
Concrete Foundations	m3	923.0	C40 (SEEAM)	4.189	495.60	5.17	0.255	3867	457443	4769	235
Concrete Columns	m3	9.0	C40 (SEEAM)	4.189	495.60	5.17	0.255	38	4460	47	2
Concrete Walls	m3	5.0	C40 (SEEAM)	4.189	495.60	5.17	0.255	21	2478	26	1
Concrete Ground Slab	m3	284.0	C40 Pump (SEEAM)	4.307	519.02	5.48	0.266	1223	147402	1555	76
Reinforcement	t	77.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	1376	103450	1747	48
Mesh	t	2.6	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	48	3590	71	2
Column Formwork	m2	170.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	9	472	44	1
Slab Formwork	m2	580.0	Formwork (Flat Slab)(SEEAM/OB)	0.043	1.95	0.26	0.007	25	1129	152	4
Superstructure											
Concrete Walls	m3	236.0	C40 (SEEAM)	4.189	495.60	5.17	0.255	989	116963	1219	60
Concrete Columns	m3	407.0	C40 (SEEAM)	4.189	495.60	5.17	0.255	1705	201711	2103	104
Concrete Slab	m3	3036.0	C30 Pump (SEEAM)	4.125	474.82	5.48	0.268	12523	1441561	16628	814
Reinforcement	t	452.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	8078	607264	10256	282
Column Formwork	m2	5362.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	280	14891	1377	40
Slab Formwork	m2	9920.0	Formwork (Shaped Soffit)(SEEAM/OB)	0.130	8.94	0.28	0.008	1288	88722	2772	82
Demolition											
Demolition	m2	11275	Demolition (Concrete)(SEEAM)	0.091	5.98	0.01	0.001	1027	67461	167	17
ReBar Removal	t	532	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	19	1257	914	37
Rubble Removal	t	6732	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	242	15916	11570	463
Base Data											
Cement	t			6.700	1193.00	3.29	0.088				
GGBS	t			1.450	78.09	8.40	0.224				
PFA	t			0.339	20.86	8.40	0.224				
Lytag	t			0.920	58.27	12.35	0.329				
Aggregates	t			1.000	45.00	1.51	0.060				

Table 22: M4 Steel 7 Floor Structure using High Energy Figures For Cement and Aggregate

Summary		M4 Steel 7 Floor	Notes	LOW VALUES FOR CEMENT AND AGGREGATES			
Structure Gross Area	m2	11275					
Materials Weight	t	5142	Total	Substructure	Superstructure	Demolition	Total
Embodied Energy	GJ/m2	3.05	GJ	4558	28941	890	34389
Embodied CO2	kg/m2	252.11	kg	492723	2291339	58481	2842542
Transportation Distance	miles/m2	3.74	miles	8653	27546	5934	42133
Transportation Time	hr/m2	0.14	hr	434	920	244	1598
Transportation Speed	MPH	26.36					

Element	Unit	No.	Rate Selected	Unit Rates Energy GJ/unit	 CO2 kg/unit	 Transportation mile/unit	 hr/unit	Total Values Energy GJ	 CO2 kg	 Transportation miles	 hours
Substructure											
Excavate and Backfill	m3	229.0	Excavation and Backfill (SEEAM)	0.058	1.16	0.02	0.001	13	267	4	0
Excavate and Dispose	m3	934.0	Excavation and Disposal (SEEAM)	0.075	4.93	1.80	0.120	70	4607	1685	112
Level & Compact	m2	1764.0	Level & Compact (SEEAM)	0.018	1.20	0.02	0.002	32	2110	35	4
Granular beds	t	447.0	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	42	2699	1052	53
Sand Blinding	t	89.3	Aggregates (New) (SEEAM)	0.093	6.04	2.35	0.118	8	539	210	11
Concrete Blinding	m3	102.6	C20 (SEEAM)	3.753	392.37	5.18	0.261	385	40237	531	27
Concrete Foundations	m3	469.0	C40 (SEEAM)	4.189	495.60	5.17	0.255	1965	232439	2423	120
Concrete Columns	m3	8.0	C40 (SEEAM)	4.189	495.60	5.17	0.255	34	3965	41	2
Concrete Ground Slab	m3	284.0	C40 Pump (SEEAM)	4.307	519.02	5.48	0.266	1223	147402	1555	76
Reinforcement	t	40.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	715	53740	908	25
Mesh	t	2.6	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	48	3590	71	2
Column Formwork	m2	119.0	Formwork (Non Slab)(SEEAM/OB)	0.052	2.78	0.26	0.008	6	330	31	1
Slab Formwork	m2	410.0	Formwork (Flat Slab)(SEEAM/OB)	0.043	1.95	0.26	0.007	18	798	107	3
Superstructure											
Lightweight Concrete	m3	1240.0	C30 Lytag Pump (SEEAM)	4.151	569.17	11.60	0.409	5147	705768	14387	507
Reinforcement	t	11.0	Reinforcement (Standard) (SEEAM/OB)	17.872	1343.50	22.69	0.625	197	14779	250	7
Mesh	t	22.0	Mesh (SEEAM/OB)	18.149	1359.03	26.71	0.732	400	29929	588	16
Steel Decking	m2	9920.0	Steel Decking (SEEAM/OB)	0.375	29.35	0.28	0.007	3721	291176	2794	70
Steelwork	t	534.0	Structural Steel (Short) (SEEAM/OB)	27.816	2083.12	10.10	0.401	14854	1112388	5395	214
Fire Protection	m2	8355.0	Fire Protection (18mm Vicuclad) (SEEA	0.553	16.43	0.49	0.013	4623	137299	4132	106
Demolition											
Demolition	m2	11275	Demolition (Steel)(SEEAM)	0.068	4.47	0.01	0.001	768	50451	111	11
ReBar Removal	t	76	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	3	179	130	5
Steel Removal	t	534	Steel Transport (Demolished)(SEEAM)	0.012	0.79	0.55	0.022	6	421	291	12
Rubble Removal	t	3143	Move Rubble Off Site (Uncrushed)(SEE	0.036	2.36	1.72	0.069	113	7430	5401	216
Base Data											
Cement	t			6.700	1193.00	3.29	0.088				
GGBS	t			1.450	78.09	8.40	0.224				
PFA	t			0.339	20.86	8.40	0.224				
Lytag	t			0.920	58.27	12.35	0.329				
Aggregates	t			1.000	45.00	1.51	0.060				