BUILDING AND ENERGY

A Historical Perspective and Study into

Possible Areas of Energy Reduction

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Recent world events have created concern about the use of energy. Energy is an essential factor in the production of buildings and one which is little known about; an effort was made in this study to provide a better understanding of some of the general relationships between energy and construction and to draw attention to possible ways of reducing energy demand. To gain a perspective in the trends in energy and methods of construction, a historical case study was undertaken which affirmed that methods of construction have become more energy intensive over the years.

The study then goes on to establish a framework from which to evaluate various strategies for reducing production energy costs. Of the various strategies it was found that extending the life of a building, along with greater economy in the use of materials, and substituting less energy-intensive materials, were the most promising ways of conserving energy, though potential also existed for reducing energy consumption through component re-use and material recycling. Energy savings were also possible, through more efficient production processing. It was also found that the potential energy savings, even though technically possible, all appeared to be constrained by attitudes and conventional economics despite the fact that many production energy saving methods were fully compatible with in-use energy savings.
At the present time the world is using capital sources of energy at an ever increasing rate. It is unlikely that income or ambient sources of energy or nuclear power will play a significant role in the supply of energy much before the turn of the century, if then. The rate of increase in energy consumption is exceeding that of population thus compounding the energy supply problem. The difference between the two rates can be largely attributed to what could be generally termed as society's development.

The aims of this study are two fold. The first is to establish that the building system, like other production systems, becomes progressively more energy intensive as the societies in which they are used become progressively more developed, largely as a result of the extravagant use of 'cheap' fossil fuels.

The second aim is to illustrate that technical means exist by which the energy consumption within the building field can be reduced, even within a developed country. Essential to this second objective was the need to clarify the meanings of common expressions such as, recycle, re-use and by-product, in order to develop a framework within which the use of materials and components from secondary sources might be better understood in relation to reducing energy demands.
The case for an energy analysis

Production energy is a hidden dimension in architectural design, which influences the entire nature of the building system. As yet its significance is little appreciated or understood by those who specify methods of construction in the developed world, even if they are consciously aware of production energy at all. In 'primitive' architecture, the designer, producer and user of a building, often one and the same, are intimately aware, albeit subconsciously, of the effort or energy expenditure involved in their traditional building systems. As a society develops, its designers are progressively removed from both the production and use of the buildings with which they are involved. The historical study developed in this thesis suggests that today's professional designer is far less adept at achieving constructional performance per unit of production energy than was his less sophisticated forebears, who lived in a far simpler society.

It could be argued that this situation arises simply because the contemporary designer is a victim of circumstance; the method of construction being determined solely on 'economic' grounds. But economic in what sense? The Oxford Dictionary defines economical as "saving or frugal: and to economise: as to use sparingly and to avoid expense". In either energy or environmental impact terms, it is questionable whether current designs are indeed economical when compared to buildings produced by more 'underdeveloped' societies now or in the past. Understanding the type, nature and amount of production energy would lead to a far more accurate understanding of real resource 'costs'. Indeed energy accounting is the only way of measuring total effort; a unit of energy is absolute and unaffected by society's values (despite the fact that the values
themselves are largely determined by the society's access to and control of energy), It is the ultimate way of comparing different methods of construction.

Even though market forces prevent excessive disparities in energy consumption between processed material systems (see Figs. 1.6 and 1.7, pp. 18-19); they by no means ensure the efficient use of energy. The disparity between 'value' added in the conventional economic sense, and energy added in the production sequence should be evident from the case study.

The cost of borrowing or holding capital in relation to stock or plant is a market force which results in the increasing demand for more energy. This is true in relation to both production energy and energy involved in using buildings. The effort to speed up production operations in order to increase or maximize return on money is the primary cause of the conflict between money and energy economics. This is most obvious in relation to the use of transport energy. Specific examples also appear in the study which show the time element leading to increased energy usage in relation to the thermal or chemical processing of materials; but the conflict between energy and conventional economics develops most noticeably with respect to those production activities based on mechanical operations. Bruce Hannon, summarizes the situation in a North American

1 The relationship between energy and conventional costs is developed in Chapter Four in the sub-section concerning the pricing mechanism (pp 215-32).

2 The increase in transport energy requirements, resulting largely from conventional economic pressures, is covered in Chapter Three, Section One of Chapter Four, but particularly in Appendixes E, F and G.

3 For examples of this see the section on cements, in particular pages 265-6 and 276.
the most ubiquitous energy increase in industrial processes is believed to have occurred via automation - that is, the displacement of labour from the production process. The ratio of production workers' wages to the cost of electricity increased steadily by 225 percent from 1951 to 1969. During that time the wholesale price index for electrical machinery increased by 50 percent. These factors indicate the pressure on the industrial decision makers to eliminate the increasingly expensive worker from the process and to substitute machines, which increase the energy intensity of the process¹.

This relationship between labour, and fuel costs invalidates the argument about the price mechanism leading to large scale substitutions from high energy to low energy systems. In addition the equipment which permits an increase in speed or productivity must itself become larger, heavier, and more complex, usually leading to centralization, which often results in additional distribution energy requirements².

Reducing labour or increasing its productivity through mechanization, with resultant increases in energy costs, brings another point up which is not limited to construction but applies to all production processes, and that is what happens to the people displaced through rationalization of mechanization? One could almost look at the displacement of people from industry from a materials (or energy) balance point of view; industries neither create nor destroy people. People rationalized or mechanized out of one narrowly defined industrial system inevitably show up in another system in a productive or, frequently, a non productive


²There is some evidence (see pages 200 to 202 and Fig.4.25) which suggests that ever increasing investment in machinery is required to produce proportionate increases in productivity; in other words we are reaching a point of diminishing returns in the replacement of man by machines.
capacity. The difficult with conventional economics is that it only
deals with narrowly defined product systems which are made increasingly
more 'economical' by the substitution of fossil fuel for man power; the
external costs of supporting the labour displaced by machine is overlooked.
This type of substitution would make little sense in an energy analysis,
even though such an analysis would be liable to the same system definition
problems. It is accepted that energy analysis, itself complicated by the
numerous methods of expressing energy (discussed in Chapter One, pages
29 to 39) also suffers through its lack of similarity.

Another reason for an energy analysis concerns the environmental
impact of construction systems. Again conventional economics simply do
not reflect adequately the external or non-market costs involved in prod-
duction. Victor¹ and Barkley and Seckler² are among many economists who
trace most common environmental problems to this externality factor.
Simply stated, the price of an item simply does not cover all the costs
of production and disposal: costs are minimized by releasing by-products
as well as the products themselves, onto communal land, into the atmosphere
or into bodies of water which, by their very nature, are shared by all.
Stephen Berry of the University of Chicago, concludes that:

Doing 'energy economics' leads us to one of the root problems
of environmental management - thrifty utilization of energy.
It is remarkable how many of the insults that we now recognize
can be traced to the use of large amounts of energy...if we
could identify areas in which there were large potential
economies to be found in energy utilization, then we would
begin, perhaps, to find and to reconcile the technical life
style we have so thoroughly adopted, with the threat of
increasing environmental insults that seem to accompany our
technology.³

¹Peter Victor, Pollution: Economics and Environment (London: Allen
and Unwin, 1972).
²Paul W. Barkley and David W. Seckler, Economic Growth and
³Stephen Berry, "Thermo-dynamics and Environmental Thirft",Bulletin
By examining production energy and its relation to the building system we can not only deal with the most significant resource problem, but can at the same time resolve many of the environmental problems that the designer is responsible for when specifying a material or method of construction which are in conventional economics 'economic'.

Transport energy requirements were also studied (Appendix D and Chapter Nine). Even though the overall consumption of energy in transporting materials is quite small in comparison to the energy involved in processing them (see Figs. 3.17 and 3.18 and 3.19), its use grows more rapidly than processing energy in absolute terms and for more abruptly (see Fig. 3.19). This rapid increase in transport energy consumption was largely attributed to shifts in more energy intensive
Conclusions

The thesis that building systems become progressively more energy intensive as a society develops is generally supported by the historical case study of British roofing systems, developed in Chapters Two and Three (pp 40-105). The conclusion drawn was that, in earlier periods of development, common unprocessed materials prevailed which had extremely low energy intensities. However, the total demand for processing energy was higher than expected because the small quantities of processed materials used were extremely energy intensive\(^1\), mainly because of the thermally inefficient methods used in their manufacture (see Appendix C). In time, the materials with either extremely high or low energy intensities disappeared for numerous, and often interrelated, socio-economic reasons, which usually accompanies development. The socio-economic factors were discussed in relation to each material in Chapter Two. In the place of the extremely high and low energy intensive materials was a group of moderately energy intensive processed materials with intensities of the same order of magnitude\(^2\).

Transport energy requirements were also studied (Appendix D to H and Chapter Three). Even though the overall consumption of energy in transporting materials is quite small in comparison to the energy involved in processing them (see Figs. 3.17 and 3.18 and 4.16), it was found to have increased far more than processing energy in absolute terms and far more abruptly (see Fig. 3.16). This rapid increase in transport energy consumption was largely attributed to shifts to more energy intensive

\(^1\) This is clearly illustrated by comparing Figs. 3.2 with 3.3, p. 115.

\(^2\) The shifts in the energy intensities is graphically summarized in Fig. 3.3, p. 115.
modes of transport operating at higher speeds over longer distances.

The thesis that technical means exist for reducing production energy was supported throughout Chapters Four, Five and Six. Chapter Four (Section Two, pp 161-206) discussed production from primary sources and concluded that the extractive and assembly operations were likely to increase in energy consumption, while material manufacturing and fabrication operations could decrease due to improved technology, particularly with respect to the utilization of low grade 'waste' heat. Unfortunately this situation favours energy intensive processed materials and not unprocessed ones. Technological improvements are, however, becoming progressively more difficult to realize; we are reaching a point of diminishing returns making future production energy cost reductions progressively harder to come by in terms of both money and energy (see Figs. c-1, 4.34 and 4.35).

Chapter Five studied the possibilities of production from secondary sources (see Fig. 5.1 and Table 5.1) either by using by-products or by recirculating into the production sequence old materials or components. The conclusion was that in the case of by-product utilization the greatest promise of energy savings were to be found by utilizing by-products which eliminated or shared thermal processes. The most interesting (and unexploited) by-products were slags for use in super sulphated cement, slags and PFA as light-weight aggregates and by-product anhydrite used as plaster. The primary recycling (Chapter Five, pp 307-331, and Fig. 5.3) of thermo-plastic scrap and the re-use of components (Chapter Six, Sections 8 and 9, pp 340-364) were also discussed as excellent methods of reducing production energy; though far greater potential for savings existed through component re-use than material recycling, as clearly shown in Figs. 5.7 to 5.9 (p. 341).
Unfortunately it was concluded that a basic conflict appears to be developing between the energy saving methods described in Chapter Four in relation to production from primary sources and those in Chapter Five which were concerned with production from secondary sources. The trends towards larger scale, highly specialized, and often remote 'rationalized' plant, which seems to result from pursuing the energy saving methods outlined in Chapter Four, are becoming progressively more incompatible with efforts to save production energy through the use of materials from secondary sources which are usually highly dispersed and of increasing variety. The co-ordination and co-operation, which are vital, especially with respect to re-use and recycling, and which historically were so evident in the building system\(^1\), have disappeared mainly due to the complex grouping of industries operating today, each having a very narrowly defined objective and representing only a small portion of a linear (as opposed to cyclic) process.

The possibility of saving production energy by passive techniques were examined in Chapter Six, and it was concluded that this approach offered the most realistic approach to reducing energy demand. Reducing the overall demand for new construction itself by either more efficient utilization of existing buildings, or through the extension of their life by better maintenance or rehabilitation. Reducing the amount of materials used in buildings by doing more with less, with the same or less material, either by using a material to perform multifunctions or by more efficient structural design was also found to be a practical solution to reducing production energy, along with the use of inherently low energy natural materials which provide very high performance per unit of energy (see Table 6.1, p. 419). Fortunately, it was found that conserving production and in-use

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\(^1\)Historically examples of recycling building materials can be found on pages 327 to 329, of re-using architectural components on pages 353 to 360, and by-product utilization in building on pages 270, 295-6 and 299.
or running energy were often quite compatible objectives.

Many of the energy saving possibilities which exist in the production sequence from both primary and secondary sources remain unexploited. This is also true of the energy saving possibilities resulting from the more rational use of materials and buildings. The inevitable conclusion is that the opportunities to reduce energy consumption which remain undeveloped are primarily a result of non-technical factors – lack of awareness, regulations and legal barriers being contributory reasons; the primary ones, often interrelated, were found to be institutional and economic in nature.¹

¹Constraints preventing the application of energy saving techniques involved in production from primary sources are found in Section 3 of Chapter Four (pp. 207-240); those encountered with the use of by-products on pages 278 to 282; primary recycling pages 319 to 326; re-use pages 348 to 353; and Section 2 of Chapter Six deals with the constraints encountered with building re-use and extended life.
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CHAPTER ONE
INTRODUCTION

The uses to which energy is employed are so very extensive, and the expense for fuel makes so considerable an article on the list of necessaries, that the importance of the subject cannot be denied. (Benjamin, Count of Rumford, 1798, p. 4).

Rumford's statement has as much, if not more, relevance today as it did almost 200 years ago. There are many articles and books about now which at the worst exploit, and the best reflect the public concern about energy. Like "Pollution" the word itself is introduced into every honest argument and dishonest advertisement until everyone who says it is immediately suspect. Which is a pity, because although the word is becoming debased the problem still remains. It should be said straight away that this thesis is not an attempt to define the energy 'crisis' or the environmental problem; for the author's feelings coincide with those of Peter Victor's on the subject of definition, when he states in his book Economics of Pollution (1972, p. 7) that:

many people writing about the environment begin by noting the inadequacy of existing definitions of the term, which they seek to remedy by offering what invariably turns out to be yet another inadequate definition. Perhaps a lesson can be learned from Lord Morley when he said he was "unable to define an elephant but would be sure to recognize one when he saw it!"

Nor will this study attempt to discuss the availability of and demand for energy resources, a highly debated subject covered by many authors, one of the better references on the subject being Availability of World Energy
Resources by D.C. Ion. Crawley's (1975) book Energy provides a good background on the general subject of energy\(^1\) and the three volume work of Penner and Icerman (1975) also entitled Energy is representative of the books available which are basically concerned with the current state-of-the-art, in both nuclear and non-nuclear energy technology. Odum (1971) and Cottrel (1955) develop the general relationship between energy and society. The concern of this study is the relationship between building and energy and the purpose is threefold:

1) to gain a historical perspective on the relation between construction and energy.

2) to investigate the possibilities which exist to reduce production energy as well as the constraints which inhibit their realization. It does not however attempt to establish methods of implementing energy saving methods, by any combinations of incentives and/or disincentives, persuasion or compulsion.

3) to establish a framework from which future energy or other environmental analyses can be made.

The study attempts to cover areas which so far have tended to be neglected, particularly with regards to historical considerations, and the effect of recycling materials and re-using components. In trying to cover such broad objects it is clear that analysis could not possibly be discussed in much depth, but the work is not intended for that purpose. It basically provides one with an awareness of the problem, and a point of

---

\(^1\)The recent concern over energy has resulted in a great many technological periodicals devoting an entire issue to the subject - The Architectural Forum (July/August 1973), Building (12 September 1975), Science, (19 April 1974), Technology Review, (February and May 1974) and Scientific American (September 1971) are examples of these special issues which are quite useful.
entry into a subject which is only at its infancy, but with vital implications in the future which is worth a great deal more research. Before developing the theme of building and energy, one needs first briefly to put construction and architectural activities into context.
Fig. 1.1
Fig. A schematic diagram of the production sequence and product and material systems.
Section One  
The Construction System and Its Demand on Environment

This section is divided into the four following areas which deal with:
1) the establishment of the production, use and deproduction or PUD sequence and the material product systems within it,
2) establishing the scale of material systems and the demand made on them by various product systems,
3) the by-product generation associated with common construction materials,
4) the availability of natural resources suitable for construction.

The PUD sequence and the material and end-product systems within it

When man adapts the environment to meet his needs, he modifies nature in some way; he taps nature for raw materials which he processes into a product which has some utility value in satisfying his needs, and these are abandoned when they have no further utility. Figure 1.1 is a schematic diagram based on this basic progression. The sequence starts and finishes in the natural environment.

The production, use, deproduction, or PUD sequence is the common denominator for all products and it forms the most logical basis for analysing energy or environmental demands. Both demands are made throughout the sequence and are not isolated to only portions of it.

Within the PUD framework one can define two groups of systems, those based on materials (including primary fuels) and those on end-products. It is clear from Fig. 1.1 that these systems overlap, each material
supplying various end-product systems while end-products usually made up of a number of materials.

This study is mainly concerned with construction or building systems and with the traditional materials associated with them. The building system is a product system whose product is architecture, it is the system which produces, maintains and disposes of buildings, and it represents a portion of the construction system (Fig. 1.1) which produces the total built environment including civil works such as roads and rail networks and utility systems. The construction system, (heavily outlined in Fig. 11) is not analogus with the construction industry, which is also shown in Fig. 1.1 along with component 'industries' (2). Likewise the building system is not analogus with the building 'industry', nor is it with proprietary building 'systems' such as CLASP. The distinction between a system and an industry should be quite clear from the illustration. An industry is defined by a production activity or activities and represents only a portion of the overall system. The same distinction can be made between material systems and material industries, for the purpose of illustration, the iron/steel industry has been shown (1) within the iron/steel system (represented by a heavily outlined horizontal box).

The distinction between an industry and a system needs to be stressed because of the significant difference between their energy consumption and demand on the environment. The building industry itself which is becoming an industry of assembly operations only, involves only a small portion of the energy demand when compared to the earlier stages in the production sequence, particularly in the manufacture of processed materials. In other words the energy and environmental impact of the on-site assembly of a wood or steel framed building carried out by the construction industry
are not significantly different; but the demand in energy and other resources and the by-products generated to produce the steel and wood frames are very different indeed in both magnitude and nature.

The scale of various material systems and the demand made on them by various product systems.

To establish the relationship between the various product systems' material demand one needs to analyse, not the individual product system, but the material systems from which they draw their materials. The U.S. Department of the Interior, Bureau of Mines Bulletin 650 Mineral Facts and Problems 1970 edition provides excellent data on the 1968 U.S. demand for minerals, the significant minerals are represented in Fig. 1.2 which also indicates the vast scale of the building systems' material demand especially when compared against other product systems irrespective of material.

A review of this graph reveals which product systems use the most of each material. As one would expect the construction system accounts for the majority of stone, clay, gypsum and wood usage, materials traditionally associated with construction. Closer examination, however reveals some unexpected product/material relationships. Of particular interest is the small demand by some of the product systems which are traditionally associates with a particular material. Take the pottery industry for example; based on clay its demand for material is in fact minute when compared to other production systems, which are not normally associated with clay. Seven times more clay is consumed in the production of metals than in providing pottery; paper mills consume about four times more.²

¹ Figure 1.2, a fold out, is created on page 521.
² Even though not clear in the Fig. 1.2 this same situation arises in relation to aluminium: one would expect the aircraft industry, a product
It should also be noted that the clay used in construction (representing 80% of the demand for clay) is not solely devoted to structural clay products (e.g. bricks and tiles) as one might expect, nearly half of the constructive demand for clay is devoted to concrete; being used almost equally as a raw ingredient in cement production and in the manufacture of cement aggregates.

Figure 1.2 also reveals that even with the more refined high performance materials the construction system still consumes the largest portion of any product system. The construction system is the largest single user of iron and steel for example, absorbing 27% of the total demand. It is surprising to find ship building and aircraft together representing only 1% of total demand; which is only one seventh the amount of steel consumed by the packaging industry. The demand for steel and iron in manufacturing automobiles is naturally great, but one can begin to see why constructional demands are even higher\(^1\). A public relations pamphlet of the recently constructed one hundred storey John Hancock centre in Chicago sums the situation up when it boastfully states that the buildings "framework is constructed with 46,000 tons of steel, enough to build 33,000 (U.S.) automobiles".

Because the architect and civil engineer are responsible for choosing such vast amounts of materials, their decisions could indeed have an

\(^1\)Unlike the States more steel is consumed by transport than by construction in the U.K.
environmental impact\(^1\) and a major demand on resources, but because of large amounts of material consumed the architect and engineer would be in a good position to incorporate some of the by-products of the production process mentioned throughout the remainder of this study. The fact that the construction industry is a major consumer in all the materials shown suggests a wide range of possible substitutions within the construction system particularly when compared to other product systems such as transport. The quantities consumed by the construction system coupled with the opportunities of substitution should in theory enable those who select construction materials to pressure those manufacturers whose methods of production have excessive environmental impact to corrective action.

By-products associated with Common Construction Materials

The breakdown of the Department of Commerce production figures (represented in Fig. 1.2 by the unshaded bars) are somewhat misleading, from on energy or environmental point of view, since it includes processed and unprocessed materials\(^2\) together. The breakdown of materials in Fig. 1.2 clearly indicates the indirect consumption of clay and limestone

\(^{1}\)This impact is not limited to the production side of the PUD sequence, the construction system also creates an immense solid waste problem assuming there is a turn over in buildings and other structures. This aspect puts a real challenge to the designer - how long does he expect the building to last; he can design for either short life with problems of removal in mind, or design much less specifically for a longer but much more indefinite life.

\(^{2}\)An unprocessed material is one which is used in its extractive state, i.e. cut timber, dimension stone, aggregate or thatch; materials whose processing is limited to that of shaping and finishing. Processed materials are materials which have undergone substantial chemical changes or changes in state, i.e. clay to brick and bauxite to aluminium.
**Fig. By-products associated with the production (from primary sources) of one unit mass of iron.**

**NOTES:**

*a* By-products from the extraction and dressing operations for limestone and coal have been omitted, as well as any by-products generated during the manufacture of coke from coal.

*b* A combined overburden and waste-to-ore ratio is assumed to be 0.5 to 1, which is quite conservative. In many open pit mines the overburden alone could well exceed this ratio; for iron ore today the maximum economic stripping ratio (ratio of the overburden to that of the ore layer) is generally about 2:1 (Lovins, 1973, p.11). By comparison, copper in the U.S. has a waste/overburden-to-ore ratio which averages about 3.5:1, or seven times the ratio assumed in this figure.

*c* The dressing operation assumed is based on the upgrading of a magnetic taconite ore averaging 22-35% Fe, to produce an ore concentrate of 50-65% Fe, which is typical of the benefication which currently takes place in the U.S. (Bravard et al, 1972, p.20). By comparison the grade of copper ore mined in the U.S. is about 0.65% which is dressed to produce a concentrate of 25% Cu.

*d* The input/output ratios of the smelting operation assumed were based on figures from Wood, et al (1965, p.285).
in the production of metals; but it makes no reference, for example, to the iron ore, coke, or even air input demands required to produce the iron and steel, or the output of slags or flue-gas from the smelting operations.

In order to better illustrate the total material involved in producing a highly processed material a graphical material balance analysis (Fig. 1.3) has been made of the substances associated with the production of one unit mass of iron. The iron production processes represented are typical of the ores and processes currently being used in America. The startling fact drawn from the illustration is the relation or ratio between by-product and product, which in this case turns out to be 13.3 to 1\(^1\). In other words the production of one unit weight of iron also produces 13.3 units of by-products\(^2\).

---

\(^1\)The ratio between product and by-product in the case of metal is largely dependent on the grade of ore being processed, the by-products increasing inversely with the grade of ore. Iron historically used a relatively high grade of ore (50-60\% Fe) but this grade is becoming scarce in the U.S. Magnetic taconite ore is the most commonly used ore averaging between 22-35\% Fe. By comparison domestic ore in the United Kingdom in 1968 averaged only 27\% Fe (domestic ore represented 44\% of the ore consumed in the U.K. and the percentage is steadily decreasing). By 'dressing' the low grade ores it is possible to concentrate the ore up to 60\% Fe, the acceptable range for smelting. Iron ores with grades of 27\% are relatively high when compared to other metals, a typical grade copper ore, for example, would be 0.6\%

\(^2\)This by-product ratio can be compared to the estimates by Dane (1972, table 1) of the amount of "new solid materials 'processed' to produce one unit of output" for the U.S. in 1970.

<table>
<thead>
<tr>
<th>Total Solid Inputs (Units of Mass)</th>
<th>Outputs</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>By-product</td>
</tr>
<tr>
<td>Aluminium</td>
<td>15.2</td>
</tr>
<tr>
<td>Lumber</td>
<td>3.39</td>
</tr>
<tr>
<td>Steel</td>
<td>9.95</td>
</tr>
</tbody>
</table>

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\(\text{Total Solid Inputs (Units of Mass)}\)

\(\text{Outputs}\)

\(\text{By-product} : 1\)

\(\text{Product} : 1\)
Figure 1.3 is based on the law of the conservation of mass (or matter) which states that in any system mass cannot be created or destroyed\(^1\). The principle is simple enough, what goes in to a process must come out in some form or other. Unfortunately trying to perceive gaseous inputs and outputs is difficult. Take the smelting operation illustrated in Fig. 1.3, we can easily perceive the (3.3) units of solid raw materials (limestone, coke and ore concentrate) but this cannot be said of the four units of air required. The same is true of the output of the smelting operation, the 1.6 units of solid (iron and slag) are easy to grasp, but the 5.7 units of flue gas are not. Added to the difficulty of perception is the fact that the ratio between solids and gas coming out is not the same as that going into the process (in:solids 3.3, Gaseous 4) - (out: solids 1.6, Gaseous 5.7). These perception problems should not however detract from this material balanced technique of analysis. Its application to the environmental problem has been put forward by a number of authorities, Victor (1972) and Kneese, Ayres and D'Arge, (1972) being some of the better known.

To see what this by-product pattern represents on a national scale the by-product ratios developed in Fig. 1.3 for iron have been applied to the iron and steel production represented in Fig. 1.2. The by-products would apply only to the portion of the demand produced from primary resources (ore) and not the portion produced from recycled iron and steel. Production from primary sources in the U.S. represents about 64% of production output (Landsberg, 1964, p. 80). Even so to produce the

\(^1\)It should be noted that the law of conservation does not apply to the volume of by-products and this fact becomes quite significant when extracting and dressing low grade ores. The 'swell factor' for mining wastes varies between 1.6 to 1.9, in other words 1m\(^3\) of solid rock makes between 1.6 and 1.9 m\(^3\) of broken rock. The swell factor for tailings produced from ore dressing are even greater, ranging from 2.2-2.4 (Lovins, 1973, p. 43). An idea of the consequence of this swell factor in Britain can be gained from John Barr's Derelict Britain (1969) and J.R. Oxeham's book Reclaiming Derelict Land (1966).
The relative percentage of the eight most abundant elements and oxides in the earth's crust, to a depth of about 10 miles (Dennis, 1965, p.10).

Typical relative percentages of the basic oxides found in natural building materials and in those oxides required to manufacture common processed building materials.

**Fig. 1.4**

**Fig. 1.5**

**Sources:**
1. Hornbostel (1961, p.113)
2. Lee (1970, p.131)
3. Dennis (1965, p.202)
4. Diamant (1970, p.27)
5. Bravard et al. (1972, p.19-20)
69 million tonnes of iron from primary sources would result in by-products amounting to about 920 million tonnes, of which 525 tonnes are solid the remainder being gaseous. It would be fair to assume that about 27% of these by-products could be allocated to the construction system which is proportional to its demand for iron. Thus the construction system's portion of the by-products associated with iron production would amount to about 248 million tonnes which roughly equals the total demand for timber, clay, gypsum, aluminium and copper combined! The total amount of slag alone almost equalled the total demand for clay.

These by-product ratios and figures are quite startling, but it should be mentioned that the term by-product is not synonymous with waste, man himself determines whether or not by-products become waste, whether they become an asset or a liability to society, a subject which will be discussed at some length in Chapter Five. It should also be made clear that the nature of by-products varies enormously, and it is extremely difficult to equate or assess the impact of a tonne of biodegradable timber residue with a tonne of slag or sulphur dioxide.

Availability of Natural resources suitable for construction

At this point it would be interesting to compare the demand indicated in Fig. 1.2 against those minerals with the greatest abundance in the earth's crust to see if there are any similarities. Figure 1.4 graphically illustrates the relative abundance of various elements within the crust. Only eight of the ninety five known elements make up 99.4% of the crust, the remaining 0.6% contains the other eighty seven elements including common metals such as, copper, lead and zinc. Of the elements which are considered solids, silicone represents the greatest portion with
27% followed by aluminium with 8%, iron with 5%, calcium 3%. Comparing this natural occurrence of elements to actual material usage shown in Fig. 1.2, one would expect to find much greater use of aluminium and much less use of copper and crushed stone, 70% of which was limestone, itself consisting of over 50% calcium.

However, nature very seldom provides elements in their elemental form, instead they are combined into compounds. Fig. 1.4 also shows the eight compounds which represent 98.6% of the earth's crust by weight. Oxygen has combined with the seven other major elements to produce their oxides, whose occurrence roughly follows that of the elements. The occurrences of oxides and the material demand shown in Fig. 1.2 are much more similar than is the comparison of elements to material demand. The four primary oxides - silicon (SiO$_2$), alumina (Al$_2$O$_3$), lime (CaO) and iron oxide (FeO and Fe$_2$O$_3$) together represent about 85% of the earth's crust, and it is these four major oxides which have been plotted in Fig. 1.5 in relation to a few processed and unprocessed materials normally associated with building, i.e. clay for bricks and tiles, glass, cement, sand and stone for comparison slag has been included as well as iron ore. Even though these materials are thought of as being totally unrelated, chemically these materials have a lot more in common than one would expect. It is apparent that the bulk of inorganic building materials are, to a large degree, manipulations of these four basic oxides. In effect, the construction system is based largely on the most abundant compounds, so the argument about running out of material resources in a construction context is not valid; and we have not even mentioned the 'renewable' organic materials, particularly wood. Indeed the fact that matter cannot be created or destroyed further reduces the argument about 'running out' of materials.
Section Two

Broad Relationships between Building and Energy, the need to analyse Production Energy and the Methods and Problems Involved.

Even though the correlation between the abundance of oxides and demand are closer than those of elements there still appear to be some discrepancies. Alumina ($\text{Al}_2\text{O}_3$) for example is the second most abundant oxide but has very little direct use in building and aluminium which is produced from it, sees extremely little use in the building industry in comparison with other materials. Iron oxide, the third most abundant oxide is again not used to any great extent in its natural form and the iron produced from this oxide represents a comparatively small amount of metal in relation to the rock and clay based materials such as concrete. Calcium oxide ranks fourth in abundance and yet the usage of it in combination with silicate materials far exceeds that of both iron and aluminium or their oxides. With iron and aluminium having such admirable properties of strength and relative lightness one would think they would be used more often based on their natural abundance. Why it it then that the rock based building materials are so popular, it is an issue of tradition or economics? It is indeed an economic issue not only in terms of money but more importantly in terms of energy. There is a significant difference between alumina and aluminium, clay and brick, limestone and cement, gypsum and plaster, sand and glass and FeO and Fe, the former are raw resources which require processing and this processing requires energy. Energy is the item that has been missing from the discussion of materials so far.

For the purpose of discussion Fig. 1.2 contains the processing energy (expressed as coal tonne equivalents, TCE) required to produce sand/
gravel, an unprocessed mineral aggregate and steel, a highly processed metal. The results are dramatic, steel requires the equivalent of 197 million tonnes of coal to produce 108 million tonnes of steel, while the equivalent of only 2.47 million tonnes of coal were required to produce the 823 million tonnes of sand and gravel. These are only rough estimates, but total accuracy is not essential, what is important is the distinct pattern than emerges between the demand for a material and the energy required to produce it - the more energy required, the less the demand of the material. This explains the apparent anomalies between, for example, the large amounts of aluminium contained in alumina but the small amounts of aluminium actually used in its elemental form. The energy issue could well be an unrecognised, but major factor in building with significant ramifications on the building process.

The graphs clearly show that the types of material and methods of construction along with their architectural implications are all related in some degree to energy. The real significance about this is that energy, even though adhering to the physical law of conservation (first law of thermodynamics) differs from matter in that it degrades into a form which is not recoverable (the second law of thermodynamics). So from a constructional point of view the resource issue is not critical in respect to materials, but in respect to energy. Of course this would apply only if capital and not income forms of energy\(^1\) were used in processing materials.

\(^1\)The term income energy refers to all sources of energy which are continuous or renewable. Income energy can be obtained from three sources: 1) the heat of the earth, 2) tidal power, or 3) solar radiation. The latter being utilized either directly; (though optical, photo or thermo electrical, or photo chemical devices) or indirectly (photosynthesis, water and wind power or the utilization of natural temperature differentials, as found in the oceans.) Capital energy refers to energy which is stored but not renewable in man's time scale and includes fission and fussionable elements or fossil fuels including peat, coal, oil or natural gas.
Figs.
1.6
1.7
Fig. 1.6 A comparison between material processing energy, material demand, and the processing energy required to meet the demand of selected building materials in the United Kingdom in 1968.

Fig. 1.7 The relationship between material's processing energy intensity and its demand, for selected building materials in the United Kingdom in 1968.
NOTES: Figs.

15*17

Concrete: Demand for concrete was based on U.K. cement production figures (CSO, 1972 and IGS, 1973), imports and exports were insignificant. Aggregate demand was calculated in relation to cement production using a 1:6 weight ratio between cement and aggregate. Processing energy (from Kakhijani and Lichtenberg, 1972, Table 1) for cement was based on a figure of 2,300 KWh/ton (.32 TCE/tonne) and aggregate on a figure of 23 KWh/ton (.003 TCE/tonne). The figure used for aggregate is slightly higher than that used for sand and gravel. This is to allow for some crushed stone aggregate which uses approximately 30 KWh/tcn (.0045 TCE/tonne) (Bravard et al, 1972). Processed aggregate such as expanded shale was not considered because of its extremely limited use in the U.K.

Steel reinforcing bars have also been excluded from the calculations.

Cement demand (U.K. 1968).... 17.8x10^6 tonnes
Aggregate demand........ 17.8x10^6 tonnes x 6 = 108x10^6 tonnes
Energy demands
Cement.......................... .32 TCE/tonne x 17.8x10^6 tonnes = 5.7 x10^6 TCE's
Aggregate..................... .003 TCE/tonne x 108x10^6 tonnes = .32x10^6 TCE's
Totals.................................... 125.8x10^6 tonnes 6.02x10^6 TCE's

Energy cost / tonne of concrete 6.02x10^6 TCE's / 125.8x10^6 tonnes = .048 TCE/tonne

Brick: U.K. demand for bricks amounted to 7.46x10^9 bricks (CSO, 1972 and IGS, 1973). In order to convert this to weight, 2.2 kg/brick was assumed. Processing energy was based on a figure of 1.74 KWh/brick (Chapman, 1973b).

Total energy demand........ 1.74 KWh/brick x 7.46x10^9bricks / 7,560 KWh/TCE =1.7x10^6TCE's
Energy cost / tonne of bricks.. 1.7x10^6 TCE / 7.46x10^9 bricks x 2.2x10^-3 tonne/brick = .006 TCE/tonne

Iron and Steel: Constructional steel demand (BSC, 1969) represented about 8.5% of the total 1968 U.K. steel demand or about 1.4x10^6 tonnes. Processing energy was taken to be 12,900 KWh/ton (1.7 TCE/tonne) (Bravard et al, 1972).

Total energy demand (const.) 1.7 TCE/ton x 1.4x10^6 tonnes = 2.4x10^6 TCE's

Copper: Constructional copper demand was estimated (Chapman, 1973b) to be 25% of the total copper demand. Processing energy was based on a figure of 22,000 KWh/ton (2.9 TCE/tonne) (Bravard et al, 1972).

U.K. 1968 copper demand (Chapman, 1973b) .54x10^6 tonnes
Constructional copper demand @ 25% .54x10^6 tonnes x .25 = 135x10^6 tonnes
Total energy demand (const.).... 2.9 TCE/tonne x 135x10^6 tonnes = 4.2x10^6 TCE's

Aluminium: Demand of aluminium for construction purposes was estimated (Chapman, 1973b) at 10% of the total aluminium demand. Processing energy was based on a figure of 73,000 KWh/ton (9.6 TCE/tonne) (Kakhijani and Lichtenberg, 1972, Table 1).

U.K. 1968 aluminium demand (Chapman, 1973b) .55x10^6 tonnes
Constructional alum. demands @ 10% .55x10^6 tonnes x .10 = .05x10^6 tonnes
Total energy demand (const.)... 9.6 TCE/tonne x .05x10^6 tonnes = .5x10^6 TCE's
Unfortunately, today's industries are based on capital forms of energy.\(^1\)

To check this energy/material relationship further, an analysis of Britain's constructional material demand\(^2\) was undertaken with respect to material processing energy costs. The U.K. construction industry's demand for the selected materials is represented in graphical form on the right side of Fig. 1.6, the materials energy intensity or the amount of energy required to process the material\(^3\) (expressed as TCE/tonne of material) is shown opposite to the demand on the left side of the figure. The inverse relation between energy intensity and usage is obvious. What is particularly interesting is that the product \((I \times D)\) which results by multiplying a material's demand \((D)\) by its energy intensity \((I)\) appears to remain fairly constant. Comparing the extreme cases of concrete and aluminium dramatically illustrates this point. Concrete tonnage exceeded aluminium's by a factor of 2,300, aluminium's energy costs exceeded those of concrete by a factor of 220, but the energy required to produce the amounts of material involved only varied by a factor of ten. The inverse relationship between energy and demand is more accurately illustrated in Fig. 1.7.

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\(^1\) About 3 percent of the total demand for energy in the United States is met by income sources and are primarily confined to hydro-electric energy. Britain is in a similar situation.

\(^2\) The year selected for the study was 1968, which allows some comparison to be made with the U.S. statistics already presented in Fig. 1.2.

\(^3\) Transport, manpower, and allowances for processing machinery have been excluded in the energy calculations. They only account for a small fraction of the total energy requirement in the case of the sample materials. Much more will be said about the various types of energy requirements in Chapters Three and Four.
There is another relationship between energy and materials which brings us back to the environmental issue mentioned earlier, in particular the use of by-products. The by-product ratio and the nature of the by-product can differ significantly between processed and unprocessed materials. The average by-product ratio associated with sand and gravel production is probably in the neighbourhood of $0.25:1\ (1:4)$ which is very low when contrasted with the by-product ratio of highly processed materials like steel whose ratio is $13:1$. Comparing sand and gravel's by-product ratio of $25:1$ and its energy intensity of $0.003\ \text{TCE/tonne}\ (0.023\ \text{kWh/kg})$ to steel's by-product ratio of $13:1$ and energy intensity of $1.83\ \text{TCE/tonne}\ (13.9\ \text{kWh/kg})$ would strongly suggest a proportional relationship between the energy of by-products generated\(^1\). This point is well illustrated in Fig. 1.2 which graphically presents the demand, the processing energy required to meet the demand and the by-products likely to have been generated, for both sand and gravel and steel. Stephen Berry of the University of Chicago also suggests this direct relationship between production energy and environmental impact.

Doing 'energy economics' leads us to one of the root problems of environmental management - thrifty utilization of energy. It is remarkable how many of the environmental insults that we now recognize can be traced to the use of large amounts of energy...if we could identify areas in which there were large potential economies to be found in energy utilization, then we would begin, perhaps, to find a way to reconciling the technical life style we have so thoroughly adopted, with the threat of increasing environmental insults that seem to accompany our technology. (Berry, 1972, p. 8)

By examining production energy and its relation to the building system we could not only deal with the most significant resource problem,

\(^1\)The nature of the by-products also varies, the waste from mining and quarrying, even though massive in scale, are solid and usually more localized and inert than the by-products involved in the chemical processes such as smelting which are energy intensive.
but could well be at the same time resolving many of the environmental problems that the architectural designer is responsible for when he specifies a material or method of construction.

The need to be concerned with production energy

Most people are generally agreed that something should be done to solve the "energy crisis" but at this point the argument begins. As will be discussed in Chapter four most effort seems to be going into the more easily definable energy production side of the equation (which also seems to be more fashionable and fundable) with little interest on the demand or consumption side of the equation. Despite the overall disinterest in conserving energy on the demand side, those involved with the building system are primarily concerned with this area. Indeed, recently there has been a new and aroused interest among architects and engineers about the energy issue. The terms 'high' and 'low' energy architecture have been brandished around but with little thought as to what defined 'low' or 'high' energy. It is a relative term which needs a great deal more study before it has any significant meaning.

An argument arises as to how the architectural energy demand should be reduced. Should effort be devoted to conserving the running or operating energy involved with buildings or should effort be applied to reducing the production energy, the amount of energy required to produce the building? Richard Stein, a New York architect, who is widely published on the subject of energy and architecture, is well aware of the energy cost over the entire building cycle; but like most current efforts in the field he concentrates on in-use
energy being primarily concerned with reducing heating, cooling and lighting energy demands through optimal building morphology, fenestration and orientation; improved insulation; the use of ambient energy and the use of 'total energy or integrated environmental systems'. Stein (1973, p. 45) presents a very good case for concentrating effort on reducing in-use energy. His argument which is the one which is usually put forward is pretty well summarized below.

Construction and operation of buildings consumed more than 57% of all electricity produced in the U.S. in 1970, 7.5% was used by the construction industry directly or indirectly through production of materials used in construction...lighting, heating, cooling and other electrical uses required almost 50%. (Stein, 1972, p. 17).

This argument is valid enough. So if in-use energy does consume so much more energy than production energy, why bother with production energy? The arguments for a study concerning production energy fall into the following four broad categories:

1) material specification
2) energy end-uses
3) insight into the methods and cost of construction
4) the compatibility of in-use and production energy conservation

1 To fully appreciate the disparity between the efforts being devoted to in-use building energy as opposed to production energy one only needs to review Energy Bibliography (AIA, 1974) or Energy conservation in Building Design, a biography published by the Property Services Agency (PSA, 1976). In fact this disparity was one of the reasons for carrying out this study - to cover areas where little work exists.

2 Another argument put forward against effort to deal with production energy is based on the idea that the pricing will automatically lower production energy costs, increased fuel prices making energy intensive systems uneconomic. The validity of this theory will be discussed at some length in chapter four. Paradoxically the same argument could be said to be true of in-use energy as well, i.e. high energy costs forcing people to economize on fuel by non-architectural means such as putting on a jersey or spending a day at the library instead of at home.
Material specification. - The first reason for being concerned with production energy has already been developed in this chapter. As pointed out, those involved in designing the built environment are responsible for specifying an immense amount of materials, as well as the by-products which go with them. Reducing production energy could well reduce the overall environmental impact. The designer of buildings has an even greater responsibility in his designs than the designer of other product systems because of the scope and scale of options which are afforded to him only. Not only is there a great range of materials to choose from but, as will be pointed out in Chapters Five and Six, opportunities exist to re-use components or even buildings which are far more limited in other product systems.

Another point to be made concerns the unavoidable nature of material specification. For a building to exist materials have to be chosen and each choice has a production energy cost which cannot be avoided. Of course the choice often has in-use energy implications as well. The thermal properties of a wall for example is also an unavoidable decision. But in this case the decision as to the performance of the wall has to a large degree, already been made and set out in regulations, the designer's real choice is selecting the materials to meet the regulations. In addition the energy lost through the wall over the life of the building is only partially the responsibility of the designer, the inside and outside temperatures which ultimately dictate the heat loss are controlled either by nature or the occupant and not by the architect.

Energy end-uses. - The argument that in-use energy is so much higher than the production energy involved in producing a building itself needs
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<th>UNITED STATES</th>
<th>UNITED KINGDOM</th>
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<td>%</td>
<td>%</td>
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<tr>
<td>Space heating</td>
<td>10</td>
<td>10</td>
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<tr>
<td>Air conditioning</td>
<td>40</td>
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<td>Cooking</td>
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<td>20</td>
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<td>Lighting</td>
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<tr>
<td>Water heating</td>
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<tr>
<td>Machine appliances</td>
<td>80</td>
<td>70</td>
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<tr>
<td>Agriculture</td>
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<tr>
<td>Engineering and</td>
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<td>Transportation</td>
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<tr>
<td>Other</td>
<td>100</td>
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</table>

Fig. Energy consumption percentage mix by final users in the U.S. (1970) and the U.K. (1972)

Mix applies to final energy assumption and does not allow for electrical generation and transmission losses. If they were included, the effect would increase commercial and household percentage mix from approximately 30% to 35%, and industrial from 30% to 40% while reducing transports percentage from 30% to 25%. These figures apply to the U.S. breakdown only, but similar shifts could be expected in the U.K. figures.

NOTE: If they were included, the effect would increase commercial and household percentage mix from approximately 30% to 35%, and industrial from 30% to 40% while reducing transports percentage from 30% to 25%. These figures apply to the U.S. breakdown only, but similar shifts could be expected in the U.K. figures.

to be examined. In Fig. 1.8 we can see the overall breakdown of end-use energy consumption in the U.S. and U.K. Roughly speaking transport accounts for about 25% of energy consumption, commercial and household, which is basically made up of space heating, lighting etc. normally associated with in-use energy, accounts for about 33%, the industrial sector accounts for the remaining 42%. So on a national basis more energy is consumed in the production processes than that associated with operating buildings. Since the construction system's material demand dominates most major material systems, it would be logical to try to reduce production energy in this area, in fact techniques or methods applicable to construction materials would most likely be applicable to other areas in the industrial sector. In addition production energy would not solely be restricted to the industrial sector but would include a certain portion of the energy consumed in transport.

Another weakness to the argument that production energy is insignificant in relation to in-use energy stems from the fact that this notion is based on advanced nations in temperate climates. The difference between production and in-use energy for less developed nations, which after all contain the vast majority of the population, would not be nearly so drastic, for many of these countries have much milder climates and even when severe climates are encountered the heating and cooling standards are much lower. Production energy becomes particularly relevant in the global context for in the next thirty years it has been estimated that the number of new buildings required will equal the amount which exist today, and a significant portion of this construction will be in mild climates where there is often no energy expended on heating or cooling.
Insight into the methods and costs of construction. Another very significant reason for studying production energy is the insight into the actual influence of energy on design in an architectural sense and on methods of construction. Production energy being a hidden dimension in architectural design, a vital force influencing the entire nature of the building system, but one which is little understood by the designer, if he is consciously aware of it at all.

In primitive architecture the designer, producer and user, who are often one and the same, are intimately aware of the effort or energy involved even though it might be subconsciously. Indeed the energy costs of producing shelter have to be low\(^1\) as those producing primitive buildings have very limited means by which large amounts of energy could be utilized\(^2\). Today's designers are removed from both production and use and it is doubtful whether they are nearly as good as the builders employed in simple societies, at getting value per unit of production energy\(^3\). Contemporary architects could argue that they are all the victims of circumstance, choice being restrained on 'economic' grounds.

\(^1\)Energy costs themselves could be the main criterion by which 'primitive' architecture could be defined. In fact it could be the criterion in settling the dispute over the definition of 'indigenous', 'vernacular' and 'primitive' architecture which for the purposes of this study have been considered synonymous.

\(^2\)Some would argue that it is because of the limited means of employing energy that makes societies and architecture 'primitive'.

\(^3\)Various authors have expressed the ingenuity and resourcefulness found in primitive and vernacular buildings, perhaps the most notable being Moholy Nagy – Nature Genius in Anonymous Architecture (1959), Paul Oliver – Shelter and Society (1969), B. Rudoski – Architecture without Architects (1964), Norbert Schoenaur – Introduction to Contemporary Indigenous Housing (1973).
But economical in what sense? The Oxford Dictionary defines economical as "saving or frugal; and to economise: as to use sparingly and to avoid expense". In either energy or environmental terms it is questionable whether current designs are indeed economical when compared to buildings produced by more underdeveloped societies including earlier societies in what would now be considered the developed world.

Understanding production energy would lead to a far more accurate understanding of 'cost'. Indeed energy budgeting is the only method of measuring total effort, and a unit of energy is empirical and unaffected by societies' values. It would be the ultimate way of comparing different methods of construction. Energy after all, is not subject to inflation.

The compatibility of in-use and production energy conservation. - In most indigenous or primitive architecture the production energy costs are quite low. However, this in no way detracts from their climatic performance, in fact most indigenous buildings are quite good in this respect (the builders/designers of such 'primitive' architecture could themselves be the ones to suffer from bad thermal performance). The energy input in relation to in-use performance of primitive or vernacular architecture such as the igloo and the thick walled clay courtyard housing of North Africa, at opposite ends of the climatic spectrum, bear witness to the possibility of low production energy costs and low running energy costs.1 In other words low production energy costs are quite compatible with low running costs.

1The effectiveness of primitive architecture modifying the climate without resorting to energy intensive mechanical heating or cooling systems is well argued by Fitch and Branch in their article "Primitive Architecture and Climate". (1960).
Indeed the large amounts of energy consumed in 'modern' buildings which makes production energy so small by comparison could itself be partly due to their use of highly processed energy intensive materials, 'economical' on a short term money basis; these materials can be used in such a way as to have very poor thermal performance. The single pane glass office blocks immediately come to mind, and this thermal deficiency can only be corrected by complicated servicing systems, requiring a large energy subsidy to run. This situation could not be tolerated in a more primitive situation, for the societies lacked both the environmental control equipment and the energy to run it. Production energy and in-use or running energy should not be thought of as being mutually exclusive. It is not an issue of saving running energy costs or production costs it is an issue of saving running and production costs. A unit of energy saved is a unit of energy saved, irrespective of whether it is in production or operation - and there are potential savings in both areas.

Methods and Problems of Production Energy Analysis

At the present time there are almost as many methods of evaluating the energy costs of a product as there are workers in the field. Where, by chance, the same product has been analysed by different methods, the results often vary widely (Chapman, 1974, p. 91).

To appreciate Chapman's statement Table 1.1 has been provided. It indicates the production energy costs for groups of common construction materials, taken from four different sources. For comparison the material energy intensities are expressed in kWh/kg.¹

¹Throughout the remainder of the study energy will be expressed in kilowatt hours (kWh) and will refer to thermal energy and not electrical, since the material energy costs used in this study have had any electrical energy used in the production process converted into primary units of energy to allow for electrical generation conversion losses which most
Table 1.1 Material Energy Costs (kWh/kg) for Selected Materials
From four sources.

<table>
<thead>
<tr>
<th>Materials</th>
<th>NATO (Kovach) 1973 (p. 56)</th>
<th>NEDO 1974 (Table 56)</th>
<th>Barnes &amp; Rankin 1975</th>
<th>Makhijani &amp; Lichtenberg 1972 (Table 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>6.95 - 13.9</td>
<td>6.9 - 9.7</td>
<td></td>
<td>13.2</td>
</tr>
<tr>
<td>Aluminium</td>
<td>16.7 - 75</td>
<td>66.6 -89</td>
<td></td>
<td>90</td>
</tr>
<tr>
<td>Copper</td>
<td>6.95 - 83</td>
<td></td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>Portland Cement</td>
<td>2.5</td>
<td></td>
<td></td>
<td>1.55</td>
</tr>
<tr>
<td>Concrete 1:2:4</td>
<td></td>
<td></td>
<td></td>
<td>.144</td>
</tr>
<tr>
<td>Sand and Gravel</td>
<td></td>
<td></td>
<td></td>
<td>.02</td>
</tr>
<tr>
<td>Glass</td>
<td>8.3 - 13.9</td>
<td>6.9 -13.8</td>
<td>4.167</td>
<td>7.2</td>
</tr>
<tr>
<td>Brick</td>
<td></td>
<td></td>
<td></td>
<td>.78</td>
</tr>
<tr>
<td>Lumber</td>
<td>1.11</td>
<td>2.7 - 5.6</td>
<td></td>
<td>6.4</td>
</tr>
<tr>
<td>Paper</td>
<td>6.95</td>
<td>2.7 - 5.6</td>
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At a glance it is quite evident that material energy costs do vary widely, which is one of the major, if not the most pressing problem facing those trying to research production energy. The causes of such a wide variation fall into three inter-related groups; the first concerns authors assumed to be around 75%. Occasionally other units of energy will be used when quoting directly from a source. The energy cost of a material will be often referred to as energy intensity and will generally be expressed as kWh/kg. As mentioned again in Chapter Three, there are a multitude of ways of expressing intensities, however, most authors generally express a material's energy intensity units of energy per unit of mass (sometimes referred to as specific energy). Below are conversion factors for converting kWh/kg from or to other combinations of energy and mass which are often encountered as means of expressing energy intensity.

Multiply By to obtain

<table>
<thead>
<tr>
<th>M Btu/s.ton</th>
<th>.3228</th>
<th>kWh/kg</th>
<th>multiply by:</th>
</tr>
</thead>
<tbody>
<tr>
<td>M Btu/1.ton</td>
<td>.2884</td>
<td></td>
<td>3.6764</td>
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<tr>
<td>Therm/1.ton</td>
<td>.0284</td>
<td></td>
<td>34.674</td>
</tr>
<tr>
<td>Btu/lb</td>
<td>.006461</td>
<td></td>
<td>154.775</td>
</tr>
<tr>
<td>Cal or kcal/lb</td>
<td>.0025639</td>
<td></td>
<td>390.03</td>
</tr>
<tr>
<td>Cal or kcal/kg</td>
<td>.001163</td>
<td></td>
<td>845.85</td>
</tr>
<tr>
<td>GJ/tonne or MJ/kg</td>
<td>.27778</td>
<td></td>
<td>3.6</td>
</tr>
<tr>
<td>MT/tonne or J/kg</td>
<td>.00027778</td>
<td></td>
<td>3600</td>
</tr>
<tr>
<td>kWh/lb</td>
<td>2.20462</td>
<td></td>
<td>4536</td>
</tr>
<tr>
<td>kWh/s.ton</td>
<td>.001102</td>
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<td>907.2</td>
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<tr>
<td>kWh/1.ton</td>
<td>.0009842</td>
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<td>1016.05</td>
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<tr>
<td>kWh/tonne</td>
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\[ k = 10^3 \quad M = 10^6 \quad G = 10^9 \]
the method of determining energy costs, the second is concerned with
the efficiency of energy conversion and the third with system definition.

Methods of determining energy costs.- There are three general methods
used today to determine the energy costs of various products; they are
the statistical method, the input/output method and the process method,
all of which are described in some detail in P.F. Chapman's article
called "Energy Costs: A review of Methods" (1974). However, a brief
description of each method will be given here.

The statistical technique simply involves dividing the energy input
into an industry by its output. For example using a data source such
as the U.K. Digest of Energy Statistics and the report on Census of
Production one finds that the brick industry in the U.K. consumed
19 x 10^9 kWh of energy in 1968 and produced 7.5 x 10^9 bricks, giving
an energy cost of 2.5 kWh per brick. This technique is only worthwhile
for finding the energy requirements for particular production activities
which are defined by an industry which is recognisable in the statistical
sources. This method becomes progressively less accurate as one progresses
down the production sequence. In the brick example one might find that
the energy consumed by the industry applied not only to that for the
kilns but also for the extraction of the clay. This is due to the
traditional definition of the industry. However, in another industry like
iron and steel industry, the energy could apply only to smelting and steel
making and some fabricating work, without including mining which is
considered as a separate extraction industry.

The statistical method also expresses the energy intensities
produced for a material as an average, the 2.5 kWh per brick mentioned
above is an average which does not take into account the different plant efficiencies or the type or size of brick, neither does it consider the indirect energy cost like those involved with manufacturing the plant. Transport cost may or may not be included, but this is largely determined on the traditional responsibilities of particular industries. Energy 'credits' for by-products or co-products are normally not taken into consideration. Nevertheless the statistical method does provide an estimate for certain industrial activities.

The second method of energy costing involves the use of national or regional economic input/output tables, usually presented in the form of a square matrix. It indicates the flow of money or commodities between industries and can show, for example, the flow of these items between the construction and steel industries. It is possible to sum up mathematically all the interactions or flows related to one particular industry. The result is a summation of all commodities required with respect to a specific output. Because the fuel industries are also included in the matrix, fuel and thus energy calculations can be made as well.

The input/output method has a number of advantages over other methods of estimating energy costs; it can be computerized fairly easily and is based on published and strictly defined economic statistics, eliminating detailed technical knowledge of the processes involved. The depth of the analysis is much greater as well, even including non-production activities accomplished by the service industries. There are

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1Additional general information on input/output analysis can be best gained from Leontief's book *Input/Output Economics* (1966); and its use for energy analysis from any of the following sources: Herendeen (1973), Wright (1973) and Carter (1974).
however, disadvantages in this input/output method; it suffers the same problem as the statistical approach having limited disaggregation of industry which results in the averaging problem previously described. In addition, the results are often expressed in terms of producers pounds or dollars and unless this is known and corrections made for inflation errors can arise, it is also possible that errors would arise if the figures were used in relation to consumer prices and not producers' costs.

The third method of energy analysis is the process method which involves tracing down energy inputs for each production activity. This method is the most accurate and can be very finely defined. There are a few very simple process analyses made later in this study. It can apply to one activity or to an accumulation of activities. For very accurate costing, a thorough understanding of the relevant manufacturing and assembly processes are required and it is unlikely any one individual would have this detailed knowledge, especially one spanning the entire PUD sequence, or when more than one family of materials are used, which is inevitable when considering the constructional system. Perhaps the greatest disadvantage to the system is the immense amount of work that it involves in order to produce energy costs.

Energy conversion efficiency.— The second item to be considered in energy costing is the efficiency of energy conversion in both the material-processing operations and in the conversion of energy from one form to another, a subject covered in Chapter Six. Energy conversion is particularly relevant to production operations powered mainly by electricity such as aluminium, copper production and shaping operations, for the conversion fuel into electricity in the U.K. averages out at an
efficiency of about 25% (electricity production divided by the energy value of the fuel input). If energy costs are developed by the 'process' method the assumed conversion efficiency of the plant can have a significant effect because of the large variation between plant efficiencies.

Another factor affecting energy costs which is allied to conversion efficiency concerns by-products and co-products and recycled materials. An apportioning problem develops when any of these are involved, for example, if slag from a blast furnace is used in the manufacture of cement, how much of the energy cost should be allocated to slag from the overall iron production costs. Co-products, which are common in the petroleum industry, for example, have similar problems. The amount of recycled 'new' or 'old' scrap used in producing recyclable materials (glass, metal, paper) also has an effect on material energy costs. Estimates of energy costs can be based on producing materials from either primary (virgin) sources, secondary sources, or a mixture of the two; with the energy intensity of the mixture falling somewhere between the other two. This is a subject discussed at some length in Chapter Five.

System definition. In describing the different methods of establishing energy costs, it was clear that each method varied in the number and type of activities included, producing variations in energy costs. Energy costing is a field which is developing so rapidly that conventions as to what should or should not be included in such estimates have yet to be developed. Whether or not conventions on system definition will ever be developed is somewhat in doubt owing to the complexity of defining production systems. Figure 1.9 is an attempt to illustrate graphically the following four major variables involved in system definition which are
required in order to establish energy costs.

Briefly the four variables are:

1) How many 'form' related production activities have been included in the energy costs? 

2) What other types of 'non-form' related activities have been included such as transport, in the energy costs?

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1Description of the various types of 'form' and 'non-form' related production activities are included in the beginning of chapter four which develops in more detail the production sequence. Essentially 'form' related activities are those which affect either the physical or chemical nature of a material or product.
3) What energy usages have been included in the energy costs?

4) How many 'generations' of plant and equipment have been included in the energy costs?

In this study product energy costs will be limited to what could generally be referred to as direct energy, that is the energy required to power the process which directly affects the 'form' or 'place' utility of the product concerned. This 'direct energy' is indicated in Fig. 1.9. Except for input/output energy analysis most energy cost estimates are restricted to this area.

Between problems arising out of the different methods of analysis, conversion efficiencies, and system definition it is no wonder that energy estimates vary widely between sources. It is not the intent of this study to do any in depth process analysis, like those of Chapman (1974)

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1 There are three types of energy usage which can be included in production energy costs. The first and most important is the direct energy required to actually operate plant and equipment. The power required to operate a kiln or a lorry are good examples of direct energy involved with form and place related processes. The power required to operate heating and ventilation systems and typewriters would be examples likely to be associated with service orientated activities. The second type of usage to be considered is the energy which is required to actually produce the plant or equipment actually involved in the production process. This would include the energy required to make the kiln, the lorry, the typewriter or the office building. The third energy usage would be that involved to produce facilities which are communal in nature but are in some part related to the production of the item being considered. Communication systems such as roads or rail roads are good examples of these facilities.

2 First generation energy would be that energy required to operate and produce the plant and equipment that was used to produce the plant and equipment or facilities directly involved with the product being analysed and so on.
to establish energy costs for a few materials. The energy costs for materials have been taken from various sources, average values had to be assumed for purposes of discussion. The intent of this study is instead to cover a broad spectrum revealing not so much the actual energy intensities of specific methods of construction but to revealing fundamental relationships between materials over a period of time. Indeed, the lack of accurate energy cost figures prevents a rigorous analysis of the subject. A point well made by the Central Policy Review Staff (CPRS, 1974) in their report *Energy Conservation*:

Too little detailed and consistent information has so far been collected to make it possible to compare all the different forms of end use. It is therefore impossible, in a report of this type, to examine precisely the potential for energy saving in every method of use in these sectors, which account for most of our fuel and energy consumption. (CPRS, 1974, p. 40).

It should be stated that a great deal of work needs to be done in establishing the energy costs of specific materials, especially the more mundane materials frequently used in construction like chipboard, strawboard, building felt and asphalt which often have by-product or co-product relationships.

Arrangement of Study

So far in Chapter one the discussion has not dealt with time; an analysis of this type is a static one. In energy, environmental, or economic events that are related are dynamic and change with time, they must be approached through a multi-period study or dynamic analysis, which looks at systems that either grow over time or whose structure changes over time, for reasons such as taste, technology or organisation.

Examining Fig. 1.2 reveals the significant changes which must have taken
place with regards to the construction system, take for example dimensional stone, in 1968 its demand was minute when compared to crushed stone; fifty years ago the situation would surely have been reversed. Clearly when studying energy in relation to the building system one must use a dynamic approach, for it is difficult to draw any conclusions about the future until something is known about the past. But in a system as highly complex and massive as the building system, whose product life can last hundreds of years, and where changes are usually perceivable only after generations a dynamic analysis must cover a sufficiently long period of time in order to see shifts and trends within a system.

How does one analyse a system as sluggish and as massive as that found in building? Clearly a historical analysis or case study needs to examine what the building system produces. Returning to the idea of the production system as diagrammed in Fig. 1.1, the building system could be imagined almost as an extrusion machine moving through time and leaving behind it a continuous trail of building materials which have been incorporated into architecture. An energy analysis of the material make up of this hypothetical trail would tell us a great deal about the past and give us some insight as to the future. Analysing the entire system would be an impossible task, it has to be limited in respect to location, time and in a degree material. A representative architectural element would be the most practical way of reducing this task to a manageable size, but still providing enough information for analysis. Chapters Two and Three provide such a historical case study. Chapter two traces the changing utilization of different British roofing materials over the centuries and chapter three with its supporting appendices A to H analyses the consequences of these shifts in terms of energy costs. The
Conclusion generally reached is that materials are becoming more energy intensive. The remainder of the study deals with the possible methods of reducing production energy demand. Chapter Four reviews the possibilities of reducing energy in production operations based on materials from primary sources. Chapter Five, examines the possibility of using both material and components from secondary sources and chapter six is concerned with energy saving through avoidance by reducing the demand for new construction; and if new construction is required, by using less materials or by substituting materials of lower energy content.

It should be mentioned that throughout the remainder of this study, the maximum use of graphic analysis has been attempted, for it is the Author's belief that in this fashion it is possible to condense a great deal of information into one figure which is easily comprehended.
CHAPTER TWO

HISTORICAL CHANGES IN BRITISH ROOFING MATERIALS

It may be helpful to offer a brief explanation of why the case study concentrates on roofing materials in Britain. As said before, to attempt to study all construction materials simultaneously, regardless of use, would be hopelessly complex if not impossible, some restriction has to be imposed. Roofing has always been the most essential building element\(^1\) and the function of roofing materials has been relatively restricted and unchanged throughout history\(^2\). More importantly, roofing materials and their development are reasonably easy to identify in literature, and in most cases it is fairly safe to assume that forces which affect particular roofing material will also have similar effects on the same

\(^1\)Using roofing, a constructional element essential to all buildings is critical in an historical analysis of such length; for it must be remembered that such basic items as floors, windows, even walls which are taken for granted today, were often missing in a peasant’s dwelling of the early middle ages. Their dwelling often consisted only of a roof. It should also be stated that if energy intensive materials are to be employed in a building one of the most logical areas for it to be used is in the building's roof.

\(^2\)The term roofing materials will be restricted in this study to those materials which provide the water barrier and will not include supplemental insulation materials or structural elements such as rafters, purlins, sacking or laths. Historically roofing materials have been restricted to this definition, with the exception of thatch which provided effective insulation as well. However, with the relatively recent introduction of self supporting 'profiled' roofing materials which perform a structural function as well, the overall function of roofing material is becoming somewhat blurred. Indeed if the use of 'profiled' roofing sheets and sandwich panels continues, a meaningful analysis of roofing materials will become extremely difficult.
material use for another constructional purpose during the same period of time (and vice versa). The length of the study goes back to the eleventh century. This might appear to be excessive but to gain a perspective which illustrates the gradual shifts in the building system which is notoriously slow to adapt to change, must extend over a significant period of time. However, extending the study further back into the Dark Ages would yield little additional information. In Britain this time span also permits coverage of the three methods of building as defined by Amos Rapoport¹ (1969, p. 8):

1. Primitive, i.e. very few building types, built by all.
2. Pre-industrial vernacular, i.e. limited building types built by tradesmen.
3. High-style and modern, i.e. many specialized building types, built by teams of specialists.

Britain was an obvious choice because of the availability of literature dealing with the historical usage of building materials. L.F. Salzman's Building in England down to 1540; Alec Clifton Taylor's The Pattern of English Building; The Illustrated Handbook of Vernacular Architecture by R.W. Brunskill; The Development of English Building Construction by C.I. Innocent and Old English Houses by Hugh Braun were particularly useful sources of information for earlier periods of British history with Marian Bowely's book Innovations in Building Materials providing the background for more recent periods. Other useful sources of background information, dealing with British

¹The period also covers the majority of technological stages in man's development, which Lewis Mumford (1955, Chapters 3 and 5) refers to as the Botechnic, Paleotechnic and Neotechnic phases of development.
and European social, economic, technological and architectural developments; as well as with developments and the production of specific materials are contained in the reference list at the end of this chapter. (Most of these sources of information were also helpful in the Chapter Three energy analysis.)

The reasons for picking an area as large as Britain was to overcome regionalism. Accuracy would have undoubtedly been improved by the selection of a smaller area such as a city or county, but it would have also presented a distorted view of the overall trends in material utilization, this being especially true in the early periods of the study, when construction remained very regional due to the general lack of trade and transport. For example, one would get a drastically premature impression of the use of slate if one were to limit the study to an area such as Westmorland, which is naturally abundant in slate. General use of slate did not occur until the development of the canal and railways. Britain on the other hand, is not too large to prohibit some movement of materials between areas. It also has a wide variety of natural resources, both organic and inorganic, which can be used for roofing and its climate is neither severe nor benign; in other words, Britain represents a geographical area where material selection has never been overly restricted because of unique or severe physical constraints.

The overall objective of this chapter is to estimate the percentage mix of roofing materials by year. It is to show the relative predominance of various roofing materials in relation to each other at a specific point in time. The figures are not quantitative in respect to either weight or volume (they are 'quantified' in the next chapter) but represent the
degree of use, which is more closely associated with roof areas. For example, in the seventeenth century thatch probably represented 80% of all the roofing being applied during that period of time. The percentages represent only the material being applied (input) to the building stock. It does not represent the material already existing in stock, it also does not take into account materials being removed from the stock through either disaster, or demolition, or deterioration.

The estimation of roofing material percentage mixes was divided into three parts. The first deal with the very early dominance of the two unprocessed organic materials, thatch and wood, and their gradual disappearance, the second part covers the emergence of clay, stone tiles and slate, the traditional inorganic roofing materials which replaced the original organic materials and the final section concerns the very

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1 We must recognize that analysing only the yearly inputs of roofing materials would favour the less durable materials since a building roofed with a very durable material, such as slate might require only one covering, while a building roofed with a less durable material with a shorter life, might have to be reroofed several times - two or three times as much of the less durable material could conceivably be required for the same effective coverage. Of course this would have to be taken into account in an energy analysis of the materials as well, one should be interested in seeing how the initial production energy costs are amortized over the material's life, in other words comparing energy consumption per year of life. In principle this durability factor should be considered, however in this study it has been ignored for two reasons: first is the difficulty of establishing comparative material lives based on durability, especially when so much depends on maintenance and environmental conditions; and second, and far more importantly, is the fact that the theoretical life of a material (even if it could be established) often bears little relation to the length of time a roofing material is actually used. A material's usage is more often than not determined, not by its physical deterioration of the material itself, but by the length of the building life to which it is applied.
rapid material substitutions which largely occurred in this century, which largely replaced the traditional inorganic materials with processed organic and inorganic materials. In order to make the assumed changes in roofing materials more easily understood, the maximum use of percentage mix graphs has been attempted.

For each of the three sections described, a page of graphs has been prepared. Each page containing an individual graph for each material as well as a composite percentage mix graph for the entire section being discussed. These graphs are located on pages 518 to 520 and are designed to be folded out when reading the section which corresponds with them; this allows the reader to continually refer to the graph even though the text concerning it might cover a number of pages. All the assumed material mixes are summarized in Fig. 2.4.
Thatch

Rafters and thatch were what made the early homes of Britain weather-proof. (Braun, 1962, p.18).

It is difficult to imagine in the twentieth century, when the use of thatch is almost non-existent, that thatch, without doubt, constituted the dominant roofing material throughout the Middle Ages and for a short period after. In fact the word thatch is derived from the word 'thack' which originally applied to any roofing material, but early roofing materials were so frequently vegetable products like wheat straw, reed or heather, that thatch acquired its more restricted meaning.

Medieval dominance of thatch

In his book House Form and Culture, Amos Rapoport talks about choice and constraints. He suggests that "the more forceful the physical constraints, and the more limited the technology and command of means, the less are the non-material aspects able to act". (1969, p.58).

He goes on to say that physical forces on a building can be examined in relation to four sets of scales. The first scale is an economic one ranging from subsistence to affluence, the second is a climatic scale ranging from severe to benign, the third concerns technological skills, and the last involves material availability. A brief examination of

1 Besides wheat straw, reeds and heather, other vegetable materials likely to be used in early Britain included sallow, broom, marram grass, various rushes, tall sedge, bracken, ferns, hay, as well as oat, barley, flax and rye straw and stubble. For the purposes of this study turf and unbaked clay will also be included under thatch. These materials were so frequently found in conjunction with thatching materials, that it would make any attempt at separation impractical.
these four areas quickly explains the universal popularity of thatch during the Middle Ages.

Economic Conditions.- The Middle Ages were feudalistic. The majority of people were serfs, deeply attached to the land. Their work was directed to the immediate satisfaction of their own wants and those of their superiors who provided protection. People grew crops and raised animals for their own consumption and the kinds and quantities of products raised were determined by basic human needs for food, clothing and shelter. For the majority there was little trade, and the little there was, was done by barter. There was no merchant class to speak of, and few craftsmen other than the smiths and weavers, who were attached to the village, but living the life of a peasant. A self-sufficient, predominately agricultural economy remained throughout the Middle Ages. It was a period of scarcity with ancient ties of blood and soil, and of family and feudal allegiance.

What were the effects of these economic conditions on material selections? They were restrictive indeed; the lack of currency, and trading eliminated all but local or 'on-hand' materials; and the choice among them was further reduced by the self-sufficiency aspect of medieval life.

It would be unlikely in Britain to find an area restricted to only one suitable material for roofing; a choice normally existed. However existence of different materials does not guarantee equal use of those available. All material has to go through some degree of collection and
processing before it is useful in construction.

It is quite logical to expect that in a scarcity situation in which a choice of local materials existed, the material chosen would be the one that satisfied the user's requirements, and involved the least amount of effort. This logic was not overlooked by the farmer of the Middle Ages, and organic thatching material was the natural choice on the basis of minimum overall effort.

Climatic Conditions. Our modern solutions to climatic problems often do not work, and our houses are made bearable by means of ingenious mechanical devices...primitive and pre-industrial builders cannot take this attitude since they lack the technology to allow them to ignore climate in design...peasant builders are faced with the task of creating shelter for a wide range of climatic conditions. For their own comfort (and occasionally even survival), they have to create, with very limited materials and technology, building which respond successfully to the climate. (Rapoport, 1969, p.84).

Britain has a wet temperate climate which not only allows the growth of thatching materials, but makes their use extremely attractive.

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1 It must be remembered that the peasant was well aware of the total effort involved with producing and applying construction materials. Unlike today, where the manufacturing and application are divided into highly specialized and isolated phases; the peasant's responsibility ranged over the entire task, from extraction or collection of the basic material, through any interim processes such as shaping, to final application of the product. One only has to compare the difference (not to mention the technical problems) between collecting, cutting and applying thatch and the manufacture and application of clay tile to quickly appreciate this point. The effort in just supplying the wood to fuel the kiln would probably be close to equalling the entire thatching operation.
Because of the high insulative value of thatch, it was well suited not only to keeping out Britain's wet weather, but keeping out its cold as well. With only one material a thatch roof resolved a multiple of environmental objectives. In an economy of technological and economic scarcity, where a high level of environmental performance was needed with the least overall effort, once again thatch was the most logical choice.

Technical Conditions.- Redfield points out that there is no technical vocabulary in a peasant society, because there is little specialization beyond age and sex, and in building terms this implies everyone is capable of building his own dwelling - and usually does (Redfield, 1965, p.72-73). Any surplus skill in these societies would be reserved for special buildings, in the case of position for the church or nobility. In fact these special buildings are the only buildings to have survived from that early period. Tradesman and metal tools were scarce and out of the reach for most. The commoner had neither the skill or the tools to handle stone or even wood roofing materials, and those materials requiring any kind of processing like lead or baked clay would surely have been eliminated. Straw and other vegetable materials were very much the peasant's medium. He worked the grasses for a livelihood so he would be familiar with their properties and more importantly had the tools (frequently of wood) and skills or technology to work it.

Technologically speaking, the structural frameworks supporting roofing materials during the Middle Ages were quite unrefined and often very flimsy (although they improved with time). There are numerous references to medieval structural instability; houses in London were so unsubstantial that the alderman were provided in 1212 with crook and cord to pull down any structure which either caught fire or did
not comply with fire regulations (Innocent, 1971, p.128). Occasional difficulties were experienced even with costlier edifices like chapel and church. The Beverley Minster, for example, collapsed in 1200 when straw was applied to the roof (Salzman, 1967, p.26).

It is obvious that the lightest roofing material would be a natural choice under such structural insecurity; and during the Middle Ages thatch was the lightest material available for roofing. Transport technology was very limited during the Middle Ages, which was a critical factor in material selection. Hamilton gives one an idea of the overland transport conditions when he states:

Till the middle of the eighteenth century, travelling was usually on horseback. The roads were still too wretched for wheeled vehicles. It took a fortnight to go from Edinburgh to London. Before setting out, a traveller usually made his will and took fond farewell of his friends. (Hamilton, 1947, p.345)

Inland water transport was not much better. Hill (1969, p.166-7) points out that bad communications made for an intense regionalism and that aristocratic privilege and vested interest often hampered improved communications, particularly water-ways, before 1640.

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1 Thatch weighs approximately 30 kg/m² (6 lbs/sq.ft). Its nearest rivals were cast lead and slate which roughly averaged out at about 45 kg/m² (9 lbs/sq. ft.). Slate is not to be confused with the limestone tiles or sandstone flags which were also used during the period but weighed anywhere from 87 to 240 kg/m² (18 to 50 lbs/sq.ft.).
Landlords' weirs and mills obstructed river navigation; and some towns opposed improved river transport as in the case of Southampton opposing water communications with Winchester in 1624. Towns which accepted water transport often limited its use by imposing tolls, but even where towns took a more positive attitude towards water transport they were resisted by the landowners along the river; the Wiltshire landowners objecting to making the Avon navigable in the seventeenth century being an example. Salzman, and Clifton-Taylor make numerous references to the high transport costs of construction materials during the Middle Ages, and Innocent (1971, p. 212) refers to the practice of white-washing common thatch roofs being curtailed except where the supply of lime was within a day's journey. It would be safe to say that for the vast majority, roofing materials would be restricted to those within a three or four mile radius from the point of application.

Material Availability.- The severe transport restrictions of the Middle Ages were perhaps most significant for the extensive medieval use of thatch. Both wild and cultivated vegetable materials were very close at hand. The following information from Hoskin's chapter on 'The Colonization of Medieval England' (1970, chap. 3, pp 75-116) helps one appreciate the vast potential sources of wild thatching material. The Domesday population of England was only about 1½ million. Major cities of today, like Portsmouth and Newcastle, were empty sites; and St. Albans had fewer than 150 to 200 people. The overall density of population was about four persons per square mile, and the most populous county of Norfolk had only ninety-five thousand people, rather less than the city of Oxford today. Perhaps half the land of the village territory still remained to be rescued from the natural wilderness; great tracks of forest, of moor and heath, marsh and fen
lay awaiting reclamation by pioneers.

From this description it is easy to see that natural thatching materials would be readily available and within walking distance. Moorlands and heather; marshes and fens contained sallow, sedge and various rushes and reeds; even forests contained ferns and bracken which could be useful for thatch.

However, thatch material was not limited to wild or natural sources; agricultural by-products were also used. In the History of the Homeland Henry Hamilton points out the fact that:

In medieval times the connection between the work of the people and their daily bread was very close. With few exceptions everyone held a piece of land, as owner or leasee or by some vague, unwritten custom. (Hamilton, 1947, p.62).

Since wheat and rye bread was the main dish of the day, and barley the main drink crop, it is easy to understand the frequent use of wheat, rye and barley straw for thatch.

In a period of low population densities and poor communications, this basic food relationship meant thatch enjoyed a natural advantage over its contemporary rivals. Stone slate and clay tiles, for example, were restricted to areas with suitable stone or clay. Often these geological areas were quite remote and bore little relation with the distribution of population, where the demands for roofs existed. On the other hand, indigenous plants suitable for thatch were common throughout the land; and the agricultural by-products useful for roofing were always closely
linked to the population and its production of food. This overall availability of thatching material is reflected by Brunskill when he speaks of "the replacement of thatch by Welsh slates, plain tiles and corrugated asbestos concealing the former use of the material over virtually the whole country". (1970, p.80). An examination of his thatch distribution map, even though applying to a much later period, bears this view out.

Availability of materials is not, however, limited to physical relationships; society can also determine the 'availability' of materials by establishing what can and cannot be used. Items like
property 'rights' or ownership, or social stratification could affect material 'availability', and quite likely did during the Middle Ages.

Cottrell (1955, p. 215) discusses the traditional land rights of a 'low energy' or peasant society as being tied to the community's benefit and not the market's. The open-field system of agriculture and the mutual use of commons and wastelands all indicate this practice in the British Isles. Under such conditions ownership over the source of natural thatching materials presented no problem, as was the case with agricultural by-products.

Cottrell (1955, p. 216) also refers to such 'low energy' society's social rules on property. Personal property such as ornaments and articles of dress was circumscribed by rules on the basis of factors like occupation, rank or class. Status was reflected largely by display or storage of scarce goods, like works of art. Under the feudal system, surely such rules existed; and could have applied even to building materials. So a scarce roofing material that suggested status might have well been excluded from general use by rule¹.

In any case the sources or manufacture of the scarcer materials like stone or clay tiles would not likely be under the control of the peasant. Quarries or kilns which supplied such materials were usually controlled by the manor, sovereign or church, and the use of

¹Even though no specific references have been found by the author as to this happening in England, this certainly happened in feudal Japan.
them was subject to permission and/or payment, neither of which were likely for most.

Permanence of Thatching.— With today's stress on material durability one wonders how thatching materials, requiring replacement every twenty to fifty years\(^1\), acquired any public acceptance. However, to the villein or cottar, permanence would not have been considered such a virtue, if considered at all. Two main reasons account for this attitude. First, the peasant society was closely tied to nature\(^2\) and had a cyclic rather than a linear concept of time. Replacement of thatch was an accepted ritual, like the planting of crops.

Second, in peasant societies, even though they enjoyed the rights to communal lands, serfs were still at the mercy of the feudal lord, and tenure was never guaranteed. If the serf wished to leave or was forced to leave and was unable to sell his house to a successor, he often took it with him.

\(^1\)The life of thatch roofs depends on the material used and the degree of skill with which it is laid. Most straws last twenty years or more and good reeds, fifty years. However a poorly constructed roof of bracken or hay may only last a few years and some reeds have been known to last up to eighty years.

\(^2\)Rapoport (1969, p. 75) suggests a very strong relation between pre-industrial man and nature. It is quite possible that an excavated and manufactured roofing product, like lead or clay tile, would have seemed un-natural or alien to the peasant's belief that nature is to be worked with; that man is subservient to the natural environment which is not to be exploited, Mumford (1955, p. 67) echoes this point by saying that mining to the peasant was, unlike agriculture, unpredictable and did not fit natural routines. Mining was not even considered a human art but a form of punishment.
Any permanent material, even if it could be afforded, would have been unwise under such conditions. C.F. Innocent in his book English Building Construction describes this mobility by saying that:

Not only were the sites of buildings changed more readily in early times, but the buildings themselves were moved. The Ancient Laws of Wales say 'let the spars and posts be cut even with the ground, and let him depart with his house... for the land is no worse for transporting the house across it, so that corn, or hay, or dike be not damaged'. Bracton, in his De Legibus Angliae distinguishes between a wooden house 'whether it is attached to the ground or not'. A clause of the Assize of Clarendon, in the year 1166, says that any who shall receive certain heretics shall have his house carried outside the town (extra villam) and burnt.

One can easily understand that in a period of such movement, a roof with a throw-away potential would be an asset.

Thatch, even in those days, could be considered such a roofing material, being so accessible in such agrarian conditions. Because the roof represented the major portion of the common building, leaving it behind when moving would have resulted in a great savings in both

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1 It is doubtful whether thatch was thrown away in the modern sense. It likely ended up as either fuel or manure. The thatched 'clachans' of Lewis still use the straw from the roof as manure. In fact it is claimed that the thatching straw from these buildings is superior to plain straw for it contains added nutrients of the soot which collected over the years in such chimneyless structures (Innocent, 1971, p.202). Homes of the early middle ages would have also contained such nutrients, for chimneys did not reach common usage until the fifteenth or sixteenth centuries.
weight and bulk. Only the structural members would require transport.

Estimation of thatch usage in the middle ages.

It can be clearly seen that thatch was the logical choice for roofing in Medieval England on economic, environmental and technological grounds as well as on material availability and cultural considerations. Gregory King estimated that eighty-eight percent of the population in England was employed in agriculture in 1688. It would be safe to assume that the figure would have been even higher six hundred years earlier, probably being over ninety-five percent. It would be equally safe to assume that thatch and shingles provided roofs for almost all of those employed in agriculture. Thatch, however, was not limited to the farmer; the nobility and the church both used thatch regularly in town and country.

Salzman refers to thousands of entries that simply tell of the purchase of straw for thatching (1967, p. 224) that are recorded; and recording itself implies use by the prominent authorities capable of writing. He goes on specifically to mention thatching being bought for such notable structures as Pevensey Castle in 1300 and Cambridge Castle in 1286. Brunskill's (1970, p. 183), thatch usage graph shown (overleaf) bears this out by showing thatch still being used even on

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1 The popularity of thatch is reflected in the frequency and devastating nature of town and village fires throughout the middle ages. London, for example, had three major fires within a span of one hundred years (1077, 1087, 1161). Winchester, Glastonbury, Chichester and Worcester all had notable fires in the twelfth century alone.
large country houses as late as the seventeenth century, and infers
the usage of thatch for structures of smaller scale.

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THATCH

Clifton-Taylor (1962, p.280) even mentions "it is probable that by
1200 thatch was beginning to all our of general use for the roofing
of buildings of importance [emphasis mine]."

It would be reasonable to expect that in the eleventh century thatch
represented about eighty-five percent of the roofing input, the
remainder being taken primarily up by shingles with traces of lead
and stone roofing. Rival materials would gradually gain acceptance
during the Middle Ages among the rich, but even at the end of the
Middle Ages thatch would have still been the dominant material,
probably losing about ten percentage points over a five hundred
year period (1000 to 1500 AD).

For all but the grandest houses...some form of
thatch provided the commonest form of roof in
most parts of the country, until well into the

Decline of Thatch

Three quarters or more of the roofing material being used in 1500
was thatch, but four hundred years later Bartlett (1911) in the eleventh
edition of the Encyclopaedia Britannica simply states that the use
of thatch has been "reduced to special cases". So one could draw a line between the two points and get a rough idea of the decline, but the curve or gradient of the line are of interest, as well as the reasons producing such a drastic change.

Unfortunately, there is no single reason for the decline of thatch; instead, a whole series of inter-related changes were taking place which were all detrimental to the use of thatch. These changes started slowly, gradually eroding away thatch's prominence in the Middle Ages; but gaining momentum in the sixteenth and seventeenth centuries and finally crushing its use in the eighteenth and nineteenth centuries. It would be beyond the scope of this thesis to discuss all the relevant changes which affected thatch. However, the one area of change that had particular significance on the decline of thatch, and which needs some discussion, concerns the agriculture and agrarian revolution which took place in Britain. Most architectural historians write off thatch with the development of the town and communications in the eighteenth and nineteenth centuries. These items certainly played their part, but it is doubtful whether either would have taken place without significant rural change, for "it is nothing less that a cockney illusion to separate the town's prosperity from the land's" (Mumford, 1961, p. 301).

Agrarian and Agricultural Developments

The most significant rural movement in England was that of 'Enclosure',

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Enclosure has a double meaning. In physical terms it refers to the rearrangement of formerly common or open fields into self contained private land units or the division of formerly common but uncultivated land (woodlands, rough grazing, 'waste', etc.) into private property. These private lands were defined by a hedge or fence. Economic historians use the term to signify substitution of individualist farming for collective husbandry. I shall use it in both senses.
a subject which has attracted a host of well know historians, all of whom appear to have differing views on its significance. Hoskins points out that enclosure hedges are of all dates from Celtic to Victorian periods and goes on to say that "it is a complex pattern with a complicated history, and generalizations do not do it justice", (1970, p.154). However, for this study some generalization of the enclosure movement will have to do on these aspects which have impact on the use of thatch.

Hoskins himself gives an excellent short historical outline of the enclosure movement in his chapter on Parliamentary Enclosure which is worth quoting,

"The enclosure of open fields into smaller fields that form our familiar world today, and the reclamation of the wild lands, had been going on intermittently and at a varying pace in every century. But after the Restoration the government ceased to interfere with the enclosure of open field by private landlords, and the pace quickened sharply. Up to about 1730 most of this enclosure was carried through by private agreements between the owners of the land in question. Very few enclosures were dealt with by act of Parliament. But under George II, and above all from the 1750's onwards, enclosure by private act of Parliament, working through special commissioners in each of the affected parishes, was the great instrument of change. From then onwards the transformation of the English landscape, or of a considerable part of it, went on at a revolutionary pace" [finishing in the mid nineteenth century] (1970, p.178).

One is able to see the acceleration of the movement with time - a factor to keep in mind for any ramifications of the enclosure movement on thatch
would be directly proportional to this acceleration. Generally speaking medieval enclosures were piecemeal and small in scale and had less impact on village life than the more large scale enclosures of later periods.

**Enclosure, commercialization and their effect on the supply of cultivated thatching materials.**—There are many stimuli to the commercialization of agriculture, but the marked rise in yields per acre, thanks largely to enclosure and the rapid increase in urban population after 1500 were the most direct causes. This commercialization was to have a detrimental effect on the supply of cultivated thatching material. There is a direct relation between population, food and shelter, as population increases so too do the demands for food and shelter. In the medieval peasant society the requirements of a community's food and shelter were considered together and were in balance with the population. A food crop would be avoided if it curtailed the use of vital building materials and vice versa. However, this situation changed with enclosure and commercialization of agriculture. Agriculture produce and rural land use in general were dependent primarily on the urban market and profit. Agricultural products fluctuated with marked demands, often quite unrelated to the needs of the local community. This meant that crops specifically grown for thatching would have to compete on the market with other agricultural products, and the urban demand for thatch would be minute as compared with that for food. No demand leads to no profit, which eliminates the growing of a specific thatch crop. However, crops are seldom grown just to satisfy roofing requirements because of the frequent appearance as a by product of cereal. This was fine when each village had its share of cereal crops but with commercialization whole areas of Britain would switch to one
profitable product, and not necessarily a cereal. Hoskins (1970, p.190) and Hill (1969, p.151) both refer to areas of England oscillating over the years between grazing and cash crops. This practice was justifiable for profit, but thatching considerations were left out entirely. Imagine the rethatching problem of a peasant whose area had been enclosed for sheep grazing.

Enclosure might well reduce (cottagers and smallholders) to simple wage labour. More than this: it would transform them and the labourers from upright members of a community, with a distinct set of rights, to inferiors dependent on the rich (Hobsbawm, 1969, p.102).

The loss of rights and the wage labour status were perhaps the most significant effects on restricting the majority from direct access to agricultural by-products suitable for thatch which hitherto they raised themselves for themselves and surely had first rights to. Now the landowner had final say.

**Enclosure and its effect on natural sources of thatch.** - The effect of commercialization of the cultivated sources of thatch was considerable, but even more significant was the effect of enclosure on natural sources of thatch. The elimination of these sources was both cultural and physical. The wild forest, moorlands, marshes, and fens which were part of a village's territory during the middle ages were the source of natural thatch. A villager's access to these sources was his common right. The right applied to all and most significantly to the lower classes, (the marginal cottagers or small-holders, etc.) who made up the bulk of the population and who were most likely to use thatch. It was precisely this group who suffered most from the enclosure movement, for they inevitably
lost these common rights. The source of reeds, bracken, sedge were only available in a restricted sense.

Not only was the commoner denied of his rights but the former common lands themselves were being divided up into enclosed private property. But regardless of being common or enclosed, wastelands such as fens and forest were physically disappearing through reclamation. Colonization, even without enclosure, had always nibbled away at waste lands; this process was involuntarily assisted when tillable land was enclosed for grazing. The individuals who had to make way for sheep or cattle were often by necessity required to colonize or squat on wastes for survival. But increase in population and the growth of the city were forcing the commercialization of waste land. Reclamation was proving profitable. Fens and forest disappeared under hoof and hoe, cottagers and commoners could no longer find protection of their rights even in wastes.

Technical Innovations.—Even though dividing and enclosing fields with hedges was a technical innovation it was not alone, other innovations besides reclamation of waste lands were in the areas of crop rotation, the introduction of new crop types, improving plants and animals through breeding, the use of fertilizers, and the general mechanization of agriculture. None of these proved to be conducive to thatch and some were even detrimental. All of these improvements began to take hold after the seventeenth century. Rotation of crops was a technical innovation which made the enclosure of open fields possible by eliminating the need for leaving a third or a half of the arable land to fallow each year. The consequences of enclosing open fields has already been discussed. Even though crop rotation involved new crops (turnips and clover) which are not suitable for thatch, the overall quantity of straw was probably not
affected for the land had effectively been doubled through the elimination of the fallowing period.

As long as the rotation included crops which were suitable for thatch the quantities would not be affected, but market gardening and fruit growing were diminishing the supply of suitable thatching materials.

Stock breeding and crop rotation had similar demands for enclosure for scientific breeding of animals required segregation which in turn involved abolition of common lands. Scientific breeding of plants also required enclosed fields. Another result of this scientific breeding produced shorter stemmed cereals which were not so suitable for thatching. Fertilization would not appear to have any direct effect on supplies, even though W. Pitt objected in 1796 to the use of thatch in Staffordshire, because it "robbed the land of manure" (Innocent, 1971, p. 189). Mechanization of agriculture clearly did have an adverse effect on thatch; not only did it remove more people from the land it also ruined the supply of straw for thatch. The introduction of the threshing machine in the seventeenth century and much later the reaping and combine harvester all damaged the fibres of straws making them unfit for thatching.

The effect on building of the enclosure movement. - It is well worth mentioning the enclosure movement's effect on buildings. Enclosure had two primary effects; the first was the tendency to split the community into either poverty or prosperity; the second was that the enclosure of open fields freed one from living in a village situation and the isolated farmstead was possible right on the enclosed land. Prosperity brought on by enclosure and profit inflation resulted in monetary gains
for those with security of tenure. This in turn led to the "great ages of rebuilding" which Hoskins and others refer to as having taken place between 1570 and 1640 and the late seventeenth and early eighteenth century. Landlords and yeomen both profited and it was the first real opportunity to utilize building technology and materials formerly restricted to the church, and the extremely wealthy. It is inevitable that stone and clay tiles flourished in such a rebuilding, but the rebuilding was primarily conceived to provide more room and privacy and stronger and more durable structures. Thatch would have remained a strong contender. Most of the first rebuilding took place in existing villages but rebuilding in the eighteenth and nineteenth century could very well have taken place on the farmstead, but what happened to the mass of people who suffered from enclosure and were in poverty? Hoskins (1970, p. 154) points out that the great rebuilding never directly reached the poorest in town and country alike, but indirectly the laws of social descent did apply; the poor were filling up the homes abandoned by those who built new either on an isolated farmstead or in another part of town. Moving into existing structures, would mean the people most likely to use thatch were not building for themselves which naturally would reduce the demand for thatch. With the change to wage labour on the farms, landowners were more likely to provide housing for his work hands, removing the farm hand from the construction process. Even though the cottages were often thatched (see Hoskins, 1970, p. 155 and 172) the choice was up to the landlord, who if so inclined could afford more costly roofing substitutes.

1The reformation greatly assisted this movement for it freed both materials and skilled craftsmen to work them.
The Enclosure Movement and Industrialization. - Not only did agricultural developments produce enough food for industry, the enclosure itself led to industrialization. Hill mentioned that "enclosure for pasture would increase employment in the clothing industry, at the same time as it reduced the number of those who lived off commons without working, and so released labour for industry" (1969, p. 151). Once common rights were lost security was lost and wage labour became a way of life; even in agriculture it became a system of cash incomes and cash sales. Increasingly, villages in which men spent their spare time or seasons weaving, knitting or mining tended to become industrial villages of full time weavers, knitters or miners and some eventually developed into industrial towns. This "putting out" industry encouraged cash transaction, and led to village specialization. If a village specialized in non agricultural products it meant another area would have to specialize in food production to feed them.

Agriculture became more specialized, and farm workers were doing less and less spinning, weaving and building themselves in their farmhouse or cottage, indeed landlords sometimes prohibited the practice. This regional trade specialization was encouraged by landowners for unlike the pre-restoration period royalties would go to them. The exploitation of resources such as coal, stone and clay which lay beneath their lands began along with transport systems to ship both food, raw materials and finished products. The effects of all this were disastrous on thatch, it was reducing the self sufficient farmer who would have been a prime user of thatch and at the same time encouraged the use of alternative materials beneficial to landowners and businessmen. But more importantly it led to the rapid expansion of industry and urban centres which were increasingly forbidding the use of thatch because of fire risks.
The seventeenth century political revolution gave rise to revolutions in trade and agriculture which had far reaching effects on the whole of society. They prepared for that take-off into the modern industrial world (Hill, 1969, p.22).

The "Revolutionary decades" or the "Revolution described by Hill between 1640 and 1660 which involved a sharp break in political history, with monied interest groups gaining control of the government had effect on thatch not limited to agriculture. Higgins and Jessop (1965, p.38) summarise the result of both revolution and the London fire which occurred in the same period on the building industry.

The challenge (of the London fire) was met by a development which was itself in line with the developing bourgeois economic culture of the time, the building craftsman as entrepreneur...

The approach of these new men was more concerned with getting the job done and realizing an investment of capital or labour in the quickest and most profitable way than it was concerned with the workmanship or the "delight" of the result... the new commercial building units tended to centre around an enterprising master craftsman from one of the old Guilds. Small enterprises undertaking brick-laying, carpentry, plumbing, etc. sprang up, each controlled by a man from the appropriate Guild background.

The fact that the building "industry" was reorganized on the existing pattern of Guilds which were themselves largely based on materials would have had a significant effect on the subsequent use of thatch. Thatch was a rural material, and Guilds, by their nature, were urban institutions; but more importantly thatch "was never thoroughly
specialized\(^1\)" (Innocent, 1971, p. 221). It was a part time, do-it-yourself material accessible to most and very well suited to the non-specialized society. Thatchers never formed Guilds, consequently thatch never received the Guild support that its rival materials had, that was so necessary for commercial success.

**Estimation of Decline**

As pointed out earlier the decline of thatch basically took place between 1500 and 1900, but when plotted out it would not be represented as a straight line, it would have taken more of an exponential curve with the gradient increasing with time. Since thatch was essentially restricted to agricultural or rural use it would be very useful to compare the decline of thatch with the decline in the population employed in agriculture as well as the decline in the rural population of Britain. Both of these population declines are represented as a percentage mix in Fig. 2.1 for comparison with the percentage mix assumed for thatch. The decline for all of these percentage mixes are roughly parallel but with the decline of thatch preceding the other two. This would be reasonable to expect since not everyone involved in agriculture or living in a rural situation had a thatched roof.

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\(^1\)Today the art of thatching has become quite specialized, but this is a rather recent (less than 150 years) development and not characteristic of an earlier period.
Wood Shingles

The availability of wood and the common use of wood framed building encourages the use of wood shingles.

The art of shingling is as old as English building. The frames of the days of the Norman Conquest were sheathed with singles; as were the roofs of many a great cathedral centuries later. (Braun, 1962, p.117).

The statement is not surprising for wooden shingles are usually associated with timber buildings commonly found in heavily forested areas.

Britain during the middle ages, was abundant in trees, a situation vividly described in Hoskins's book *Making of an English Landscape.*

Around every village [in the eleventh century] stretched its open fields, each covering a few hundred acres, but hardly anywhere had these fields reached the frontiers of the village territory. If one walked half a mile, a mile at most, out from the village, one came to the edges of the wild to a wide stretch of moory or boggy ground that formed a temporary barrier, or the massed tree trunks of the primeval woods still waiting the axe (p.82)...In medieval England: there were tens of thousands of oak to be seen in places where we now see a few hundred... From rising ground England must have seemed one great forest an almost unbroken sea of tree tops, with a thin blue spiral of smoke rising here and there at long intervals. (Hoskins, 1970, p. 82 and 86).

1 Wood shingles were the most common form of wood roofing but the discussion would also apply to boarded roofs as well.

2 In England shingles were always of oak which was the most common wood available and provided a fairly durable roof.
Under such conditions timber buildings were the rule, Brunskill illustrates this coverage in Map 2.2.

It is reasonable to assume that the uses of shingles were closely related with heavy timber walled and framed buildings, for carpenters whose medium was wood would surely have preferred using the same...
material for roofing, which was also a great deal lighter and much easier to find, shape and transport than either clay or stone tiles. Braun also mentions the shingle by-product relation with timber structures - "Rafters were covered with rough planking produced as a by-product of the squaring of the logs, and, as a crowning refinement, finished with wooden 'thatch-tile' of shingles made from waste timber". (Braun, 1962, p. 22)

One could expect to find shingles common in a period of colonization where the clearing of woodlands not only provided essential land for tillage, but also a natural building and roofing material. This certainly occurred in the colonization of the United States and it would be quite natural to expect when England was being colonized\textsuperscript{1} in the twelfth and thirteenth centuries. In fact up to the eleventh and twelfth centuries even the more significant buildings like churches, bridges and stockades were constructed primarily of wood.

The use of shingling on significant buildings in the thirteenth and early fourteenth centuries is documented by both Salzman and Innocent, and include such notable examples as Salisbury Cathedral and "the 1500 'shyngle' bought from Hugh Hattere of Croydon in 1329 for use at Westminster". (Salzman, 1967, p. 228).

\textsuperscript{1} Colonization would have taken place in three basic forms: First the gradual expansion of open fields in existing villages. Second, in the development of 'chartered' new towns which flourished during the twelfth century, in the thousands of isolated woodland farmsteads which Hoskins frequently refers to.
Estimation of Use.

In estimating what portion of roofing was done by shingles, a comparison needs to be made with its contemporary rival - thatch. Shingles provided a number of advantages over thatch, they were less attractive to vermin, were more durable\(^1\), and were less likely to catch fire\(^2\).

However, even with these advantages, shingles could never equal thatch, for it is doubtful that shingles reached the peasant in much quantity. Its use on cathedrals indicates that it must have been thought of as a superior material, even Braun's described it as a 'crowning refinement'! Hoskins also illustrates that a timber structure would not necessarily guarantee a shingle roof when describing the English eleventh century churches as "inconspicuous little log huts, roofed with thatch". (Hoskins, 1970, p. 82). The following points would all prevent the mass utilization of the shingle.

1. Wood, because of its superior fuel and structural properties, would always be more costly than thatching materials. Reeds for thatch would have been equally available during colonization in the bogs and marshes that Hoskins mentions, and straw for thatching was an unavoidable agricultural by-product closely associated with the peasant. Problems of ownership were also much less likely to arise

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\(^1\)Replacement of shingles occurred at fifty to one hundred year intervals, whereas thatch needed replacement every twenty to fifty years.

\(^2\)Shingles were mentioned as an acceptable alternate when thatch was initially banned from London in 1212 because of the hazards of fire.
2. Wood was heavier than thatching materials, increasing both structural and transport costs. Thatch being light cellular had an additional advantage of providing not only water resistance but thermal insulation.

3. Oak needed long seasoning periods and being a very solid material required much more effort to work than thatch. The peasant's medium was straw and shingles would probably involve a tradesman, for supply or application which would have put it out of the reach of many do-it-yourself peasants.

4. The durability of the shingle would not have been considered a significant asset in a relatively insecure peasant society, which as Rapoport mentions, tends to have a cyclic rather than linear conception of life.

5. The practical problem securing the roof to the building also presented a problem with tile type material. Nails were scarce and shingles could not be tied down like thatch.

All of these reasons kept shingles from reaching the lower rungs of the social ladder. Shingles probably reached their peak utilization between the eighth and twelfth centuries, but it is doubtful whether they exceeded ten percent of the roofing material being applied annually.

**Decline of the Shingle.**

The decline of the wood shingle was probably initiated with the Norman Conquest. The Norman's came from an area well acquainted with stone construction and their preference would have been for more durable materials than shingle or thatch. Moreover, the Normans placed much of the woodlands, which would have been the source for shingles, off limits
to the peasant. Following their conquest vast game preserves of 'forests' were created with severe penalties against poaching and trespass. Royal forests reached their peak in the twelfth century under Henry II when the 'forest law' applied to as much as one third of the whole country.

The colonization movement which had flourished in the twelfth century was slowing down at the end of the thirteenth century and was brought to an abrupt halt with the Black Death in the mid-fourteenth century, which reduced the population by somewhere between one third and one half and resulted in an actual retreat from marginal lands.

The period between the Plague and 1500 Hoskins indicates that a great deal of building, and more importantly re-building, took place. Most of the building concerned parish churches, castles and bridges and was normally carried out in stone, giving a clear indication of the trend away from wood in general.

The primary reason for the decline of shingles was simply the disappearance of oak trees. Mumford refers to the middle ages as one of wood and water, and the demand for wood for tools, shelter and fuel grew steadily with time and population. Salzman mentions that "even as early as 1233 there were complaints of the difficulty of finding really good timber in the Forests at Windsor and Cornbury", (Salzman, 1967, p. 240) and the demand for wood would only gain momentum after that date.

Industry which used wood for all of its machines was steadily increasing particularly the metal trades which Mumford (1955, p. 120) claims was responsible for the destruction of the forests. The demand for wood
by the metal trade was indeed great; mining required wooden shoring, carts, and tracks and the smelting and forging operations consumed vast amounts of wood as fuel. However, industry's demand was not limited to the manufacture of metals, the production of quick lime, glass and even the competitive ceramic tile all were placing demands on wood as a fuel. The rapid increase in ship building had an equal impact on the woodlands. Wood was also providing fuel for domestic life as well. The shortage of wood was further compounded by the constant pressure for more arable and open grazing land.

With such demands on wood it is easy to see why wood for shingles would have a low priority, especially when thatch provided a cheaper substitute and stone and clay tiles a more durable and fire proof alternative.

Clifton-Taylor (1962, p. 53) mentions that the latter substitution was taking place as early as the twelfth century. Salzman refers to the rapid increase in the price of shingles and the import and substitution of inferior woods taking place in the fourteenth century due to the demand for timber, and states that 'even as early as 1314,

1A good concise description of the demand for wood as a fuel in England during the Middle Ages is instanced in William H. TeBrake's (1975) article entitled "Air Pollution and the Fuel Crises in Pre-Industrial London, 1250-1650".

2Grazing during the Middle Ages often took place in forests with unfortunate ramifications. Grazing animals would eat among other things young tree saplings which prevented natural replacement. Wind and erosion were other problems encountered with reforestation.
when various buildings roofed with shingles in the manor held by Queen Margaret were in dower need of repair, it was found that it would be much cheaper to re-roof them with stone slates or earthen tiles than with shingles". (Salzman, 1967, p. 229).

So we can see the decline of shingles starting about the late twelfth century and dropping off rapidly after the fourteenth century and dissappearing for all practical purposes in the fifteenth century. This disappearance of shingles is confirmed by Innocent when he refers to "Professor Thorold Rogers finding" that the use of shingles hardly lasted over the fourteenth century". The Encyclopaedia Britannica (Burton, 1911) neatly summarizes the history of the shingle, simply by saying:

Another kind of roofing tile, largely used in pre-Norman times, and for some centuries later for certain purposes, was made of thin pieces of split wood, generally of oak; these are called "shingles".

Lead roofing was the exception. Technically speaking it was by far the most advanced roofing material. Quite surprisingly it was used by the Saxons as early as the seventh century. However, the great expense of lead limited its use to the very rich and even then it was used only in unusual roofing conditions, requiring either a very low pitch, such as those found in fortifications or Norman church towers, or very long eaves with low fire risk as was the case with large cathedrals. Because of lead's very limited use (which probably never exceeded one or two per cent of the total roof requirement) it will not be discussed.
The middle ages witnessed the disappearance of the wood shingle and a slight reduction in the utilization of thatch. After the middle ages the decline of thatch accelerated with time until its virtual elimination in the early part of the twentieth century. The decrease in these organic roofing materials meant a corresponding increase in the use of inorganic substitutes. Until the mid nineteenth century only two basic types of inorganic materials were used, those based on stone and clay.

The discussion of the substitution of these materials has been broken roughly into two chronological time periods which overlap during the industrial revolution (roughly 1780 to 1890). The first period deals primarily with clay tiles and heavy stone roofing made from sandstone, limestone and 'English' slate. These types of stone are distributed throughout Britain and consequently their usage was far more common during the middle ages, when difficulties of transport localized a material use. Even the lighter weight Welsh, Cornish and Westmoreland slates, which were later to provide such a large proportion of Britain's...
roofing needs, were by and large only local materials during this period. It is only in the second period, i.e. during and after the industrial revolution, that a clear distinction will be made between stone and slate.

It is a safe assumption that during the middle ages buildings of the crown were the first to reflect any change in material trends. A good indication of this occurred in the reign of Henry II, when "in 1260 he gave orders for the shingles to be taken off the roof of his great kitchen in Marlborough castle, which was to be covered with stone tiles, while a chamber in the high tower was to be stripped of its thatch and roofed with the shingles from the kitchen" (Salzman, 1967, p.228). This record is particularly relevant to roofing, for not only does it mark the use of a new inorganic material, it also establishes the 'pecking order' or priority of materials for the affluent. It can be seen from this example that the permanent inorganic materials, in this case stone, were primarily replacing shingles, the most durable and expensive roof covering; with a more indirect replacement of thatch.

of roofing made from these materials is discussed and shown graphically in Maps 2.3 and 2.4 later in this chapter (p. 79).
In other words, up to the fourteenth or fifteenth century the increase in the inorganic roofing materials corresponded to a similar decrease in shingles with only a minor effect on thatch. It was a case of one relatively expensive material replacing another, both of which were out of the reach of the vast majority. To emphasize this substitution of inorganic for organic, Salzman provides further evidence:

Even as early as 1314, when various buildings roofed with shingles in the manors held by Queen Margaret in dower were in need of repair, it was found that it would be much cheaper to re-roof them with stone slate or earthen tiles [emphasis mine] than with shingles. (Salzman 1967, p.229)

**Competition between clay tiles and stone roofing up to the Industrial Revolution**

Salzman illustrates above not only the substitution of inorganic for organic, but the substitution within the inorganic field of 'stone slate or earthen tile'. As early as the end of the twelfth century William Fitzstephen again points out this choice between tile and stone in his book *A description of the most noble city of London*:

> It was long since thought good policy in our fore-fathers time wisely to provide, namely, in the year of Christ 1189... that all men in this city should build their houses of stone up to a certain height and to cover them with slate or baked tile [emphasis mine], (Clifton-Taylor 1962, p.254).

This problem is not one of establishing the organic/inorganic relationship, it is establishing the relationship between clay and stone, for the references quoted infer equal acceptability and assessibility. It is quite likely, however, that the use of clay tile roofing exceeded that of stone between their early medieval acceptance in Britain which was roughly at the same time, and the industrial revolution. Geographical factors, co-product or by-product material relationships, weight and ease of application were the four principle areas where the clay tile had a
2.3 Distribution of population in 1700 (Darby, 1956, Fig. 83), clay tiles and stone roofing (Brumskill, 1970, pp. 181-182), and major slate quarries.

LEGEND Maps 2.3 and 2.4
Population per square mile
- about 2000
- over 260
- 150-200
- 100-150
- 50-100
- under 50

Roofing materials
- mainly sandstone
- mainly limestone
- clay tiles
- slate quarries

2.4 Distribution of population in 1801 (Darby, 1956, Fig. 8A), clay tiles and stone roofing (Brumskill, 1970, pp. 181-182), and major slate quarries.
distinct advantage over stone, which would have resulted in the former's higher percentage mix.

Geographical factors. Because medieval communications were so limited, geographical considerations were vital to the selection of either slate or tile. The analysis of supply and demand is the first item to consider. Supply of either stone or clay was largely dependant on geological factors and demand on demographic factors. Until the seventeenth or eighteenth century, Britain's population was concentrated in the south and east. Geologically speaking this area is notable for its lack of suitable stone for roofing but possessed ample clay for tiles. This situation clearly shown in Map 2.3 would naturally have favoured the use of clay tiles.

A review of the map also reveals that clay was further favoured in that a higher proportion of the total area of suitable roofing stone was covered by clay suitable for tile, than the other way around. Indeed, the overburden covering a stone quarry could well be suitable for building ceramics. Donovan Purcell in his book Cambridge Stone describes this happening in Rutland and discusses the results of this situation.

For some time previously brickmaking had gone on side by side with stone quarrying, the brick clays which overlie the freestone being carried into brickworks in horsedrawn tip carts. Brick making has continued but the old stone quarries became grass covered mounds and shrub-filled hollows... (Purcell, 1967, p.68).

In this situation the clay product survived when the stone product failed.

Economic geography encouraged the use of clay tiles over those of stone. Not only was the population concentrated in the south and east of England, economic prosperity existed there as well. Trade with Flanders had much to do with this prosperity, a very important factor in the tile's favour.
Maps
2.5
2.6
Map 2.5

Distribution of stone walling and stone roofing


Map 2.6

Distribution of brick walling and clay tile roofing

SOURCE: Brunskill (1970, pp. 175 and 182)
Even though the geology of the south and east naturally favoured tile, this advantage was not exploited until after the introduction of tiles from Flanders. The wool trade with the continent, for example, had three complementary effects which promoted the use of tile. First, trade resulted in development of Guilds and Yeomenry who would begin to afford materials other than thatch; second, the transport of tiles as ballast was a direct by-product of the Flemish trade itself; and third, the commercial intercourse eventually led to the immigration of large numbers of workmen and weavers from Flanders during Elizabeth's reign which would have influenced architectural taste as well as tile production.

Co-product and by-product relationship. The relationship between walling and roofing materials again favoured the clay tile. The chances of clay being suitable for both brick and tile was much greater than walling stone being suitable for roofing, an item easily discernable by comparing Map 2.5 (stone roofing and walling) with Map 2.6 (clay tile roofing and brick walling). Also the left over of any stone dressing operations would end up as rubble infill for walls and not tile for roofs; unlike the relationship found between the wood shingle and timber framed wall. In fact quarries for walling stone and roofing stone were usually separated. Production of brick and tile on the other hand were far more complementary, Clifton-Taylor (1962, p.254) in fact mentions that "it was formally essential to fire bricks and tiles together for

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Where co-product stone was suitable for both slate and walls a by-product relation could exist. Innocent (1971, p.177) suggests this happened in the middle ages by referring to "(Professor Thorold Rogers) thought that slate making in Oxfordshire quarries was a by-industry, for building stones were obtained from quarries as well as slates, and he supposed that the quarrymen, when the demand for building stones was slack, employed their time in splitting, dressing, and boring such stone as was available for slates".

1
those tiles exposed to the greatest heat would have warped and banks of bricks were therefore arranged to shield them. Besides being closely connected to brick manufacturing, tiles had an additional fillip by being associated with other ceramic products both in and out of the building field. In areas of suitable clay a firm or individual could be found producing floor tiles, and earthen vessels along with plain tiles; stone did not enjoy this relationship.

Weight. Clay tiles were generally lighter than stone tiles or flags, this reduced both transport costs and structural framework. Tile, particularly pantiles, were light enough even to replace thatch roofs.

Ease of application. The need for skilled labour and the time required for site work have always been major factors influencing cost. The clay tile again held the advantage over the stone slate. Stone slates were usually sorted according to their approximate sizes, but were by no means exactly alike, varying slightly in thickness and size. In addition, an individual roof would not be limited to only one size of slate, but incorporated a series of the basic sizes; the largest and thickest range of slates being placed at the eaves, and the thinnest

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1 Pantiles were introduced to Britain in the seventeenth century. These single lapped tiles had a much greater effective gauge than the plain double lapped tile and consequently weighed only two-thirds as much. Pantiles weighing from 44 to 55 Kg/m² (9-11 lbs/ft²) while the weight range for plain tiles was from 73 to 90 Kg/m² (15 to 18 lbs/ft²). Interestingly enough, these lighter tiles were originally used only for agricultural buildings and not those used for human habitation. A very similar situation exists today between single lap concrete tiles commonly used for housing and the much lighter corrugated asbestos cement sheet which are, by and large, restricted to industrial buildings including those of agriculture.

2 Weight was not the only consideration in replacing thatch, pitch had to be considered as well. Tiles functioned well at the steep thatch roof angles, whereas heavy stone slates used much lower angles of pitch.
smallest range of slate being used at the ridge with graduating courses between. Needless to say both time and skill were required in matching adjacent slates. The clay tile was quite uniform\(^1\) by comparison and an individual roof would certainly be limited to one size which reduced the time and skill required for laying both purlins and tiles.

**Utilisation of clay tiles before the Industrial Revolution**

It is quite evident that from geographical and technical considerations the use of the clay tile would have been more widespread than the use of stone. Salzman supports this view, when discussing the absence of references to tiled roofs in early records.

The probable deduction to be made from the paucity of these references is not that tile was rarely used on the royal estates, but that it was so generally in use that, unless lead or some other material was definitely named; it might be assumed that the roofs would be tiled... (Salzman, 1967 p.229).

With tile developing a major role in roofing it is logical to find its use increasing faster than that of stone. Historical events also help to establish the most prominent periods of use.

It is fairly well established that the Saxon's did not use tiles. Manufacturing of tiles in Britain had probably begun by the twelfth century though most tiles were initially imported from the Low Countries. By the end of the thirteenth century tile production had spread to at least fourteen counties (Clifton-Taylor, 1962, p.225). Tile production was given additional impetus in the fourteenth century with the establishment of the brick industry in England along with an increase in

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\(^1\)Edward IV in 1477 laid down standards on both clay preparation and dimensions for the plain tile, but the dimensions continued to vary slightly because of the difficulty in maintaining kiln temperatures and technology, and some manufacturers neglected the regulations altogether. George I laid down a statute reaffirming these standards in 1725 and an act of parliament established a standard size for pantiles at about the same time.
interest and production of clay floor tiles. This tendency developed faster during the sixteenth century with the 'great rebuilding' in which "the ranks of the house-builders, masons and wrights - swelled by the addition of a new craft, that of the bricklayers. By the reign of Henry VIII, brick had been accepted as a suitable material for construction of the very finest buildings". (Braun, 1962, p.80). The timber shortage became acute in the sixteenth century and the newly arrived surveyor-architect sought out structural substitutes for wood. Brick was the natural choice in stoneless areas and by the end of the century good clay deposits had been located and developed into brick and tile producing areas. The substitution of wood as a fuel by coal in the seventeenth century greatly assisted the increased use of tiles and bricks. Before this substitution took place the brick and tile industry, like the iron and glass industries was threatened by the timber famine of the late sixteenth and early seventeenth centuries. The usage probably reached its peak during the Stuart period of the seventeenth and early eighteenth century. The emphasis on brick construction during this period was reflected in the actions of the first Stuart king to take the throne James I being "appalled at the fire risk (of London buildings) he had an order promulgated that in future the city house fronts were to be built of brick. Announcing himself as a new Augustus, he said he would change the face of London 'From Stykkes to brykkes'". (Braun, 1962, p.69). The King's orders would have promoted the use of clay products, but ironically it was the very fire which Jame I had tried to prevent that really pushed both brick and tile to the forefront. The London fire of 1666 established the brickmakers role as the most significant building trade taking over from the Medieval wright and mason. The London fire could not have come at a better time for the clay based
industries; for it co-incided perfectly with two other quite complementary historical events. 1) Fires plagued other cities both before and after London's great fire, the more notable occurring at Northampton in 1675, Blandford and Tiverton in 1736 and Wincarton in 1747. Like London, these fires would have undoubtedly resulted in codes requiring baked clay or other non-combustable material. Demand for tiles would have increased following such legislation; and the cities themselves were beginning to expand for the problems of food supply, and plague which had previously limited urban growth, were not present in Queen Anne's reign. 2) James II was removed by William of Orange in 1688. The new Monarch would have encouraged Dutch architectural influences after the brief period of French influences under both Charles II and James II. This Dutch influence with its abundant use of brick and tile reached its culmination after William and Mary in the Queen Anne style of architecture (early eighteenth century). This Dutch influence and the trade with Holland was largely responsible for the introduction of the more versatile and lightweight pantile in the late seventeenth century. The pantile gained quick acceptance and London absorbed large amounts of them in the first half of the eighteenth century.

In reviewing the history of tile one can see its use increasing with time reaching a peak in the late seventeenth and eighteenth centuries due to the favourable circumstances described. Clifton-Taylor, even though speaking of brick, illustrates the effect of these factors in helping to extend the use of clay products down to the general public.

It was not until the last quarter of the seventeenth century that, thanks to falling prices, the taste for this material (brick) really gathered momentum, spreading downwards at last to the humblest cottage dweller, and fanning outwards over parts of the country that had up to this time possessed few or no buildings in brick. (Clifton-Taylor, 1962, p.215).
Utilization of stone roofing

Stone roofing never enjoyed tile's strong connection with continental trade nor the close relationship between walling and roofing materials (refer Maps 2.4 and 2.5). Nevertheless, like tiles, they did gain some popularity as a durable fireproof, roofing material during the middle ages; and even gained acceptance for more common buildings after the middle ages. There would be little point in trying to summarize the historical usage of stone slates, when Clifton-Taylor does it well and briefly in the fourth chapter of Patterns of English Building.

Stone slates, not always rectangular, were used by the Romans but Saxon buildings would usually have been too flimsy to support their weight, and they were still a rarity in the thirteenth century, even in the Cotswolds. From the fourteenth century, primarily in order to reduce the risk of fire, stone began to be used for the roofs of private houses as well as of Churches and other public buildings where it was available and where the clients could afford it. From Tudor times until the first quarter of the nineteenth century stone (as distinct from slate) became the favourite roofing material over wide areas of England, which included parts of Sussex and Surrey, Dorset and Somerset; the whole of the Cotswolds, Northern Oxfordshire, Northamptonshire and Rutland; all the counties along the Welsh border; and large parts of all the Northern Counties from Derbyshire to Northumberland. Some of the stone slates were sandstones (Clifton-Taylor, 1962, p.114).

Local availability and cost were critical in preventing the stone slate from becoming universally accepted - it was expensive, and extremely heavy, capable of dominating fairly localized areas which contained suitable stone. In other words a lighter and more convenient product like slate or clay could compete in a stone roof area, whereas the stone would have had great difficulty in competing in a clay or slate area.

However, two items occurred which would have made the use of stone roofing reach its peak (assumed to be 17% of the total roofing mix) at the end of the 18th and the beginning of the 19th centuries.
1) The population density shifted during the 1700's from the south and east to the north and west where industry had been developing rapidly in the 17th and 18th centuries. This development was primarily due to three reasons: First, people removed from the land by the enclosure movement provided a cheap source of labour for new industries. Second, the north and west were areas where industry could develop with comparatively little interference from the old guilds and third, the area was abundant in energy to drive the new industries. Initially water provided motive power while wood, which also was only available in more remote areas, provided a fuel for industrial heat processes. Later coal found in the same general areas, gradually replaced water and wood as a source of energy for industry. This shift in population density to the north and west would have been far more favourable to stone roofing than clay roofing because it effectively shifted the demand from the south and east which were essentially clay areas to areas more abundant in stone which was suitable for roofing. The effect of this shift can be seen by comparing Map 2.4 (p.79) which includes the distribution of clay and stone roofing as well as the population density of 1801 with Map 2.3 which is essentially the same except the population represented is that of 1700.

2) The development of inland waterways largely brought about by the industrial activities in the area, would have expanded the coverage of stone roofing materials along with its competitors. The developments of canals would have been more beneficial to stone and clay than slate initially since the deposits of slate were located along the western extremities of Britain and not directly linked to the inland system of waterways. However, the next 'mania' in inland transport, that of railways did reach these extremities and this was to effectively bring a halt to stone roofs in the 19th century.
Transport seems to be the basic reason given for stone's decline; however the difficulty of mechanizing the extraction and dressing of stone and the skill required laying stone tiles, along with the structural problems in supporting them all contributed to the decline of stone roofing. The use of stone in industrial and urban areas was further limited by the fact that much of the stone roofing was susceptible to attack from the sulphur laden air which arose with the introduction of coal as a fuel.

The abruptness of the decline of stone roofing is again provided by Clifton-Taylor (1962, p.170) when he describes the history of stone roofing in Leicestershire and Nottinghamshire both counties served by the famous Swithland quarries.

By 1600 a Swithland slate roof was probably the rule rather than the exception for larger houses ... during the Georgian period even the humblest cottages would often be so roofed...but in the 19th century mass produced Welsh slate had captured the market. The last quarry of Swithland slate ceased working.

The competition between clay tiles and slate during and after the Industrial Revolution.

Agricultural, economic, urban, social and industrial transformations were all taking their toll on organic roofing materials. Stone and tiles were taking over and, from the discussion so far it is clear that tiles were being used more widely during the middle ages, reaching their peak just before the Industrial Revolution (1750-1840). However, during the Industrial Revolution, up to the early 20th century the use of clay tile was to be overtaken by the use of slate. 1) Production mechanization, 2) transport and fuel requirements, 3) quality control, 4) architectural considerations, 5) taxation, were the five broad areas which brought about the rapid increase and eventual domination of roofing materials by slate. These areas not only affected the decline of the clay tiles, but most operated against stone roofing as well.
Production mechanization. Because the clay tile is a manufactured product, one would have expected tile utilization to have continued to dominate the inorganic field, expanding right along with other products so closely associated with the Industrial Revolution, like those of cotton and iron whose rapid expansion was characterised by capitalization, mechanization and specialization, i.e. the division of labour.

The tile industry was well suited for such a change. Even before the industrial tile making could become an organised industry where there was good access to clay and fuel there was transport and a demand for the tile. Woolwich for example, had a flourishing little tile industry at the end of the middle ages; but industries like these were labour and not capital intensive where production was done by hand and was to remain so until after the Industrial Revolution had largely taken place. Mechanization did not occur in the tile industry until after the 1850's and even then with a great deal of difficulty (hand molded of sand-face plain tile are still being produced). Industrialist employers no doubt would have benefitted from such mechanization but its introduction was as welcome to the employees of the brick and tile works as the thrashing machine was to the farm labourer. Labour opposed mechanization violently in 1861, for example, two Manchester brickmakers introduced machines to their production line and within a year the machinery had been blown up by irate labourers (Bowley, 1960, p.65). Also there was organized resistance to machinery being introduced to brick and tile making from the unions.

As long as the tile industry remained un-mechanized, the hand splitting and shaping of slates would not be disadvantageous. In fact it is likely to find the overall cost of hand labour to produce slate actually being less than that to produce the same amount of tile. Productivity in the slate industry for example would not have been as affected by
weather and season since slate could be quarried and split all year around whilst the tile industry at that time required clay to be weathered and green bricks to be dried naturally, both of which were affected by the seasons and good weather. Weathering was in fact made compulsory in the Act for Making of Tile of 1471, in which

\[
\text{Earth whereof any such Tile shall be made shall be dugged and cast up before the First Day of November next before that they shall be made, and that the same Earth be stirred and turned before the First day of February then next following the same digging and casting up, and not wrought before the First day of March the next following; and that the same Earth before it be put to making Tile be truely wrought and tried from Stones. (Dobson, 1931, p.9).}
\]

This act only gives some idea of the preparation work required before clay could be fired. Essentially, clay requires the following production sequences: it first has to be extracted, then broken up (by turning or by putting it through a pug mill or wire cutting machines) and mixed with any additional raw materials before being weathered, preferably through the winter. The clay should be turned over during this weathering period. After which the impurities such as stone have to be removed\(^1\) and in some cases the clay needs to be washed\(^2\).

The weathered and cleaned clay then has to be pugged and ground before it can be moulded or shaped into tiles. These green tiles require subsequent drying (3 weeks on average for naturally dried hand made tiles) before being finally fired, which itself involves much labour in the handling of both tiles and fuel.

\[^1\text{The removal of stones was usually done by treading the clay with bare feet. Ackworth, in his book The Manufacturing of Roofing Tiles published in 1924 mentions (p.18) that only "some (emphasis mine) tile manufacturers have machines for removing stones."}\]

\[^2\text{Washing clay involves mixing it with an equal amount of water to produce a slurry by which the heavy impurities are settled off. After settling the clay needs to be dried.}\]
Slate, on the other hand requires only quarrying and shaping operations. So even if slate production were done by hand, which it largely was before 1850, slate would have been less labour intensive. But slate was to be even more advantaged over clay. Because of the limited number of slate deposits the ones were developed were very large indeed and the control of these quarries were held by a relatively small number of companies. Consequently mechanization, capitalization and specialization were more easily introduced. Furthermore the areas around slate quarries provided few other industrial opportunities so management had more control on what was to be accepted in the way of mechanization. The Dictionary of Architecture of 1892 (s.v. slate) describes the consequences of mechanization.

Until about 1854 slates were only hand made by the Mathews's patent slate-cutting machine then perfected, (one of a number of patented slate-cutting machines), a workman dressed at the quarry in three hours 1,404 slates, equal to 4 tons 4 cwt. 3 qv. 23 lb. [1939 Kg/hr] without breaking a single slate and all square. The best quarryman cannot dress more than from 3 to 4 tons a day (11 working hours) [277 to 370 Kg/hr], and seldom square.

Even though the opportunities for mechanizing in the tile industry were far greater than that of slate, slate was to initially benefit by mechanizing the areas of production which were capable of it.

Transport and fuel requirements. The Industrial Revolution would have never come about without a 'Revolution' in transport, and all historians seem to agree on this point. The transport revolution started along with the political upheavals in the seventeenth century, shipping tonnage doubled in that century, making shipping the third or fourth greatest industry in the country. A boom in the improvement of river communication also took place between 1688 and 1701, and was followed
on land in the eighteenth century with the creation of turnpikes and 'enclosure' roads.

Because of the low value, heavy weight and bulky nature of the materials, it was the canal "mania" (1760-1830), in which 3000 miles of canal were built, followed by the railroad "mania" (1830-1900) which really played a part in the industrialization and choice of building materials. The efficiencies of the canal are particularly dramatic, and various authors have used numerous examples to illustrate this point. A horse, for example, could draw 80 times as much weight by pulling a canal barge instead of a cart on a soft road, and 400 times as much as the pack horse could carry (Hill, 1969, p.249) and canals could cut the cost per ton between Liverpool and Manchester or Birmingham by 80% (Hobsbawm, 1969, p.146).

The effect of these economies on roofing was drastic. Pennant observed the results in 1782 along the Grand Junction canal between Trent and Mersey: "the cottage instead of being half covered with miserable thatch, is now covered with a substantial covering of tiles or slates, brought from the distant hills of Wales or Cumberland". (Hoskins, 1970, p.254). Unfortunately, it is not clear whether Pennant's 'tiles' were clay or slate. Most architectural historians connect canals with slate, but the canal benefitted stone roofing and tile production as well.

1. These road improvements would not have benefitted the transportation of building materials nearly as much as those improvements in water transport. In fact road transport never played a significant role in the long distance movement of bulk building materials until the introduction of the lorry in the twentieth century.
Clifton-Taylor points out:

later the situation [in which tiles were the least common roofing material in north and west England up to Elizabeth I] changed, and by 1830, largely owing to the making of canals, Staffordshire and Shropshire had become the most important tile producing counties (Clifton-Taylor 1962, p.256).

Tiles benefitted from the canals in that they reduced the cost of fuel which, after all, is what the canals were initially about, i.e. using less energy to move more energy. Hill (1969, p.249) emphasises the economic advantages of shipping by canal stating that "Transport by road was at least four times as expensive per ton mile as by canal: twenty times as expensive for coal" in the late eighteenth century.

In fact the price of coal rose sharply after heavy rains if road transport were used, clay tiles were still at a disadvantage when compared to slate, despite the reduced cost of fuel brought about by canal, after all slate and stone roofing were unprocessed materials and required no fuel for processing at all. Transport economies were not limited to fuel - they also resulted in effectively extending the marketable area for both tile, stone and slate. But again slate would have benefitted more from transport economies than tile for it is a bit like the old puzzle - which weigh more a ton of feathers or a ton of lead? Naturally a ton of Welsh slates and a ton of stone or clay.

1Fuel costs are still affecting material costs. Marion Bowley in summarizing the price of brick in the twentieth century states that "the materials which had risen most in price are those most dependent on coal in some form for essential production processes, e.g. burning, firing or melting" (Bowley, 1960, p.153).

2The first canal to be constructed in 1760 was for the Duke of Bridgewater and went from Manchester to his coal mines at Worsley. Hobsbaum (1969, p.46) refers to "the impetus for them [the canals] came from the home market and more especially from the growing demand of the cities for food [fuel for humans] and fuel [coal]."

3This is one of the few examples where both money and energy savings are in harmony. Later transport made shifts, i.e. canal to rail and rail to road, money savings resulted in higher energy costs.
tiles weight the same, but the roof covered by a ton of tiles is substantially smaller than that covered by slate (probably \(1/2 - 1/3\) the size, depending on the type of tile and the thickness of the slate). In addition slate would have benefitted from the shift in population densities during the 18th century described earlier in relation to stone roofing. The population shifted from the south and east to the north and west which were much closer to the slate deposits in Wales, Cornwall, Cumberland and Westmorland shown in Map 2.6, (p. 81).

Not only did slate have an advantage on inland transport, it also had the advantage of being easily shipped by sea; most deposits of slate being located close to the sea (see Map 2.6). The Penrllayn slate quarry, the largest in Britain, had its own six mile private railway to a sea port and much of the slate produced by this quarry was moved by sea especially before the era of rail. Slate from Ireland would have been shipped entirely by sea and that from Scotland by either sea or rail.

Quality control and durability. The manufacture of clay tile requires a great deal of skill, which involves both temperature control and the type of clay. Both effect the ultimate quality of tile produced; and there is some evidence that great variations existed in the quality of tiles particularly in the middle ages. Salzman (1967, p.230) relates the common complaints about the lack of both uniformity in size and quality of fifteenth century tiles. Many of the tiles "would last only four or five years instead of forty or fifty and this is borne out by the manorial accounts, which show that a surprising amount of tiling repair had to be carried out every year". In fact it was these complaints that led to the 1477 act which regulated the process of manufacture and size, though it is doubtful whether the regulations
had much initial success. Even the Victorians were still having some trouble with the quality control of tile products. Dobson (1931, p.21) mentions that their affection for bright red roof was "largely responsible for the lamination of tiles [a form of disintegration due to improper materials, mixing or inefficient burning] on so many of the roofs of houses built during the closing years of the nineteenth century". Interestingly enough the lamination problem occurred more often in machine made tiles than those produced by hand, this led to the "common remark that old workers understood their jobs better than those of the present day". But Dobson (p.22) adds that "no doubt the old makers also had their failures, and had to strip roofs on which their tiles had served for less than twenty years".

Nature, in producing slate metamorphically guaranteed a certain degree of quality control and failures do not appear to be as common. Indeed its durability was well understood by early British Architects. Sir Balthazar Gerbier, for example when giving counsel and advice to all builders in the year 1662 considered that lead and 'bleu slates' were the best roof covering for a house, while Holme in 1688 thought that "slates of 'blew slaggy marble' were the best for duration considering their cheapness" (Innocent, 1971, p.174). Slates uniformity in size, which was being demanded by Architect and Surveyor and builder alike was also as good as that of tile.

Architectural considerations. Slate was to prove far more versatile than tile. As mentioned the Architectural Society felt slate was quite acceptable for what Burnskill would refer to as 'polite' or stylized buildings, and the shift away from brick and tile dominated Queen Anne style to the stone look desired in the Georgian period would have favoured slate; besides the roof itself received
less emphasis in the Georgian period, frequently being hidden behind parapets requiring lower roof pitches than could be achieved with the clay tiles. Slate proved as suitable in both agricultural and industrial vernacular architecture as well. The low pitch, light weight, non-combustibility and resistance to polluted air made it ideal for the new factories and warehouses, but slate was just as suitable for replacing rural high pitched thatch roofs. So slates, unlike the tile covered everything from cottage, through factory to manse.

Taxation. Both slate and tile were taxed in the late eighteenth and early nineteenth centuries. The tax on slates, however, was removed in 1831 nearly twenty years before the tax was removed from tile in 1850. This tax advantage could not have come at a more opportune time, with both industry and cities exploding.

Utilization of slate.
The benefits of slate have long been appreciated. In the latter part of the twelfth century, slate starts to appear regularly on records, but its use is to be restricted to slate areas – the Lake District, Furness, Leicester, Cornwall and Devon. In the case of Cornish and Devon slate; its use expanded outside the local areas along the south coast, a result no doubt of the quarries being quite close to the sea allowing delivery by boat. Welsh slates were being used in Chester in the fourteenth century (again easy sea connections) and had reached Shropshire by the end of the middle ages. Slates early widespread use was reflected quite early on;'...by 1792', says Sir John Summerson, '1200' tons a year [of Welsh slate] were being exported from the Penrhyn Quarries alone, and London rapidly became
a slate-roofed city." (Clifton-Taylor, 1962, p.172). But it was not until George III 1820-1830 and the introduction of canals that its use really started to become widespread throughout Britain. Transport development coupled with the other factors just discussed led to the decline in the use of tile, stone and thatch and to the rapid increase of the utilization of slate, particularly Welsh slate, during and after Britain's period of industrialisation. Indeed most of the factors which favoured slate and direct economic significance which resulted simply in slate being economically more competitive than rival roofing materials. This, no doubt, is largely responsible for the "very great increases in the use of slate in all parts of Britain in the nineteenth century" referred to by Davey (1961, p.153), he even goes so far as to say that "for a time slates practically replaced tiles". At the turn of this century slates overall dominance (assumed at 60 per cent of the roofing mix) again is confirmed in the 1911 edition of the Encyclopaedia Britannica (Bartlett, 1911) referring to slate as being "by far the most generally used of all materials for roof covering".
Section Three (fold out Fig. 2.3, p. 518)

Processed Roofing Materials of the Late Nineteenth and Twentieth Century

The dominance of slate significantly delayed the emergence of processed materials (other than clay tiles) until the late nineteenth century; only a few years before reliable national production figures became available early in the twentieth century.

These figures greatly reduce the need for discussions on material usage estimation, which were required when discussing earlier periods. However, developments in roofing materials were so dramatic during the twentieth century that some discussion is warranted, particularly in respect to innovations in materials and methods of production, a subject that Marion Bowley (1960) devotes an entire book to.

Innovations in Production

Developments in the clay tile industry, historically the only major manufactured roofing material, clearly illustrates the result of all three kinds of production innovations classified by Bowley (1960, p. 374), "Absolute and net cost - reducing innovations", the first category of innovations were achieved in the tile industry primarily through "innovations of the Industrial Revolution type". These were innovations springing from the general technological and scientific advances of the nineteenth century and included the mechanization of winning the clay from deposits, and the use of pug mills for clay mixing. The second type of innovation which Bowley refers to as the type "being stimulated by changes in the relative prices of resources" (1960, p. 390)

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1 The first census of production containing quantities of roofing materials appeared in 1707.
was experienced in the tile industry with regards to fuel resources. As previously mentioned fuel costs played a substantial part in the expense of producing tile which had given slate an economical advantage. This advantage however was effectively reduced when "the relative price of resource (fuel) was reduced" by the use of more efficient continuous kilns¹ and the use of drier clays available only through the use of mechanical presses. The "stiff plastic" clay pressing system also applied to the third type of production innovation described by Bowley as the type which "increase the availability of existing products" (1960, p.391). The press brought into use types of clays previously difficult to utilize for tiles, thus expanding the potential area of manufacture. All of these innovations helped clay tiles make a come back in the first quarter of the twentieth century and reaching their peak utilization in the 1930's, when their use actually surpassed that of slate².

Innovation Products

Innovations in production certainly helped the clay tiles in gaining additional markets, but more important to shifts in roofing materials during the twentieth century were the innovations in materials

¹The industry had traditionally used intermittently fired kilns; the switch from the traditional tile kiln to the continuous type kiln, similar to that which took place in the pottery industry, would probably have increased fuel efficiencies from three to six times. Traditional kilns only utilized between five and ten percent of the heat produced whereas the continuous utilized thirty to forty per cent of the heat (Singer et al. 1958, Vol.II, p.296). For a description of the use and types of continuous kilns in the tile and brick industry one should refer to the numerous works by Searle and Dobson.

²Besides the major benefits from production innovations the tile industry also benefitted from the elimination of the tax in 1890 and the changes in the architectural styles which were more sympathetic to tile.
themselves. Bowley describes (1960, p.399) four types of innovations affecting construction materials, all of which have roofing material examples.

1) **An introduction to materials already produced for other purposes:** this applied to materials previously too expensive for general building purposes, but whose cost was reduced enough for building by the adoption of production innovations. In the case of roofing, all of the basic metals fall under this category along with asphalt, roofing felts, plastics and glass.

2) **An introduction of a new material invented or discovered.** Clearly asbestos cement tiles and corrugated sheets provided the roofing example in this category.

3) **Modification or variation of an existing building material.** The clay tile could be classed under this category, for the extremely uniform tile product emerging from the industrialized plant, could essentially be considered a modified product when compared to its traditional forerunner, a point all architectural historians seem to mention with dismay because of the undesirable aesthetic consequences.

4) **A new component made from an existing material already used in building.** The concrete tile belongs to this type of product innovation.

Innovations in both production and products developed mostly in the nineteenth century but their dramatic effects on roofing materials did not occur until the twentieth century as Fig.2.4 illustrates, but one thing the economist Bowley neglects is the true nature of many of the newly emerging materials. A brief discussion at this point of one of the most unpretentious roofing material—galvanized corrugated iron, is well worthwhile to illustrate the changing nature of roofing materials.
Development of the composite materials. Iron and steel were the metals of industrialization, and their widespread use in the building field was inevitable. But the use of ferrous metals for roofing would be limited, unless protected from oxidation. If not protected the endurance of sheet iron or steel would have been quite similar to that of thatch. Ironically, the non-ferrous metal zinc, played a more significant role in promoting iron's use for roofing than iron itself. By applying a thin coat of zinc to sheet iron, through the simple process of dipping sheet iron into molten zinc, the French chemist M. Sorel in 1836 resolved iron's corrosion problems by this "galvanizing" process. More importantly, Sorel had set the trend for roofing materials of the future. He had developed the composite material. The application of a thin coat of zinc over iron resulted in a composite material which combined the best properties of both materials; the strength and cheapness of iron with the anti-corrosion characteristics of zinc.

Combining zinc and iron produced a composite in a material sense, but the development of iron roofing was to incorporate composite techniques in a structural sense as well. Eight years earlier than Sorel applied zinc to iron, R. Walter of Rotherhithe first applied corrugations to

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1This was by no means the first example of a composite building material. Adobe, for example, is a composite material combining straw and mud that has been used for centuries. Even in the English roofing field composites had been encountered before; the white washing of thatch to improve its resistance to fire was a very early example of roofing composite. The critical difference between white washed thatch and galvanized iron was where and when the materials were combined to form the eventual composite. Galvanizing was done well before the construction stage and the combination of iron and zinc was conceived not as the separate roofing products but as one integrated whole. Whitewash, on the other hand, was conceived of as a distinctly separate material from that of thatch and its application occurred during or even after the construction phase.
Iron roofing, an ancient world technique used to stiffen bronze. These corrugations greatly increased the span and load which could be carried by a given thickness of iron. In other words the corrugated sheet iron had become a composite in the sense that one material was performing two separate functions – structural and environmental, previous roofing materials acted as environmental skins only, with little inherent load bearing characteristics.

The iron, zinc and corrugations were all combined on a commercial scale in Wolverhampton in 1838 to produce a revolutionary roofing material. The usage of galvanized corrugated iron was further enhanced by its versatility as a universal cladding material with capabilities of being applied to either wall or roof.

The efficiencies of composite were soon realized and corrugated galvanized iron literally started to cover the world, initially benefitting from the rapid expansion of colonialism and the discovery of gold. Even though it gained rapid acceptance on a world market its acceptance on the home market was much more restrained despite the overall efficiencies.

Galvanized iron was soon followed in the nineteenth and twentieth centuries by other composite roofing products; corrugated asbestos cement being the most obvious but built up bituminous roofing representing another. These composites, like that of corrugated iron,

1. Thatch could also be considered a composite in an environmental and not a structural sense, for it combined both waterproofing and insulation characteristics into one material.

2. Slates and clay tiles were other materials used for both roofing and walling, but they were primarily thought of as a roofing material and never gained much acceptance as a walling material and when applied it was only as a water resistant skin over an existing but less durable wall.
never dominated the market like slate or currently concrete tile.
Subjective considerations, mainly appearance and not physical performance appear to be the factors in the relatively limited acceptance of these technologically advanced materials. The concrete tile, an ersatz for the more familiar roofing materials, such as slate or tile, dominates the roofing field instead of the cheaper, lighter, and often equally durable composites developed at an earlier date. But the use of these composites for utilitarian structures for farming and industry gave them a stigma in the public eye which seems to have prevented their cutting into the major market for house roofs. Any forecasts about the future of roofing materials will have to be judged with the fact that the product has to be visually acceptable to the public, regardless of how technically advanced or efficient its use.

Roofing material utilization in the late nineteenth and twentieth centuries
During the nineteenth century, Britain was finally transformed from a predominantly agricultural and rural nation into an industrial and urban one (Fig. 2.1). The population of England and Wales rose from around ten to thirty five million. This growing population required an enormous increase in dwellings and industrial, commercial, and public buildings. Urbanization meant more shops, churches, theatres, schools and hospitals; industry and commerce required administrative buildings, factories and warehouses; and the newly emerging railway companies also required a great many new buildings. Much of the building stock in existence at the beginning of the twentieth century had been built in the preceding one hundred years, in step with industrial and economic expansion. With more and new types of buildings required, the building and building materials industry, which now were completely separate entities, had to expand rapidly;
in fact at a faster rate than population growth. The situation had considerable effect on roofing materials.

A review of the inorganic roofing materials during the last century indicates that Welsh slate was meeting most of the demand during this rapid period of expansion. Slate was not only organic materials but also its inorganic rivals—clay tile and stone slate. In the second half of the nineteenth century slate probably reached its peak usage, providing over half the roofing requirement, with tiles providing roughly a quarter. The remaining roofing consisted of either the highly processed organic and inorganic materials quickly appearing on the market as a result of industrialization or the remaining unprocessed materials—thatch\(^1\) and stone.

We have a good idea of the material mix at the turn of the century and Cullen\(^2\) (1967) in his study on the usage of building materials establishes the roofing mix in 1966. Between those dates the central statistics office's *Annual Abstract of Statistics* (Nos. 85 to 109) provide comparative production figures for the major roofing materials,

\(^1\) Thatch had completely lost its dominance well before the late nineteenth century, but its use in rural areas persisted well into the early twentieth. Ray Stannard Baker in his autobiography *American Chronicle* (1945) describes his rural excursions in the British Isles during the first world war in which he witnessed the use of thatch. He refers for example to "romantic old thatched villages" near Bridgend (p. 357) as well as to "cottages freshly thatched and white washed" (p. 336) in Ireland where thatch is still used a great deal in the country.

\(^2\) The percentage mix derived from Cullen's roofing area figure (1967, Table 1) are as follows:

<table>
<thead>
<tr>
<th>Roofing Material</th>
<th>Percentage</th>
</tr>
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<tbody>
<tr>
<td>Concrete Tiles</td>
<td>47%</td>
</tr>
<tr>
<td>Asphalt and felts (processed organic)</td>
<td>25%</td>
</tr>
<tr>
<td>Asbestos Cement</td>
<td>15%</td>
</tr>
<tr>
<td>Clay Tiles</td>
<td>8%</td>
</tr>
<tr>
<td>Copper, aluminium and patent metal</td>
<td>3%</td>
</tr>
<tr>
<td>Slate</td>
<td>2%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>

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i.e. concrete tiles, clay tile and slate, which date back to 1935 and the Census of Production provide some data on roofing materials in 1907, 1912, 1924, 1930 and 1933. Except for 1924 the data presented in the Census of Production has limited usefulness, since both the units of measurement and the materials covered vary from year to year. Unfortunately data is lacking in the utilization or production of the other major roofing systems involving metal, asbestos cement or processed organic materials, i.e. asphalt and felts. Consequently the following assumptions have to be made concerning the utilization of these materials.

1) Metals. Cullen indicates that copper, aluminium and patent metal collectively represented only two percent of the 1966 roofing demand. Metals probably represented a larger portion in the late 1800's and early 1900's when substitutes like corrugated asbestos and asphalt products were just being developed. There were surely fluctuations between non-ferrous metals (lead, zinc and copper) but corrugated iron took a commanding lead, and it would be reasonable to assume metals became a noticeable roofing product in the first half of the nineteenth century, gradually expanding in use until World War I, at which time they probably represented between five and ten per cent.

1 For the purposes of this study production and demand are considered equal.

2 Glass gained some acceptance as a roofing material during the nineteenth century when production innovations made possible large amounts of relatively cheap glass. No doubt its use was inspired by the Crystal Palace at the Great Exhibition of 1851 along with the contemporary craze for conservatories, botanical gardens and glass covered stations. However, it was always a novelty roof used on speciality buildings and never gained general acceptance. In its fashionable period, lasting roughly 70 years between 1830 and 1900, it probably never reached one per cent of the demand and certainly not enough to justify inclusion into this study.
<table>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CLAY TILES (m² x 10⁶)</td>
<td>5.4</td>
<td>11.4</td>
<td>14</td>
<td>4.8</td>
<td>7.8</td>
<td>6.5</td>
<td>6.7</td>
<td>7.6</td>
<td>5.4</td>
<td>3.9</td>
<td>3.5</td>
<td>3.1</td>
<td>2.7</td>
<td>1.6</td>
<td>1.4</td>
</tr>
<tr>
<td>CONCRETE TILES (m² x 10⁶)</td>
<td>20.7%</td>
<td>27.6%</td>
<td>21%</td>
<td>26%</td>
<td>18%</td>
<td>20%</td>
<td>26%</td>
<td>18%</td>
<td>20%</td>
<td>18%</td>
<td>20%</td>
<td>18%</td>
<td>20%</td>
<td>18%</td>
<td>20%</td>
</tr>
<tr>
<td>SLATE (m² x 10⁶)</td>
<td>2.0</td>
<td>6.6</td>
<td>6.1</td>
<td>2.6</td>
<td>2.0</td>
<td>2.6</td>
<td>2.3</td>
<td>2.2</td>
<td>1.7</td>
<td>1.4</td>
<td>1.4</td>
<td>1.1</td>
<td>0.88</td>
<td>0.66</td>
<td>-</td>
</tr>
<tr>
<td>TOTAL (m² x 10⁶)</td>
<td>12.5</td>
<td>23.9</td>
<td>29</td>
<td>10.6</td>
<td>18.8</td>
<td>17.1</td>
<td>21</td>
<td>28.9</td>
<td>25.9</td>
<td>26.3</td>
<td>25.9</td>
<td>30.5</td>
<td>28.3</td>
<td>23.6</td>
<td>20%</td>
</tr>
<tr>
<td>ASBESTOS CEMENT SHEETS (tonnes x 10³)</td>
<td>12.0</td>
<td>23.9</td>
<td>29</td>
<td>10.6</td>
<td>18.8</td>
<td>17.1</td>
<td>21</td>
<td>28.9</td>
<td>25.9</td>
<td>26.3</td>
<td>25.9</td>
<td>30.5</td>
<td>28.3</td>
<td>23.6</td>
<td>20%</td>
</tr>
</tbody>
</table>

*The 1924 figures from the Census of Production were presented on a tonnage basis, i.e. 376 tons x 10⁶ for slate and 351 tons x 10³ for clay tiles. For comparative purposes these figures were converted to area using an assumed roofing weight of 40 kg/m² for slate and 65 kg/m² for clay tiles.*

**NOTE:**
The figures in this table have been converted into m² x 10⁶ from squares x 10³ (1935 to 1954), yds² x 10³ (1956 to 1960) and m² x 10⁶ (1962 to 1970).
of the demand. After that date their use diminished to the 1966 figure. Any production figures from the actual manufacturers of patent metal roofs could be misleading because of the large amounts traditionally exported abroad and the lack of distinction between roofing and walling demands.

2) Asbestos Cement. This material was invented in 1889 and was first introduced in tile and sheet form to Britain in 1904 from Belgium. In 1910 the patent on asbestos cement expired and in 1918 three British firms began to produce asbestos cement products. A steady increase in the percentage mix of asbestos cement roofing was assumed from the early 1920's to the fifteen percent estimated by Cullen for 1966. This increase in the utilization is generally confirmed by production figures (on a tonnage basis) of asbestos cement flat and corrugated sheeting shown in table 2.1.

3) Asphalt, roofing paper and felts - (processed organic). It is very difficult to calculate the usage of these materials, not only because of the lack of data but also because of the numerous methods of application, e.g. number of plys, the amount of under-coating etc. Because of their close association it would be reasonable to assume that the increase in the rate of utilization would be very similar among these materials. It would also be a reasonable assumption that they emerged on a commercial scale in the mid nineteenth century and steadily increased in use along with the expansion of the paper, coal gas and petroleum industries which they were probably closely associated with as co-products or by-products. The increasing use of flat roofs especially for commercial and industrial buildings also would have lead to the increase in usage which could not have accelerated with time up to 25 per cent mix estimated by Cullen for 1966.
Table 2.1 indicates U.K. production figures for clay tiles, concrete tile and slate covering a period of forty-six years. The percentage mix between these three major roofing materials is also shown in Table 2.1. In order to establish the percentage mix which these three materials represent out of the total roofing requirement; the percent mix represented by processed organic metal, and asbestos cement was subtracted from the total and the remaining portion divided in the same proportions as the material mixes shown in Table 2.1 (between slate and concrete and clay tiles).

In closing we have seen in the nine hundred year period between 1000 and 1900 the complete reversal in roofing materials - from organic to inorganic. However, in the twentieth century we have witnessed violent fluctuations in the roofing materials used, Fig.2.4 graphically shows that as much change has taken place in the last 70 years as had taken place in the previous 900 years, but the changes were of a different nature, concerning primarily the change from unprocessed to processed materials and not the substitution of inorganic for organic.
CHAPTER THREE

AN ENERGY ANALYSIS OF ROOFING MATERIALS

The last Chapter was devoted to establishing the substitution of roofing materials in Britain since the eleventh century, the results of which are graphically summarized in Fig. 2.4. This Chapter, along with its supporting Appendixes A to H, analyse the production energy required by these materials. The objective is to see what trends have developed over the years in relation to the energy intensiveness of the materials, the relative increase in the amount of energy used in roofing with and without increases in their demand, the rates at which these items have taken place and the likely trends in the future, and their consequence on energy demand. Of course roofing materials represent only one constructional element and to extrapolate any conclusions drawn from an energy analysis of them to other constructional elements obviously contains some risk, never the less, such an analysis does provide at least a nucleus around which future investigation into the relation between material and energy can take place.
Before proceeding with the analysis of production energy, it is necessary to expand further the term production. In conventional economics, production is defined as either, the making of commodities more useful to mankind or the rendering of services which satisfy human wants directly. This study is concerned only with the first, that of making commodities useful. In production as a commodity gains usefulness, value is added or in other words the utility of the commodity is increased. Increases in utility can be achieved by changes in time, place or form, all of which involve the flows of both money and energy. The most significant utility change in energy terms are those associated with form. Extractive, agricultural, manufacturing, and construction are the major classification of industries which deal with increasing 'form and utility' by processing raw, partly finished or finished commodities; and it was this aspect of production which received attention in the first Chapter.

Production energy concerned with processing or increasing the form utility of roofing materials will be the first type of production energy to be discussed. Trade, finance and transport are industries primarily concerned with 'place' and 'time' utility and are devoted to increasing a commodity's availability and not its physical/chemical characteristics or 'form'.

It will be demonstrated later in this Chapter that trade and financial activities constitute only a small portion of total production energy. They are also extremely difficult to estimate especially in a historical context. Because of these factors they will not be included.
Transportation, on the other hand is critical in increasing a material's place utility and is slightly easier to estimate. It has been historically such an important factor in material usage, especially those which are unprocessed, that a transport energy analysis will be made even though its contribution to overall energy consumption is small.

The Use of a Graphical Analysis

In order to make the production energy analysis more concise and comprehensible, an effort has been made to present the analysis in a strictly graphical form, actual data and calculation for the graphs being contained in a series of supporting appendixes (A to H). In analysing energy requirements for roofing materials it is worth reviewing Fig. 2.4 which already displays the shifts in materials. Shifts before 1600 were relatively gradual and consistent in nature, because of this, it was felt that there was little point in carrying the analysis any further back than 1600; for trends established by that date could easily be projected back over the remaining 600 years.

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1. Appendixes A to C concern processing energy and D to H with transport. Actual figures for graphs 3.1 to 3.20 can be found in Tables A-1 for processing and D-1 for transport.

2. Reducing the analysis to 400 years is a graphical asset, allowing three related graphs to be shown on the same page, using the same scales as those used in Chapter Two. For comparative purposes this was felt preferable to either using a foreshortened scale which visually distorted the graphs by emphasising earlier periods; or constructing graphs to cover the entire period using a uniform scale but on separate pages. In the case of most graphs the latter method produced charts with long, thin 'tails' hardly discernable after 1500. Changing the vertical scale led to distortions.
The majority of graphs in Chapter Three contain both a composite graph and individual graphs for each component which makes it up. Nine reference dates are used in constructing the graphs and divide the years between 1600 and 1966 into eight periods. The first two periods are of one hundred years covering the time between 1600 and 1800, the next two are fifty years and cover the nineteenth century, the twentieth century being divided into four intervals of twenty-five, thirteen, twelve and sixteen years each instead of the nine periods used in the expanded mix graph in Chapter Two. This reduction in time periods corresponds to the acceleration of material shifts in the nineteenth and twentieth century. The individual mix graphs are arranged in chronological order with the oldest materials at the top of the page. Presenting them in the same order enables one to easily see what affect factors, such as energy intensity, have on the basic percentage mix.

In Chapter Three graphs and calculations are not only reduced in time but have been abridged with respect to materials. Cement tiles and asbestos cement are grouped into one cement based category, stone and slate have been grouped together and asphalt and paper based roofing materials are grouped into a processed organic category. These consolidations can be seen when comparing percentage material mix graphs Fig. 3.1 (p. 115) with Fig. 2.4.
In Chapter One processing energy was discussed in relation to various building materials. The energy requirements to produce these materials was expressed in coal tonne equivalent (TCE's) per unit of mass (tonne). This was done in order to express energy in a more physical way which could be compared to other materials mentioned in the same Chapter. Processing energy intensity in the remainder of this study will be expressed in the more conventional terms of kWh/kg.¹

The energy analysis of roofing (and other constructional elements) energy intensity will be expressed per unit of area, i.e. kWh/kg, energy per unit of mass being somewhat misleading. To appreciate the difference between mass and area energy intensities, a comparison of profiled aluminium and steel roofing will be made. The energy intensity of the former on a unit of mass basis is extremely high from

¹One of the major difficulties today in energy analysis is the numerous ways in which energy intensity can be expressed. Energy intensity relates energy to a unit of quantity, both energy and quantity can be expressed in various ways and systems. Units of energy, for example, can be expressed (as in Chapter One) as a unit quantity of fuel, with an assumed calorific value, (e.g. barrels of oil, cubic feet of gas, tons of coal) or more conventionally in metric or imperial units of energy/heat (e.g. kcals, BTU's, therms, joules and kWh's). The unit of quantity likewise can be expressed in a number of ways both physical and non-physical. Mass, area and volume are the usual ways of representing quantity and again both metric and imperial systems are used. Non-physical units of quantity include money (e.g. kWh per dollar), unit of production (e.g. kWh per brick or tile) and in the case of fuels and food in terms of energy (e.g. kWh's required to produce a kWh). The numerous ways of stating both energy and quantities has resulted in almost unlimited numbers of combinations which are continually requiring conversion from one to another before any meaningful comparison can be made.
Figs.
3.1
3.2
3.3
Fig. 31 Percentage mix of roofing materials (K mix)

Fig. 32 Percentage mix of relative processing energy (Fig. 3A)

Fig. 33 Percentage mix of processing energy intensities expressed in order of magnitude (kWh/m²)
primary sources - 73 kWh/kg while the latter only requires about 13 kWh/kg. The ratio between these two being 6 to 1. However, the ratio of energy intensities on a unit of area basis is less than 2 to 1 (219 kWh/m² for profiled aluminium versus 137 kWh/m² for steel roofing, from Appendix B); this being due to the weight of the aluminium roof which is far less than that of steel.

The energy intensity of roofing varies enormously, covering four orders of magnitude. Thatch, an unprocessed material falls into the lowest range (0.1-1 kWh/m²) with the highly processed metals and early clay tiles falling into the highest range (100-1000 kWh/m²).

Figure 3.2 has been constructed to show the effect of such extreme variations in processing energy. It represents a percentage mix graph arranged in the same manner as Fig. 3.1, but instead of representing the proportion of roofing materials used at a given time, it represents the proportion of energy used to process the various materials. In

1 Strictly speaking mass and weight are different units. Mass referring to the quantity of matter in a body, while weight refers to the gravitational force upon it. However in this study the terms mass and weight will be used interchangeably.

2 In Appendix B the energy intensities for the six roofing types are developed on a unit of area basis from specific energy, i.e. unit of energy per unit of mass figures currently available. Appendix C establishes efficiency factors which are used to adjust the energy intensity of processed materials upwards for earlier periods in time, in order to reflect the less sophisticated and efficient processing methods. These factors are denoted in Table C-1.

3 Calculating the processing energy for an unprocessed material such as thatch might appear to be a contradiction in terms, but using the definition of an unprocessed material established in Chapter One, this would be limited to only the energy involved in the mechanical extraction, shaping or finishing procedures. It should also be noted that 'income' sources of energy such as solar and wind power are not included in the energy costs.
Fig. 3.4. Relative processing energy.
(energy intensity x % mix)

Fig. 3.5. Quantity of roofing materials.
(% mix x population)

Fig. 3.6. Relative processing energy consumed.
(energy intensity x % mix x population)
other words, it indicates what share of the total amount of energy that went into processing roofing materials, a particular material used. Stone and thatch, which were major roofing materials and occupying most of material in Fig. 3.1 are quite insignificant in Fig. 3.2; being almost entirely replaced by the two early processed materials - clay tiles and metal.

An impression of the changes in processing energy intensities over the last 400 years is gained from Fig. 3.3 reflecting a percentage mix of material processing energy intensities. The intensities are grouped into four orders of magnitude, i.e. 1 to 1, 1 to 10, 10 to 100 and 100 to 1000 kWh/m² and are shaded to reflect these intensities (i.e. the darkest shading representing the highest intensity and vice versa). It can be seen that the major roofing systems have become more energy intensive with time with the substitution of unprocessed materials with processed ones, the individual graphs indicate a series of 'waves' moving from left to right, each successive wave being one order of magnitude higher than the next.

A more accurate picture of the changes in processing energy can be obtained by weighting the material mix with the actual energy intensity of each material; in other words multiplying the percentage mix of a material by its energy intensity. This relative energy which is shown in Fig. 3.4 reflects the amount of energy used in roofing materials if there were no increase in demand. To appreciate the increase in energy it should be pointed out that if all the material used were to have the same energy intensity as thatch the end result would have been a graph like Fig. 3.4 consisting of a parallel line one unit off the base line! The peak between 1850 and 1925 is due not to the
The overall use of energy and building material is not only dependent on energy intensity. The quantity of materials used is equally as important. Since accurate quantitative data on roofing materials is non-existent before 1900 another method has to be used in order to provide an idea as to the effect of increased demand over the years. The most appropriate method of establishing the growth in demand for roofing would be based on population increases.

The reader may question the validity of the assumption, that demand for roofing is proportional to population. Parry Lewis in his book *Building Cycles and Britain's Growth* (1965, p. 165) find this to be the case, stating "the general agreement in the timing of fluctuations in population growth and house building is unmistakeable". It would be reasonable to assume that other types of building would also increase with population. Indeed consideration was given that the number of structures and roofage area would increase faster than population because of the demand for new building types, particularly with regards to agriculture, industry, transport and commerce. On the other hand the increasing use of multi-storey buildings would effectively reduce roofage in relation to population. These two influences produce compensating errors, making the estimated change in material demand on a population basis a fairly reliable estimate.
Figure 3.5 depicts the product of material mix and population. 

It represents a quantity weighted material mix\(^1\). 

It can be seen that the increase in demand results merely in the amplification of the percentage mix, with the exception of thatch whose position is reversed. This being due to its very early popularity when demand would have been quite small compared to today for the population in 1600 amounted to about 4 million.

In energy terms, the relative energy consumed is most relevant. This represents the relative energy shown in Fig. 3.4 adjusted to the increase in demand, shown in Fig. 3.5. The result represented in Fig. 3.6 most nearly reflects the overall energy consumed by year in processing roofing materials in absolute terms. The increase in energy consumption is quite dramatic with increases in quantity and energy intensities amplifying each other, i.e. the use of more materials with higher average energy intensities. Improved processing techniques are effectively offset by additional demand. To appreciate the increase in energy consumption to provide roofing one has to realize that if all roofing materials in 1966 had an energy intensity equal to that of thatch, the relative energy consumed would have amounted to 55 instead of the 1700 indicated in Fig. 3.6. On the other hand if the materials retained their respective energy costs but with the demand remaining at the 1600 level the maximum reached would have amounted to about 200.

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\(^1\)This quantity factor is based on increased roof coverage and not on the quantity of material by either weight or surface area though there is a strong relationship between them. Pitch assumptions would have to be made in order to reflect roofing surface area and weight per unit of area would need to be considered if the quality factor was based on mass. But these considerations have been taken into account with calculation of energy intensities.
Transport Energy

The energy involved in increasing a roofing material's time/place utility is much smaller than that involved with form utility, but calculation is far more complex and hypothetical. In order to arrive at the transport energy intensity of materials four variables have to be considered. The first concerns the roofing weight, which takes into consideration an assumed roof pitch\(^1\). The second factor involves an estimated distance of travel for the materials as though they are primarily based on the mode of transport used\(^2\). The distances assumed for each mode increase with time to allow for improvements in transport and trading conditions. The third item deals with the energy intensity of the transport mode itself\(^3\).

The final factor to be assumed was the model mix for each material, since materials were not exclusively limited to one mode or another\(^4\).

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\(^1\) The values used in calculating roofing weights per unit of horizontal cover are contained in Appendix B (steps 1-6).

\(^2\) The distance travelled is estimated in Appendix H and is summarized in Table H-1.

\(^3\) These are calculated in Appendix E and like processing energy requirements they have been estimated under current conditions and adjusted upwards to allow for deteriorating conditions and the use of less efficient equipment. Appendix F is concerned with these adjustments the results of which can be found in Table F-2.

\(^4\) Assumed modal splits are not to be interpreted as completely independent from one another. Take for example transport of clay tiles in 1950 (table D-1, col. E) the 80:20 split between lorry and rail does not signify that 20\% of clay tiles were shipped only by rail and the rest only by lorry; it means that out of the total transport effort (kg/km) that were involved with clay tiles 20\% went by rail while 80\% went by lorry even though some of the journeys would have involved both modes. Thatch is an exception, its assumed transportation being limited to land vehicles powered by either human or animal.
Fig. 3.7 Percentage mix of materials and transport modes with transport energy intensity ranges indicated (ranges are those used in Fig. 3.8).

Fig. 3.8 Percentage mix of relative transport energy (Fig. 3.9).

Fig. 3.9 Percentage mix of transport energy intensities expressed in order of magnitude (kWh/m²).
modal mix is dealt with in Appendix G.1.

The actual calculations involved in estimating the transport energy intensity for each material type are as follows: the weight (kg/m²) \((A)^2\) is multiplied by the distance (km) \((B)\) to produce a weight/distance factor \((\text{kgkm/m}^2)\) \((C)\) which in turn is multiplied by the mode energy intensity \((\text{wh/kgkm})\) \((D)\). This produces the material transport energy intensity \((\text{kWh/m}^2)\) for each material and mode. At this point the graphics and methods of establishing relative energy and relative energy consumed are handled in the same way as those already used in analysing processing energy.²

Figures 3.7 to 3.12 are arranged by material in the same fashion as those used for processing energy (Figs. 3.1 to 3.6). The material percentage mix graph with the assumed transport modal mix superimposed is shown in Fig. 3.7. A percentage mix graph arranged in the same way as Fig. 3.7, but indicating the portion of the transport energy which was used to transport a specific material is illustrated in Fig. 3.8. There is a fairly strong resemblance between the two graphs, unlike the equivalent processing energy graphs (Figs. 3.1 and 3.2) discussed earlier, which were quite dissimilar, indicating little relation between amount of material used and its portion of the overall processing.

1. Overall modal mix is presented in Table G-1 in Figs. G-2, G-3.
2. The bracketted letters and numbers refer to the relevant column in the calculation table D-1.
3. Table D-1 does include an additional column \((E)\) which concerns the percentage modal mix for each material (each material representing 100%) the figures in column \((E)\) represent modal split as well, but in relation to all materials (all materials representing 100%).
3.10 Relative transport energy (energy intensity x % mix)

3.11 Quantity of roofing materials with transport mode split indicated (% mix x population)

3.12 Relative transport energy consumed (energy intensity x % mix x population)

KEY to Figs. 3.10-3.12

o = cart
i = inland waterway
s = sea transport
r = railway
l = lorry
w = combined water transport (i+s)
AC = asbestos cement
CT = concrete tiles
energy used.

The actual changes in transport energy intensities are reflected in Fig. 3.9 a percentage mix chart like Fig. 3.3, the intensities are grouped into four orders of magnitude, i.e. .001 to .01, .01 to .1, .1 to 1 and 1 to 10 kWh/m², which are shaded accordingly, darker shading representing higher energy intensity. It can be seen that, like Fig 3.3, the overall shift in transport energy intensity is similar to that of processing energy - from a lower to a higher intensity. The shift however was due more to changes in modes of transport than the changes in material. The change in transport mode also has a much more dramatic effect on relative energy (Fig. 3.10) which very abruptly increases in the latter half of the nineteenth century with the introduction of the railway.

The transport mix adjusted to reflect increased demand is represented in Fig. 3.11 and the final relative energy consumed by transport is shown in Fig. 3.12. It is worth noting with respect to the relative energy consumed that if all transport had the same energy intensity as that of thatch which resulted from a fairly light material, moved over a very short distance, over land, and using an animate source of power, the total relative energy consumed would amount to about 55 on the scale of 200 in Fig. 3.12. It would be 5.5 if all the transport energy costs were similar to those encountered when shipping stone or clay tiles which were heavy materials moved over medium distances using a transport mode with a quite low energy intensity, i.e. inland waterway. If all roofing materials were to have been moved by vehicles with an energy intensity as low as that of sailing ship, even over long distances the relative amount consumed in 1966 would have amounted to roughly .55!
Figs.
3.13
3.14
Fig. 3.13  Histograms indicating transport energy intensities expressed in orders of magnitude.

Fig. 3.14  Histograms indicating processing energy intensities expressed in orders of magnitude.

**KEY**

- 1 kWh/m²
- 0.001 to 0.01
- 0.01 to 0.1
- 0.1 to 1
- 1 to 10
- 10 to 100
- 100 to 1000
A Concluding Comparison Between Processing and Transport Energies

The shifts in processing energy intensities are achieved in fairly ordered steps or waves seen in Fig. 3.3, a percentage mix graph. The lowest intensity range \(0.1 - 1 \text{ kWh/m}^2\), being replaced by the next order \(1 - 10\) during the late 1800's but soon overtaken by the current range of energy intensity \(10 - 100\). A histogram, Fig. 3.14 expresses this same shift and better shows the periods of transition. These transition periods can be identified when the heights of the vertical bars are roughly equal. The period between 1700 and 1800 represents the first transition from \(0.1 - 1\) to \(1 - 10\) and 1925-1938 shows the second transition period to \(10 - 100\). The relative shortness of the latter period is worth noting as well as the fact that up to 1850 the material energy intensities were either quite low or very high with a complete void in the mid range of \(10 - 100 \text{ kWh/m}^2\), which would dominate 100 years later. The highest range \(100 - 1000\) always remained small and independent until this century when energy and economics seems to be forcing it out altogether. Roofing materials have consolidated in the \(10\) to \(100\) range and are not likely to go up but perhaps more importantly to go down unless there are some drastic changes in either energy cost or social structure. One should not be complacent about this stabilization; a two fold increase in the order of magnitude of a material's energy intensity presumably reduces manufacturing and site skills and labour by perhaps two or three times does expose a nonsensical energy situation that has wide implications on the future of the so called mechanization or industrialization of building.

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1 The first shift, i.e. unprocessed organic to unprocessed inorganic materials, was much less concerned with replacing labour and skills involved in roofing than it was with the replacement of agricultural labour as a whole. The first change was also related more to performance and towards the more durable and non combustible material.
Transportation follows a wave pattern similar to the one described in Appendix G for modal mixes as might be expected. Rail and lorry, with similar intensities, have in effect combined thus eliminating one 'wave' in Fig. 3.9 (versus fig. G-3). What is unique about transport intensities is the nature of the mid 'wave'. Transport energy only increased by a magnitude order of one since 1600 moving from the 1 - 1 to the 1 - 10 range and the decline of the earlier causing the natural rise of the latter, the transition period occurring between 1850 and 1900 (Fig. 3.14) primarily due to steam power. What is interesting about this shift is the appearance of a smaller mid shift to an energy intensity which is lower than the one preceding, quite unlike processing where the major mid shift was to an intensity falling between the preceding and succeeding ranges. Like processing it is difficult to see how transport intensities could increase to the next order, neither is it reasonable to expect it to return to a lower order, so long as processed, non local materials are used.

Figure 3.15 is a percentage mix graph combining both processing and transport energy intensities as shown in Figs. 3.3 and 3.9. What becomes clear is the elimination of the extreme high and low energy intensities and the increase in the intensities for both categories, so much so that processing energy of the nineteenth century is of the same magnitude as the transport energy intensity of the twentieth century.

Relative Energies

A percentage mix representation of energy intensities expressed in orders of magnitude is helpful to get a general idea of shifts, but relative energy provides a better idea in terms of overall energy levels
Figure 3.13: Percentage mix breakdown of the energy consumed in maintenance and construction in the U.S. in 1963 (data from Ballard and Lees, 1973, TAMEI, Sectors 1101, 1102, and 1201) with likely mix projections into the past and future.

Figure 3.15: Combined percentage mixes for processing and transport energy intensities expressed in orders of magnitude (kWh/m²).

Figure 3.16: Comparison of the rates of change of relative energy for processing and transport.

Figure 3.17: Comparison of processing and transport relative energy.
unaffected by increases in demand, Fig. 3.17 compares at the same scale the relative energy of transport (Fig. 3.10) with that for processing (Fig. 3.4).

Transport's relatively small contribution to overall energy costs is immediately seen. In this case study it amounted to roughly 9 percent of transport and processing energies combined in 1966, though transport's percentage of the total energy requirements has fluctuated slightly over the years as indicated below:

Transport's percentage of total production energy costs (excludes site work application and wholesale retail and financing).

<table>
<thead>
<tr>
<th>Year</th>
<th>Transport's Percentage</th>
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<tbody>
<tr>
<td>1600</td>
<td>3%</td>
</tr>
<tr>
<td>1700</td>
<td>2%</td>
</tr>
<tr>
<td>1800</td>
<td>1.4%</td>
</tr>
<tr>
<td>1850</td>
<td>4%</td>
</tr>
<tr>
<td>1900</td>
<td>6%</td>
</tr>
<tr>
<td>1925</td>
<td>7.8%</td>
</tr>
<tr>
<td>1938</td>
<td>6%</td>
</tr>
<tr>
<td>1950</td>
<td>7.5%</td>
</tr>
<tr>
<td>1966</td>
<td>8.6%</td>
</tr>
</tbody>
</table>

The amount falls from 3% in 1600 to a low point of 1.4% in the early nineteenth century, which coincided with the maximum amount of waterborne transport; then steadily increasing after that date to the 1966 percentage. The relative energies for processing and transport have also been plotted out on a logarithmic scale (Fig. 3.16) to indicate the rates of change. It is quite clear that the energy increase associated with processing were far more steady and gradual even though greater in magnitude than those of transport, which shows a very abrupt increase between 1850 and 1900.

The relationship between transport and material processing is quite similar to the one determined by Bullard and Herendeen (1973, sectors 1101, 1102, 1201) for residential and non-residential new construction and even residential maintenance sectors of the U.S. economy in 1963, shown in Fig. 3.18. The case study only involved material processing
off site (except for thatch) and transport. Bullard and Herendeen's study involves all production energy costs, and what is interesting is the fact that transportation's portion of the time/place sector of production is less than the amount involved in wholesale and retailing materials, as well as being less than the energy used in site work by the construction industry, which itself is a minor part of the 'form' related portion of production.

It would be interesting to speculate on the changes that have or will occur in the total production energy mix. An estimation of this has been made and is indicated by dashed lines in fig. 3.18 with regards to the 'form' portion of production. It is obvious that on site processing would steadily increase the further one retreats in history. If prefabrication, or industrialization continues, the 'construction industry' or site work energy will decrease especially in relation to material processing unless continual major improvements in processing efficiencies can be made. Most of the proposals for more pre-finished buildings involve the use of light-weight highly refined and normally energy-intensive materials such as metals and plastics. As for the time/place portion of production it would be fairly safe to assume that energy involved in the selling and financing of material is a relatively recent (i.e. since 1800) item, previously being non existent or incorporated in the building industry. This area will likely increase in energy terms particularly with increased prefabrication using selling techniques similar to those used with the more durable consumer goods.

---

1 Some of the construction industries' share of energy would inevitably be for transport of either men, equipment or materials and should be included under transport but because the estimate was based on an economic input/output model its portion is unknown.
Figs.
3.19
3.20
Fig. 3.19 Comparison of the rates of change of the relative energy consumed by processing and transport.

Fig. 3.20 Comparison of the relative energy consumed by processing and transport.
Transport's portion is hard to predict; it will probably increase in magnitude due to the use of more processed materials whose raw constituents come from great distances and with the possibility of material backhauling arising out of pre-finished components; but whether transport increases would be more rapid than either material processing, distribution or financing is difficult to say. If transport's increase in energy is at a slower rate than the energy required in processing, the percentage mix would actually go down. On the other hand, there are not likely to be many great reductions in transport energy requirements because of the continuing trends towards total road transport. If break throughs do occur in processing techniques, which is possible with some materials, processing's portion of the energy costs would go down in relation to transport's relatively fixed position and thus increasing transport's portion of the energy mix.

Increase in Material Demand and Relative Energy Consumed.

Mix is worth discussing, but what is really significant, in relation to non-renewable resources such as fossil fuels, is the energy consumed. Figs. 3.19 and 3.20 show the overall increase in energy consumption and their rates of change involved with roofing material, also plotted with population as a guide to the increase in demand. In the first 150 years the relative energy consumed follows demand then accelerates rapidly with the substitution of processed for unprocessed materials which involve low efficiency production techniques and the transfer to steam powered transport. In the twentieth century relative energy consumed actually decreased with the switch to more efficient engines and improved routes in the transportation field and to lower intensity materials as well as improved techniques in producing them. These improvements are largely offset by the increase in demand
producing a level relative consumption of energy. But the energy intensities, both transport and processing, appear to be stabilizing in certain ranges. The energy reduction in the twentieth century was due primarily to the slight reduction in the very energy intensive metals coupled with the elimination of the more glaring inefficiencies in processing techniques. It is quite likely that we have already made the easiest substitutions and improvements and that energy reductions in the future will be increasingly more difficult to obtain. An up swing in the relative energy consumed in transport is noticeable in the more recent years and it is quite likely that processing has already or will start an upward swing equalling and perhaps exceeding that caused by demand with the continual pressure to replace labour and less sophisticated materials. To maintain a constant energy consumption level would require perpetual increases in either the substitution to lower intensity materials and methods of distribution or the improvements in the efficiencies of the existing methods and materials. The relevance of trying to keep energy consumption in building at its lowest point becomes apparent when considering the global situation. In terms of population, it is inevitable that a second world will grow on top of this one within 30 years\(^1\), it is time to rethink our values and design for a 'sufficiency society'. Figure 3.20 is dramatic enough spread over 400 years and involving a total population growth of 50 million, but one has only to think of a similar graph with a horizontal scale of only 30 years and a vertical based on a demand factor increase of almost 2,000 million.\(^2\)

---

\(^1\) A concise description of the population explosion is contained in the *Scientific American* (Vol. 231, Sept. 1974) which is devoted to that issue.

\(^2\) This figure represents only underdeveloped countries, many of which are currently using low energy roofing systems like thatch and will by trying to emerge into twentieth century in a very short period of time.
The specifiers of materials in both developed and underdeveloped nations must begin to appreciate the energy consequences of the materials which they select and a basic understanding of materials and energy is mandatory before any systematic approach to this problem can be attempted.
CHAPTER FOUR

PRODUCTION FROM PRIMARY SOURCES

The last Chapter demonstrated the marked increase in energy consumption in order to provide only one small element of the constructional system; no doubt other increases will have occurred throughout the entire building area. Are there any likely areas of potential energy savings, and if so where do they lie? This, and the remaining two chapters are largely devoted to this question.

The investigation uses as a framework the PUD sequence developed in Chapter One. This Chapter principally concerned with production using raw materials from natural or primary sources is divided into three major sections, while the next Chapter deals with production from secondary sources. The first section expands the production sequence and discusses in more detail energy usage in it, using the production of roofing materials and steel to illustrate various trends and graphic methods of analysis. Its objective is to familiarize one with the stages in the production sequence and to give a historical perspective to it. The second section attempts to forecast changes in energy consumption due to technical reasons which are likely to occur in each of the four major sub-divisions of production (material extraction, manufacture and fabrication, and component assembly). The third and last section is concerned with mainly non-technical constraints affecting those areas of production where potential energy savings are technically most likely to occur.
The PUD sequence has been broken down into 'form' related steps or activities in Fig. 4.1 each of which will be discussed.

The first major division in production and deproduction is the general division between material processing and component assembly. The distinction between the two is critical, the first involves basic materials or matter such as metal, wood and plastics, the second concerns an object or thing such as a nail, window, door or wall irrespective of the material that the component is made of. The distinction between material and component defines the terms recycle which applies to materials and the re-use of components both of which are discussed in the next chapter.

![Production/Deproduction 'form' related activities](image)

Material processing can be broken down into three major areas; 1) extraction of raw materials, 2) the manufacturing of processed materials and 3) the fabrication of materials into units, elements or consumer products. These three areas can be further subdivided.
Extraction.- consists of two primary activities, those of winning and dressing\(^1\). Winning applies to the actual removing of material from its natural state, mining, lumbering and harvesting are all examples. Closely associated with winning is material dressing, ore benefication which can involve comminution (crushing and grinding) sizing by screen or classifier; concentrating, by electro-static, gravitational or floatation techniques; agglomerating, by compacting, briquetting, pelletizing or sintering; heat hardening; and auxiliary operations like de-watering, drying and washing. These are primarily performed by mechanical means, and with the exception of some sintering and heat hardening do not affect the chemical composition of the materials involved. Even though extraction is included in the production process it is primarily a negative operation involved in taking materials apart. Those products of winning and dressing which are to be further modified in the material manufacture stage shall be called dressed feed material.

Material Manufacturing.- is involved with chemical change normally accomplished by thermo/chemical reactions. It is this stage that a material must go through to be classified as a 'processed' material, a term commonly used in the previous chapters. Material manufacturing

\(^1\)Since terminology has largely developed around specific materials and not production activities, there is some difficulty arriving at terminology which is applicable to a variety of materials, but concerning the same basic production stage or activity. For example, crops are harvested, minerals and coal are mined or quarried, gas and oil are extracted and trees are felled even though they represent identical activities in the production sequence, that of removing raw natural resources. An attempt has been made to develop terminology which is descriptive but without strong connotations to one particular material. However, some terms have been taken from a particular material production vocabulary 'dress', for example, has been taken from the metal extraction industry.
Table 4.1  Fabrication activities: shaping, forming, finishing and treating.

<table>
<thead>
<tr>
<th>Table 4.1</th>
<th>Various methods of categorising components.</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Heimsath  (1973, p.9)</th>
<th>Martin (1971, p.78)</th>
<th>COMPONENTS</th>
<th>Foster (1973, p.30)</th>
<th>This study</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNITS or COMPONENTS</td>
<td>SECTIONAL MATERIAL</td>
<td>WIRE</td>
<td>SECTIONS</td>
<td>UNITS</td>
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<tr>
<td></td>
<td></td>
<td>BARS</td>
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<td>STEEL SECTIONS</td>
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<td>COMPONENT PARTS</td>
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<td>SCREWS</td>
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<td>NAILS</td>
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<td>NUTS &amp; BOLTS</td>
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<td>PIPE</td>
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<td>COMPONENT SUB-ASSEMBLIES</td>
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<td>TAPS</td>
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<td>STEEL STANCHION</td>
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<td>SUB-SYSTEMS or ASSEMBLIES</td>
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<td>DOOR &amp; FRAME</td>
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<td></td>
<td>WINDOWS</td>
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<td>COMPONENT ASSEMBLIES</td>
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<td>HEATING SYSTEM</td>
<td></td>
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<td></td>
<td>PREFAB 'WET' UNITS</td>
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<tr>
<td>SYSTEMS or ASSEMBLIES</td>
<td></td>
<td>FACILITY</td>
<td>END PRODUCT, FACILITY or BUILDING</td>
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<td>ASSEMBLIES</td>
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</table>

**Table 4.1**

Forming by casting or moulding chemically setting liquids or thermoplastic materials, with or without the application of pressure.

**CASTING**
- Continuous casting
- Investment casting
- Sand casting
- Die casting
- Shell casting
- Remnant mould casting

**MOULDING**
- Vacuum moulding
- Injection moulding
- Rational moulding
- Transfer moulding
- Slow moulding
- Extrusions

Chipless forming of hot or cold, pliable or rigid, solid materials through the application of force (squeezing, shearing, bending or stretching) or intense heat and including:

**HOT PROCESSES**
- Forging
- Calendering
- Laser cutting
- Torch cutting

**OR COLD PROCESSES**
- Extrusion
- Rolling
- Coating
- Swaging
- Spinning

**COLD PROCESSES**
- Forger moulding
- Vacuum moulding
- Bending
- Compressive moulding
- Laminating

Forming by chip cutting of rigid and usually cold solid materials and including:

**CONTINUOUS CHIP**
- Turning
- Boring
- Shaping
- Planing

**SMALL INTERRUPTED CHIP**
- Sawing
- Drilling
- Countersinking
- Countering

**FINISHING and treating methods.**

**FINISHING**
- Cleaning
- Blasting
- Deburring

**MATERIAL HEAT TREATING**
- Plating
- Polishing
- Burring

**MATERIAL COATING**
- Annealing
- Tempering
- Heat hardening
- Painting
- Galvanising
- Preserving

**METALWORKING**
- Grinding
- Broaching
- Honing
- Lapping

**Table 4.2**

<table>
<thead>
<tr>
<th>Heimsath  (1973, p.9)</th>
<th>Martin (1971, p.78)</th>
<th>COMPONENTS</th>
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</table>

**Table 4.2**

Various methods of categorising components.
can be divided into three loosely defined areas those of conversion, refining and blending. The first two, like extraction are largely subtractive in nature, removing, separating or breaking down material but at a much smaller scale, that of chemical elements and compounds. Blending is the first additive step in the production process and involves the mixture of elements, compounds or solutions. The alloying of metals is a good example of this activity.

Fabrication.- is the last stage in the material processing, and it is in this area that materials are transformed into components or objects. It is primarily concerned with shaping or forming, treating and finishing operations of which there are numerous types as outlined in Table 4.1. Fabrication can be divided into two steps. The first involves fabricating monolithic materials, the second is the fabrication of composite materials\(^1\). Shaping, finishing and treatment can take place

---

1The term composite material is a very broad term. In principle, composite can be constructed by either man or nature by combining two or more materials together. This can be accomplished at various scales. Below is a chart of composites arranged roughly in order of scale, the first group consists of micro constituents so small that for the purpose of this paper have been included in the blending stage of material manufacture and not fabrication. The composites considered under fabrication are those whose constituents can be easily seen by the naked eye and possess properties that are unattainable by the individual constituents acting separately. In addition composites are fabricated in such a way that separation would result in total destruction of the material. On a larger scale composites can be made but through the assembling of components which with care could be separated apart and and still retain their original form.

<table>
<thead>
<tr>
<th>Production activity</th>
<th>Method</th>
<th>Constituents</th>
<th>Man made examples</th>
<th>Natural examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blend</td>
<td>Alloy</td>
<td>Chemical elements and compounds</td>
<td>Bronze</td>
<td>Igneous rocks</td>
</tr>
<tr>
<td></td>
<td>Diffuse</td>
<td>Powdor</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Compact</td>
<td>Powder</td>
<td></td>
<td>Metamorphic rocks</td>
</tr>
<tr>
<td>Composite fabrication</td>
<td>Dipped</td>
<td>Matrix + powder(filler)</td>
<td>Chipboard</td>
<td>Conglomerate rock</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Matrix + flakes</td>
<td></td>
<td>Wood</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Matrix + particles</td>
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<td></td>
<td></td>
<td>Matrix + whiskers</td>
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<td></td>
<td></td>
<td>Matrix + fibres</td>
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<td></td>
<td></td>
<td>Matrix + rods</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Matrix + layers</td>
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<tr>
<td></td>
<td>Laminate</td>
<td>Matrix + sheets</td>
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<tr>
<td></td>
<td>Bond</td>
<td>Matrix + layers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assemble</td>
<td>Adhesives</td>
<td>Components</td>
<td>Brick wall</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fasteners</td>
<td></td>
<td>Dry wall construction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(nails, bolts etc)</td>
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</table>
and in both steps glass fibres, for example, are shaped in the first step and incorporated into matrix to produce glass reinforced plastics within the second which itself might be further shaped. The operations involved in fabrication are principally mechanical with some thermal. Exothermic chemical reactions are also possible in the manufacture of composites such as concrete.

Component Assembly

Component assembly is normally mechanical in nature and merely involves assembling components into progressively more complex ones and eventually into the end product. There are numerous methods of breaking down assembly operations as indicated in Table 4.2. However, for this study broad areas have been established, the assembly of compound units, elements and end products.

Deproduction and Use

In the deproduction phase component disassembly is naturally the reverse order of assembly, this is not true however of material deprocessing which duplicates only the extract portion of the processing operations; and unlike disassembly the sequence of events, win and dress, are in the same order as found in the production phase. This is due to the negative nature of extraction mentioned earlier. In addition the term win would only apply if the product was being considered for its material content or as a man made ore, if the product is considered a liability or

---

\(^{1}\)S. L. Blum (1970, p. 113) puts forward the use of this term in lieu of scrap or waste, "favouring the word ore and prefaced with the term 'man made' to help establish the concept of potential recycle. In this way changing the 'word picture' from no use or discarded [waste and scrap] to potential use."
waste this step would be more appropriately called demolition, destruction or disposal. Dressing would not be required in this disposal situation.

The use phase of the PUD sequence could be considered non-existent in relation to material usage, for the materials involved in repair, maintenance and alterations could be considered an extension of production or deproduction. Particularly in the case of a building where it is initially 'completed', but continually undergoing change throughout its existence.

**Historical Trends Within the Production Sequence**

It would be worthwhile to devote the next few pages to illustrate the various activities described by using the production of some of the common roofing materials dealt with in Chapter Two and Three for examples. Using roofing materials provides an opportunity to further examine the energy ramifications of historical changes in materials. Five roofing materials have been selected to be representative of development periods. Thatch has been chosen to represent common roofing practice in the seventeenth century, stone tiles for the late nineteenth century with slate and concrete tiles being typical of the early and mid twentieth century. A sandwich panel\(^1\) has also been included to represent

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\(^1\) The comparison of tile or slate with a sandwich panel is somewhat unfair, for the panel is to a degree self supporting and has superior thermal properties as well as providing an interior finish; even so the normal wood support structure for the conventional roofing materials would be quite low in energy terms, certainly nowhere near that of sandwich construction. Even if one were to only consider one steel facing to the panel perhaps in a corrugated fashion the energy requirement would still be well above the others.
what many believe to be the likely roofing technique of the future.

Increasing Complexity in the Production System.—Fig. 4.3 is a schematic production flow diagram for each roofing type with production activities indicated by a sharp pip. Obviously it is not necessary for a material to pass through each progressive step nor is it necessary that the steps be separated as illustrated by thatch where the distinction between application normally and assembly operation and fabrication (shaping) are ill-defined. The sequence of steps generally follows the one outlined but can vary, as in the case of applying a surface coating which, in essence creates a composite material but frequently occurs during or after final assembly. The first three materials are unprocessed and skip the material manufacturing section entirely. There is a direct correlation between the progression of time and the increase in activities, the earlier and more primitive forms requiring progressively less activities with the more advanced more modern materials requiring progressively more steps.

1 There are numerous combinations of materials of which a sandwich panel can be constructed. The one selected for this study could be considered typical, consisting of a 75 mm foam PVC core faced with a 0.5 mm steel sheet. To simplify the study adhesive materials between skin and core and steel surface coatings have been excluded.

2 The activities required for concrete tiles and particularly the sandwich panel have been somewhat simplified and reduced in number. Fuel production and energy transmission has been left out entirely. With manufactured materials such as PVC and steel fuel requirements would in some cases match in weight the finished material being manufactured. Besides the elimination of surface treatment and adhesives, transport and organizational requirements for producing chlorine from raw materials has been left out and thus simplifying the manufacture of PVC used in the sandwich panel.
There appears to be a series of production thresholds - the introduction of each common form of roofing introduced a major new operation to the production sequences, a situation is clearly indicated in Fig. 4.2. Even though this threshold matrix is developed around roofing materials it would generally apply to other construction materials.

Fig. 4.4 outlines the organizational structure likely to be required to provide each type of roofing. The increase in institutional complexity is immediately apparent and corresponds with the additional production activities. It would be interesting to speculate as to the relationship between energy intensity and organizational complexity. Could an organizational structure as complex as the one shown for the sandwich panel exist in a low energy society? This proliferation of organizations will be mentioned again later in this chapter, as well as the next, as a constraint in reducing production energy consumption.

Energy Trends in Transport. - Between each event in the production and deproduction sequence there is an opportunity for a change in time and or place utility. Using symbols to represent various steps we can reconstruct a schematic diagram 4.3 on a graphic scale to reflect movements which reasonably be expected in increasing place utility for the same roofing methods. The results in energy terms are quite interesting and worth discussion. Like the transport analysis in Chapter Three, three basic items were considered, distance travelled, the weight/distance factor and mode energy intensity; the product of the latter two producing

---

1 The assumptions and calculations made for these three factors plus those from material processing are presented in note and tabular form. The data concerning transport can be found in accompanying Figs. 4.5 and 4.7. Data concerning processing can be found accompanying Figs. 4.11 to 4.13. The assumptions made were selected to co-incide as much as possible with those used in chapter three, however they are not averages and represent
Fig. 4.5
Flow diagram showing production transport mileage for five roofing types.

Legend:
- Horse cart/human
- Canal barge
- Train, steam
- Train, diesel
- Ship, super tanker
- Ship, ore carrier
- Total, Scale A
- Total, Scale B

EXCAVATE MATERIAL MANUFACTURE FABRICATION ASSEMBLY

Fig. 4.6
Flow diagram showing production transport weight - distance for five roofing types.
Concerning transport requirements for a m² (horizontal area) of five different roofing materials.

<table>
<thead>
<tr>
<th>Material or Component</th>
<th>Journey</th>
<th>Mode</th>
<th>Distance Traveled per M² (assumed)</th>
<th>Weight of Roofing Material (from App. B) kg/m² per 10⁻³</th>
<th>Weight/Dist. Factor</th>
<th>Sub-Total</th>
<th>Sub-Total Weight (kg/m²)</th>
<th>Sub-Total Weight (kg/m²) per 10⁻³</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TILES (1900)</strong></td>
<td>Quarry</td>
<td>Horse/horse</td>
<td>2.0</td>
<td>0.0907</td>
<td>0.666</td>
<td>2.5</td>
<td>0.4</td>
<td>E</td>
</tr>
<tr>
<td></td>
<td>Canal</td>
<td>Horse/horse</td>
<td>50.0</td>
<td>0.0907</td>
<td>0.509</td>
<td>0.2</td>
<td>0.17</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td>Quarry</td>
<td>Horse/horse</td>
<td>4.0</td>
<td>0.0907</td>
<td>0.233</td>
<td>2.8</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>Horse/horse</td>
<td>112.0</td>
<td>0.515</td>
<td>1.37</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TILES (1990)</strong></td>
<td>Quarry</td>
<td>Horse/horse</td>
<td>5.0</td>
<td>0.0462</td>
<td>0.231</td>
<td>1.0</td>
<td>0.231</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td>Main R. R. Line</td>
<td>Horse/horse</td>
<td>95.0</td>
<td>0.0462</td>
<td>4.39</td>
<td>1.2</td>
<td>0.466</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Goods station</td>
<td>Horse/horse</td>
<td>12.0</td>
<td>0.0462</td>
<td>0.556</td>
<td>1.2</td>
<td>0.660</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>Horse/horse</td>
<td>122.0</td>
<td>5.175</td>
<td>5.266</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CONCRETE TILES (1950)</strong></td>
<td>Reservoir</td>
<td>Tile fabrica¬</td>
<td>10.0</td>
<td>0.00612</td>
<td>0.0612</td>
<td>0.09</td>
<td>0.0037</td>
<td>E</td>
</tr>
<tr>
<td></td>
<td>Quarry</td>
<td>Cemnt plant</td>
<td>50.0</td>
<td>0.01335</td>
<td>0.1335</td>
<td>0.8</td>
<td>0.066</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Clay &amp; Limestone</td>
<td>Cemnt plant</td>
<td>10.0</td>
<td>0.01335</td>
<td>0.1335</td>
<td>0.8</td>
<td>0.066</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>Cemnt plant</td>
<td>60.0</td>
<td>1.0</td>
<td>0.765</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cement</strong></td>
<td>Cemnt plant</td>
<td>Tile fabrica¬</td>
<td>60.0</td>
<td>0.00852</td>
<td>0.044</td>
<td>0.8</td>
<td>0.396</td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>Tile fabrica¬</td>
<td>66.0</td>
<td>2.902</td>
<td>1.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Iron ore (imported)</strong></td>
<td>Mine</td>
<td>Ship</td>
<td>100.0</td>
<td>0.01727</td>
<td>1.727</td>
<td>0.014</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sea voyage</td>
<td>On carrier</td>
<td>4.42</td>
<td>0.01727</td>
<td>0.112</td>
<td>0.0035</td>
<td>G</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Exhausted (assumed)</td>
<td>On carrier</td>
<td>50.0</td>
<td>0.00066</td>
<td>0.063</td>
<td>0.08</td>
<td>0.093</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Blast fuel petroleum extraction</td>
<td>Short pipeline</td>
<td>15,500</td>
<td>0.0084</td>
<td>126.17</td>
<td>0.0165</td>
<td>1.69</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sub-total</td>
<td></td>
<td>22,090</td>
<td>239.25</td>
<td>6.914</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Steel</strong></td>
<td>Steel complex</td>
<td>Panel fabrica¬</td>
<td>75.0</td>
<td>0.00554</td>
<td>0.468</td>
<td>0.84</td>
<td>0.514</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td>Petrochemical complex</td>
<td>Panel fabrica¬</td>
<td>100.0</td>
<td>0.00554</td>
<td>0.594</td>
<td>0.8</td>
<td>0.475</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>Panel fabrica¬</td>
<td>22,560</td>
<td>229.49</td>
<td>7.09</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Bare concrete</strong></td>
<td>Panel fabrica¬</td>
<td>Mobile home assembly plant</td>
<td>50.0</td>
<td>0.01458</td>
<td>0.729</td>
<td>0.8</td>
<td>0.583</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td>Mobile home assembly plant</td>
<td>Mobile home</td>
<td>50.0</td>
<td>0.01458</td>
<td>0.729</td>
<td>0.8</td>
<td>0.583</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>Mobile home</td>
<td>22,360</td>
<td>253.95</td>
<td>9.07</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1. (Campbell, 1977, Table V)
2. The weight of the raw materials used in the manufacture of cement was determined by multiplying the weight of the finished cement by 1.62. This factor was derived from 1965 U.S. cement production figures (Gosses, Ayers & D'Argo, 1972, p.44), in which 65x10⁶ tons of portland cement was manufactured from 102x10⁶ tons of mineral ingredients.
3. The finished panel being considered is based on the following assumptions:
4. A roof angle of 25°, resulting in a requirement of 1.2m of panel for a 10m² of floor area (1 x 1m x 1m x 1m). A roof covering of special PCC (72 kg/m²), resulting in a core weight of 5.9 kg/m² (10 x 1.2m x 0.67m x 0.49m) x 72 kg/m² = 5.9 x 10⁻³ kg/m².
5. A beam in concrete was computed to be 1.27 (Open University, 1977, p.47) between petrochemical feedstock and PCC, resulting in 0.41 kg/m². Average, 0.5 x 10⁻³ kg/m².
6. Lime (1070 kg/m³) and steel (1770 kg/m³) assume 0.75 on both sides of the core, resulting in a steel weight of 0.5 kg/m². 4.6 kg/m² of lime/lime (0.7 kg/m³) and steel (0.8 kg/m²) are used per 10⁻³ kg/m².
7. The weight of iron ore (kg/m²) was multiplied by the weight of the finished steel taking into account the following non-fuel raw materials (see Chapter 1):
8. 1.4 lb of iron per tonne of iron ore, 0.7 kg of pig iron per 8.64 kg of pig iron, and 4.37 kg/m² of iron ore (4.37 kg iron/kg) of pig iron.
9. The resistance of recorded in PCC figures.
10. (Johnson, 1977, p.440)
11. (Beggs Report 1972, p.54) refers to imported iron ore to the U.S. being transported an average 4,500 miles by sea at 25 GJ/10⁶ tons (64.45 GJ/10⁶ tons),
Figs.
4.7
4.8
4.9
Fig. 4.7 Flow diagram showing production transport energy requirements for five roofing types.

- Horse cart/human
- Canal barge
- Lorry
- Pipeline
- Train; steam
- Train, diesel
- Ship; super tanker
- Totals

Fig. 4.8 Transport energy requirements divided into production categories for five types of roofing.

- Stone tile
- Slate
- Concrete tile
- Laminate panel
- Wood

Fig. 4.9 Percentage mix of transport energy requirements for five roofing types indicating the production stage at which materials or components are transported.
the transport energy requirement.

Fig. 4.5 shows material/component mileage or the distance covered to provide each particular type of roof. The increases are enormous, and particular attention should be given to the fact that two scales have to be used in order to illustrate the entire mileage network on the same graph; Scale B being one hundred times greater than Scale A. Thatch might have involved a total of 5 km whereas the sandwich panel of the future might well be in the 25,000 km range, or about 5,000 times greater. The increases in mileage fall in line with historical progression. Material/component distances can be very misleading however, the weight/distance factor can be more revealing. Fig. 4.6 illustrates this point, the difference in magnitude between thatch and the sandwich panel being roughly 1,000 times instead of 5,000 (0.25 tonne km vs 257 tonne km).

It is also interesting to note that slate could have well involved more tonne km than its replacement fifty years later, the concrete tile.

Of most interest to this study are the increases in energy consumption represented in Fig. 4.7 and 4.8, what is surprising is the difference between the extremes. The panel, even though having a high weight/distance factor, is only twelve times more energy intensive than thatch, amazing when compared to the great differentials in distance and

a hypothetical roofing situation which would likely have occurred for each material. The elimination of fuels reduces to some extent the transport requirements for roofing which involve processed materials, the most affected transport factor would be distance. Coking coal for example, often weighing as much as the finished steel produced from it, currently is imported from the U.S. adding over 6,000 km to overall mileage and could well involve more transport energy than that required for mid-east feedstock.
tonne mileage. This truly reflects the effect of a mode's energy intensity on overall energy requirements; in this case a supertanker vs. the pack horse. Fig. 4.10 compares the results of Figs. 4.5-4.7 and highlights the reduction in magnitude between mileage, tonne mileage and transport energy as well as indicating the 'ordering' of each material in relation to the three criteria.

Transport requirements have not only changed in magnitude over the years, but have changed with respect to the production stage at which either the material or components are moved. Fig. 4.9, a percentage mix graph, breaks down the overall transport energy requirements into four general categories; those related to extraction, material manufacturing, fabrication and assembly. Movements would not only pertain to those within a category for example movements between conversion and blending in the material manufacturing stage of production but would also apply to the transport required to move materials or components to the next basic operation, moving concrete tiles, for example, from the pre-cast plant (composite fabrication) to the site would be included under fabrication and not assembly. The historical fluctuations in the percentage mix have been quite extreme though after 400 years a complete cycle appears to have been made with the extremes in chronology and technology having surprisingly similar movement patterns even though there
are vast differences in their magnitude as indicated in Fig. 4.8.

In each of the extremes (thatch and the panel) the transport of natural raw or dressed materials constitutes the majority of the overall transport requirement. Stone, slate and concrete tiles having the same general format, have quite similar energy distributions as well, the transport of the fabricated unit predominating almost exclusively with stone and slate. Naturally, with the use of manufactured or processed materials, there is an additional transport category but with the concrete tile and panel example this does not constitute a major transport energy requirement.

Any shifts towards off site assembly (prefabrication) of elements or buildings will lead to additional assembly related transport\(^1\) requirements and this type of transport has been shown in the sandwich panel example. Any percentage increase in assembly related transport would most likely result in a corresponding decrease in fabrication related movements; because assembly operations\(^2\) would very likely be located near fabrication

\(^1\)An example of this type of assembly related transport would be the movement of roofing materials already incorporated into a roofing element or into the roof of a mobile building instead of the traditional technique of moving a fabricated unit such as a concrete tile to the site for application.

\(^2\)A comprehensive study produced by Cox and Goodman (1956) which concerned the marketing of housebuilding materials but involved in a typical suburban Philadelphia home and included material movement data (ton miles) from extraction to application. The study indicated that there was little back or cross hauling in material and component hauling, and that the general material flow travelled by the shortest possible route. It is likely the same situation occurs in the U.K. but the generalization should not be applied to a developing nation which could be abundant in iron ore, for example, but which could also be shipping it thousands of miles to developed nations to be processed and fabricated only to be sent back in the form of corrugated iron roofing.
Figs.
4.11
4.12
4.13
Fig. 4.11

Flow diagram showing production processing energy for five roofing types.

Fig. 4.12

Processing energy requirements divided into production categories for five roofing types.

Fig. 4.13

Percentage mix of processing energy requirements for five roofing types.
# Processing Energy Requirements

## Table: Processing Energy Requirements for a \( m^2 \) (horizontal) of five roofing types

<table>
<thead>
<tr>
<th>Material</th>
<th>Extract ( \text{kJ/m}^2 )</th>
<th>Mat'l. Manufacturing ( \text{kJ/m}^2 )</th>
<th>Fabrication ( \text{kJ/m}^2 )</th>
<th>Assembly ( \text{kJ/m}^2 )</th>
<th>Total ( \text{kJ/m}^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tonghi</strong> (1960)</td>
<td>0.5 (50%)</td>
<td>0.7 (70%)</td>
<td>0.0 (10%)</td>
<td>1.0 (100%)</td>
<td>1.2 (100%)</td>
</tr>
<tr>
<td><strong>Stone tile</strong></td>
<td>2.5 (50%)</td>
<td>1.1 (20%)</td>
<td>0.9 (22%)</td>
<td>4.3 (100%)</td>
<td>6.9 (100%)</td>
</tr>
<tr>
<td><strong>Slat</strong> (1990)</td>
<td>4.1 (65%)</td>
<td>1.5 (25%)</td>
<td>0.4 (10%)</td>
<td>6.0 (100%)</td>
<td>8.4 (100%)</td>
</tr>
<tr>
<td><strong>Concrete tile</strong> (1960)</td>
<td>2.6 (65%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Notes:
1. The total processing energy requirements for tonghi, stone tile and slat is estimated in Appendix B. These figures are only rough estimations, and would vary considerably with local conditions. The breakdown of totals into the major production areas is also subject to wide variations according to the type of stone, slate or tonghi used, and to refinement of the end-product. The percentage breakdown listed should not be considered as anything more than educated; this is especially true of the first two materials, where the distinction between production activities is ill-defined.

2. Assembly or application energy costs for concrete tile was assumed to be \( 0.1 \text{ kWh/m}^2 \) or a quarter of those assumed for slate. Air curing of the tiles was also assumed. The energy costs for extracting raw materials for cement manufacture were based on the following: 13.25 kJ/m\(^2\) of raw materials (as per Appendix and Calculations, Notes and Sources for Figs. 4.3 to 4.14). 7.62 kWh/m\(^2\) for winning and dressing (Bravard, Florida & Portage 1972) \( 0.31 \text{ kWh/m}^2 \). Energy costs for the crushing and grinding of cement clinker (cement fabrication) was based on the crushing and grinding of 8.24 kg (App. B) of clinker \( 0.07 \text{ kWh/m}^2 \) (Bravard, Florida & Portage 1972, p. 59), and resulting in a cement fabrication energy cost of \( 0.63 \text{ kWh/m}^2 \) covered by concrete tile. Cement manufacturing energy costs (kWh) would therefore be \( 19 \text{ kWh/m}^2 \) (App. B) \( 0.65 \text{ kWh/m}^2 \) or \( 10.66 \text{ kWh/m}^2 \).

3. For a description of the sandwich panel being considered, including constituent material weights and assumptions, see Calculations, Notes and Sources for Figs. 4.3 to 4.14.

4. The energy costs of providing the finished steel sheets was based on Bravard, Florida & Portage's (1972, Table 4) calculations for the U.S. steel industry, and using a conversion factor of 1,516 kg of raw steel per kg of finished steel. A 29% reduction was also assumed for the manufacture of iron and steel and the fabrication of steel due to improved plant and processing techniques.

### Formulas:
- **Extract:**
  - limestone, mix & dress: \( 0.08 \text{ kg/m}^2 \)
  - iron ore, mine: \( 0.06 \text{ kg/m}^2 \)
  - iron ore, beneficiation: \( 0.12 \text{ kg/m}^2 \)
  - iron ore, total: \( 0.20 \text{ kg/m}^2 \)

- **Total:**
  - Extract: \( 0.18 \text{ kg/m}^2 \)

### Material Manufacturing:
- Iron: \( 1.37 \text{ kg/m}^2 \)
- Steel: \( 1.57 \text{ kg/m}^2 \)

### Fabrication:
- Total: \( 0.75 \text{ kg/m}^2 \)

### Production Total:
- \( 2.49 \text{ kg/m}^2 \)

### Notes:
1. The energy costs of PVU were based on Smith's (1969, Table II) figure of \( 16,620 \text{ kcal/kg} \) (19.32 kWh/kg). Energy costs for extraction, i.e., drilling and crude distillation, and fabrication i.e., foaming and moulding, were each assumed at 3% of the overall PVU figure. In addition Smith's figure was reduced by 20% to allow for improvements in processing efficiencies. The energy cost breakdown for PVU would be as follows:
   - \( 5.94 \text{ kWh/m}^2 \)
   - \( 1.92 \text{ kWh/m}^2 \)
   - \( 9.84 \text{ kWh/m}^2 \)

2. Alteration of the composite sandwich panel was assumed to be \( 1.5 \text{ kWh/m}^2 \), while panel assembly was assumed to be \( 0.5 \text{ kWh/m}^2 \), or half that allowed for concrete tiles.
plants, however this gets into the subject of economic geography.

Energy Trends in Processing.- The energy involved in 'form utility' can be analysed using the same graphical techniques as those used for transport. Fig. 4.11 is a schematic flow diagram scaled to show how much and where processing energy expenditures occur. This is again shown in a bar graph in Fig. 4.12. The shifts in where the energy is actually expended in the production process, most clearly represented in percentage mix graph Fig. 4.13. The energy expended on the assembly or application as a proportion of the total of production energy costs has steadily decreased over the years with more and more credence being given to the idea of minimized site work and skills. The earliest example, that of thatch, would maximize both these factors, while the sandwich panel would represent the other extreme with the entire elimination of site work. The remaining materials falling between the two extremes in chronological order. The decrease in site work appears to have brought a corresponding increase in the percent of energy use in extraction efforts of the unprocessed materials. With the introduction of processed materials the percentage mix dramatically changed being completely dominated by energy expenditures involved with material manufacturing.

There seems to be a correlation between the obsession to reduce site labour and skills and the introduction of processed materials. If this is so the consequences in energy terms, could be disastrous - an effort to minimize site labour, (almost negligible in energy terms) leading to the choice of increasingly sophisticated processed materials often with enormous material manufacturing energy costs. This phenomenon is easily discernable in Fig. 4.12 where the energy costs of the earlier unprocessed roofing materials are dwarfed by the sandwich panel and to a considerable
Figs.
4.14
4.15
4.16
The Use of 'Profiles'.— Another way that the production system can be analysed graphically would be through the development of a material, or product 'profiles', based on the production activities outlined in Fig. 4.1. These profiles are easily constructed (though the data on which they are based is elusive indeed) basically being a series of vertical bar graphs with each bar representing a production activity. The length of the bar representing the amount of energy used. A cumulative profile can also be constructed in which the bars are added sequentially to each other.

A series of energy profiles for the roofing materials already discussed are represented in Figs. 4.14-4.16. Attention should be paid to the fact that the panel profile utilizes a vertical scale ten times greater than the others. Fig. 4.14 represents transport energy costs and Fig. 4.15 processing energy. The accumulation profiles express the overall amounts and increases of energy used and already discussed in relation to Figs. 4.8 and 4.12. Relationships between processing and transport energy costs are similar to those already discussed in Chapter Three; that is form related energy demands far exceeding those associated with transport; with the unusual exception of slate (an unprocessed material which was transported long distances by an energy intensive mode). Transport and processing energies have been combined in Fig. 4.16, indicating even better the relationships between the two.

The shift trends concerning both amounts and areas of energy utilization are revealed by the shape of the cumulative profiles, the earlier unprocessed materials assume a rather uniform low slope; while the
NOTES:

See Fig. 4.12 CALCULATIONS (column 4, structural steel) and NOTES.

Extractive solid by-products are the same as those used in Fig. 1.1 and exclude those associated with limestone and fuel extraction. By-product generation for iron/steel making and steel fabrication includes 'new' scrap and is based on Landsberg's (1964, Fig. 21) flow diagram of ferrous metals through the U.S. economy in 1960. The amounts of new and obsolete scrap recycled are from the same source.

See Figs. 4.11-13, NOTES (No.4, col. 4). Assume assembly energy 0.01 kWh/kg.
more recent processed materials have a very pronounced rectilinear form; with a very steep initial angle followed by a very gradual slope \(^1\) (resulting from the early stages in production involving great quantities of energy). The shape of the profiles has a great deal to do with the potential savings possible through recycling materials and the re-use of components, a subject which will be discussed in the next chapter.

The idea of profiles is by no means restricted to energy intensities. Fig. 4.17 contains profiles pertaining to steel production and includes not only an energy intensity profile but also one for by-products \(^2\) and price (all of which are based on a unit of mass). Every material or product has a unique profile of its own for each of these three criteria and an effort to establish information contained in this type of graph of the more commonly used construction materials would be well worth

\(^1\)It is this very difference in energy profiles which has developed over the years which provides one of the strongest, but yet unheard argument for conserving period and vernacular buildings. Not only did the early buildings possess a low energy profile, the profile itself consisted primarily of energy produced by man and not fossil fuels as the case is today. These early profiles just cannot be reproduced today where economics have brought about a vast disparity between power produced by fuels and that produced by man.

\(^2\)The by-product represented in Fig. 4.17 is for solids only and thus the magnitude is much lower, than for the iron production by-products represented in Chapter One. Steel and iron scrap generated in the production process are also included as by-products even though the majority is re-utilized or recycled within the production system.
additional research but is well beyond the scope of this thesis\(^1\).

Without this additional information some generalization will be made using steel as an example. These will undoubtedly not apply to all materials nor in the same degree, nevertheless the trends broadly speaking would apply to most manufactured materials used today. When comparing price, by-products and energy, one thing emerges which is both relevant and ominous from an environmental point of view. The profile for price differs significantly than that of either energy or by-products which have a strong resemblance.

Price has a concave accumulative profile indicating that the greatest price increases occur in the latter portion of the production sequence. In other words a fabrication and final assembly and consumed sales are very price sensitive; on the other hand the by-products and energy profiles are reversed with most energy expenditures and by-product generation occuring at the beginning of the production sequence, this is especially so of by-products. This would suggest that pricing would not be so very sensitive to energy cost and even less to by-product formation. In

\(^1\)Profile analysis is not restricted to energy, by-products or pricing. Profiles for other items such as man-hours could be equally revealing. Profiles of common building materials should be a great assistance in selecting those with low environmental demands for profiles facilitate comparison, especially when they utilize common scales. Being graphic in nature profiles should appeal to the designer who is visually orientated and who is often responsible for specifying products. A fairer comparison is also likely through the use of profiles since, at a glance, one knows what production activities have been included, a situation not likely to occur with the use of a single figure.
conventional practice designers are very cost conscious and an increase in application cost (site work) of a material could easily override any environmental or energy considerations. This is strongly suggested in the roofing example Fig. 4.2 with large increases occurring in processing energy to primarily simplify application and site skills. The pricing mechanism and its affect on energy consumption will be discussed in more detail in the last section of this chapter.

If the situation outlined above is correct we can see that energy consumption will steadily increase, the consequences of which have already been suggested in Chapter Three. So how and where are energy savings possible, what can be done?
In this section a review will be made of production operations in an attempt to forecast the likelihood of increases or decreases in energy consumption due to technological changes. Coverage of production energy conservation will be kept fairly brief in this study. This subject is covered in far more detail in the rush of recent energy conservation reports, some of which are listed below; brought out largely in response to recent world events that affected both the cost and availability of fossil fuels.

<table>
<thead>
<tr>
<th>Organization</th>
<th>Title</th>
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<tr>
<td>National Economic Development Office (NEDO, 1974b)</td>
<td>Energy Conservation in the United Kingdom</td>
</tr>
<tr>
<td>NATO Science Committee Report (Kovach 1973)</td>
<td>The Technology of Efficient Energy Utilization</td>
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The energy forecast will be based on the four major production areas: extraction, material manufacturing, fabrication and assembly; but before going into these specific areas, mention will be made of potential transport and industrial 'housekeeping' energy savings which could be realized anywhere in the production sequence.

Possible Transport and 'Housekeeping' Energy Savings

Direct transport energy savings can occur in three broad areas (outlined in Table F-1) those related directly to the vehicle, those related to the operation of the vehicle, and those related to the route over which the vehicle passes.¹

Vehicle related energy savings can be accomplished by reducing dead weight, (bigger lorries with lighter bodies); the use of more efficient energy convertors (increased use of diesel, electrical or hybrid propulsion systems and regenerative breaking systems); and reduction of mechanical or fluid dynamic resistances (improved aerodynamics, the use of radial tyres and fan cut-out devices, etc.)

¹There is some question as to the effect of pollution control measures on transport energy consumption. The NEDO report (1974b, p. 95) states:
the reduction of emissions from the petrol engine is likely to involve an energy loss that may be as high as 10% of the total energy in petrol... and lead removal from the petrol would involve extra energy costs in the region of a few percent of the total.

These findings are debateable; since the use of stratified charge and diesel internal combustion engines; the Stirling external combustion engines and electrical or hybrid propulsion systems all of which have been suggested as means of reducing pollution are also more efficient thermodynamically which results in energy savings. In fact any device which reduces fuel consumption would have the effect of reducing pollution, since in a conventional engine most of the pollutants generated are directly related to the amount of fuel consumed. Likewise a shift in mode from say automobile to bus, could reduce pollution and energy consumption at the same time.
In the future we can expect some energy savings in all these areas particularly with respect to the most common haulage made - the lorry. However, there are limits. Lorries cannot get a great deal larger, and the change to diesel has to a large degree, already taken place. Radial tyres, improved aerodynamics, fan cut-outs, and improved gearing provide the best opportunities to reduce vehicle related energy consumption.

Operationally related transport savings are also possible, lowering speeds is probably the most easily implemented and effective in this category. However, there is not much hope for any drastic speed reduction in the future. Rationalized loads (increased load factors) and reductions in haulage distances are operational considerations which have great potential, but energy savings are in reality not likely to arise from these areas, in fact distances could well increase in the future as discussed in the last section and later in this section. Minor route related energy savings for lorries could be expected in the future with improved road, especially those which eliminate urban traffic congestion, however, the savings resulting from less stopping and starting could be offset by the increased speeds likely to be experienced on the new roads. Indirect energy costs related to transport\(^1\) (the energy involved producing vehicles, fuel and routes, and vehicle support systems) are, if anything likely to increase in the future.

\(^1\)Indirect transport energy costs are higher than one would expect. Eric Hirst (1972, p. 36) calculated these indirect energies for the U.S. automobile in 1960, 1968 and 1970 and found that only 51% of the energy cost was direct (those of gasoline consumption) 11% was devoted to petroleum refining, 7% to automobile manufacturing, 7% for automobile retails and sales, 25% to the 'repair' maintenance, insurance, replacement parts, accessories, parking, tolls, taxes, etc.
Direct and indirect energy savings related to transport systems do not seem to offer any significant energy savings. A more commonly suggested method of reducing haulage energy costs involves modal switching, for example transferring lorry and auto traffic to rail or barge, unfortunately there is general agreement that these substitutions are either unlikely or will be on a very limited scale. Even the increase in fuel costs have apparently little effect, one mode switching the NEDO Report on the impact of increased energy costs (1974a. p. 20) states that

the difference between the impact of fuel costs on separate modes is not, it would appear, great enough to outweigh the importance of other factors, so that rising fuel prices will, in themselves, have little effect on modal split.

In fact the current modal trends discussed in Appendix P-H, indicate that the lower intensity modes like rail, are giving way to the higher intensity modes like road and air, the reverse of the recommendations. Without modal switches no dramatic savings could be expected in the transport field.

Even if transport energy requirements could be reduced by any of the techniques discussed, the overall effect would be minor in relation to overall energy involved in production especially in processed material, though the savings would have a much more dramatic effect on unprocessed materials commonly used in construction like those of lumber and gravel.

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1 Most of the energy conservation reports listed earlier, devote some attention to measures which would reduce current transport energy costs, with emphasis being placed on transport of people and not freight. In addition to the general conservation reports, specific articles have been written on the energy costs of transport and include: Anthony Sebald's (1974) report called Energy Intensity of Barge and Rail Hauling, Anthony Curtis' (1974) series on "Design for an Economy Car", Mortimer's (1974) report "The Energy Costs of Road and Rail Transport UK 1968", and John Pierce (1975) article "Fuel Consumption of Automobiles".
Recently there has been a great deal of press coverage on industrial fuel savings which can result from simply tuning up plant equipment, diligent management practices in plant operation, careful use of lighting and air conditioning and other efficiency measures which can be adapted at little or no cost and fall into the general category of housekeeping. Most organizations could and are saving a great deal of energy without revolutionary technological change through the application of such simple but unglamorous housekeeping techniques. Lockheed Aircraft Corporation, for example, saved one million dollars on its power bill last year by such simple measures as setting the air conditioning thermostat at 24°C instead of 22°C, and the first step to conserve energy at one large manufacturing plant in the south eastern United States was merely to replace several hundred broken windows through which heated or refrigerated air had been leaking for years; General Motors cut the utility bill for one large plant by similar rational frugality. The effect of such housekeeping energy saving techniques on a particular material's energy intensity is impossible to calculate, but this method of reducing energy costs should certainly be the first to be used in any attempt to conserve production energy.

Extraction

In the long run extraction is an area where there is little hope of energy savings in the future, in fact increases are quite likely to occur in relation to a number of materials. A discussion of extraction energy costs will be divided into two parts, the first concerning minerals and the second non-minerals. Common to both areas is the trend towards larger machinery. Increasing the size of machinery could lead to some reduction in extraction energy costs, though 'economy of scale' if one is committed
Variations in energy cost of copper in relation to grade of ore. (Chapman, 1973a, fig. 2)

Relation between mining energy and mining production. (Lovering, 1973, p. 122)
to mechanization. However, there are limits to how big the machines can get and often their use is restricted to very remote areas which require additional transport costs. In any case the savings would be easily offset in mineral extraction by reduced grades of ore which themselves demand larger machines.

Mineral Extraction

The energy costs of the extraction of minerals will almost inevitably increase. This is due to the fact that the most accessible and highest grade ores which have been in effect dressed by natural forces, are first to be worked and with increased demand low grade ores will have to be sought. The extraction and dressing energy costs will increase inversely with the grade of ore, the lower the grade, the higher the energy demand per unit of extraction. Chapman (1973, Fig. 2) clearly shows (Fig. 4.18) this exponential trend with copper and the principle would generally apply to other materials as well.

There are two reasons for this inverse relationship between energy and grade. The first concerns the ore tenor (percentage of desirable minerals contained in the ore). As the tenor decreases, the sheer amount of ore required to be mined would naturally increase. For example, to produce the same end results using an ore with a grade of 20% would require three times as much ore as that required from a 60% ore. The former would require three times the extractive effort, in winning, dressing and transport within the mine.

The second reason for extraction energy increases is due to increases in comminution (crushing and grinding) energy. In addition to the amount
of ore requiring processing, lower grade ore also results in additional processing. As the grade of ore decreases, the dispersal of the mineral being sought within the ore increases. This results in more ore crushing and grinding in order to remove the mineral from the gangue. The energy required by increased comminution is directly related to Rittinger's Law of crushing, in which the energy consumed in crushing or grinding is proportional to the amount of new surface produced by the operation. In other words, more new surface is produced, thus more energy required, in crushing a tonne of 10 mm particles down to 5 mm particles than by crushing a tonne of similar material from 300 mm down to 150 mm particles. This general rule follows from simple geometry and we can see at once that fine grinding would require more energy than course crushing; and fine grinding is also intrinsically more expensive in equipment energy costs than course crushing. Another factor in comminution is the hardness or toughness of the ore being worked, if future sources of ore are to be found in harder rocks like quartz or trap, energy costs will surely increase.

Besides the likelihood of more ore having to be mined and requiring more comminution, there is also the chance in the future of increases in overburden removal requiring additional energy expenditures. This is especially true when one considers increasing labour costs which have encouraged the recent trend towards vast open pit mines where it is possible to employ mechanization programmes on a scale not possible underground. Fig. 4.19 shows the results of mechanization in U.S. mining and indicating vast increases in energy consumption (being related to horse power) but without corresponding increases in overall production quantities. Labour productivity in the mining industry no doubt increased significantly, but only with the corresponding decrease in energy productivity, a subject to be discussed again in respect to timber extraction.
and the general area of assembly.

In the shorter term some energy savings can be expected in the U.K. but the substitution of high grade imported ore, for lower grade domestic ore. The best example of this happening is in the steel industry, who are currently phasing out low grade domestic ores with an average metallic content of 28% with imported foreign ores averaging 62% metallic content. The fraction of imported ore has increased from about half in 1960 to about two thirds in 1972. Laws (1974) estimated that a plant utilizing all home grade ores in the 1960's would require 2.8 kWh/kg (10MJ) of crude steel more energy than one using all foreign ore\(^1\). The NEDO report (1974b, p. 55) estimates that the energy costs of overseas transport of foreign iron ore would be about 0.3 kWh/kg of pig iron; the energy cost for sintering and and benification of domestic ores being far in excess of those required for transport.

Returning to the long term energy savings in the extractive area one must consider the possibility of untapped marine mineral deposits. The sea itself contains about \(1.3 \times 10^9 \text{ km}^3\) of sea water, an amount so large that quantities of dissolved substances are large but the concentrations are so low that extraction is quite energy intensive. Perhaps the energy

\(^1\)This issue of importing low energy raw materials is an interesting one in relation to Great Britain, especially in respect to the balance of payments problem. In the case of iron the question arises as to whether it is better to save energy by importing high grade ores, or to use domestic low grade ores requiring higher energy costs. Unfortunately in the current situation the choice is not clear because the fuel powering British industry comes from both domestic and imported sources. The same question of whether to import low energy materials or use higher energy domestic materials arises in relation to other materials as well. The notable example in the construction field involves the option of selecting either imported timber a low energy material or brick a higher intensity material but using domestic resources, a subject investigated by Banks (1975).
requirements could be lessened if solar distillation was used, the clear water being used for domestic purposes and the brine being used as a low grade mineral ore. With current technology, however, minerals extracted from sea water are more energy intensive than those obtained from the land. Energy savings might be realized by the development of sea bed deposits particularly nodules which contain nickel, cobalt and copper. But the energy intensity of extracting from the sea bed is an unknown quantity at the moment.

Leaching techniques, especially those involved with aluminium and copper ores, could hold some potential for energy savings. But again at this point in time their use is in most cases more energy intensive than the thermo chemical techniques currently used. Their primary advantage is making available new types of ores or lower grades of ores which could have more effect on reducing transport energy by making possible the exploitation of mineral deposits that are much closer to markets and material manufacturing plants. Unfortunately, as it has been pointed out previously the transport energies are usually relatively small compared with those of extraction and material manufacture, especially when sea transport is used.

Non-Mineral Extraction

As with minerals the extraction of non-minerals is also likely to become more energy intensive. Stone, for example, is being quarried progressively further away from the demand areas because of environmental pressures¹ and it is often crushed to produce a substitute for gravel

¹Ironically environmental pressures could in some cases lead to a reduction in transport energy. In the U.K. for example, marine dredging of sand and gravel is becoming more popular (Institute of Geological Science, 1973, p. 6). Being a marine operation, transport by barge is
which nature itself has accomplished the extraction process, and before the introduction of concrete, stone was used as a large masonry unit which had the effect of reducing the overall amount of cutting required (Rittinger's Law) as well as reducing the energy intensive cement to bind the stones together.

The most common of the unprocessed materials used today in construction is timber. As in stone production the winning and dressing of forest products is becoming more energy intensive; the Swedish Timber Council's report *Forest, Saw and Handling* (1973) boasts of the following 'progress' currently being made in forestry techniques:

> Until recently the trees were felled by hand using axe and saw. The power saw, which replaced these tools is itself already on the way to being old fashioned...recent years have seen the development of special machines for tree felling... the feller/buncher both cuts the tree and lifts it away and the lumber/bucker machine picks up the whole tree and trims it of branches. The logs are cut and sorted by the machine and placed on the ground in piles. The machine can handle two trees per minute and is operated by two men (p. 2 and 3)...

One can well imagine the energy consequences of this type of mechanical progress and progress has not been limited to form related activities, transport is becoming more energy intensive as well:

> The trees or logs used to be dragged by horse to the edge of a river and floated down to the saw mills. Today 60% of all logs for the saw mills or pulp mill travel by road in lorries, usually required thus utilizing the low energy intensity of water transport. A shift to marine haulage is quite unique in today's transport situation. In America underground mining of rock is becoming more common (Department of Interior, Bureau of Mines, 1970, p. 1223) because of the reduction of environmental problems which in turn make it possible to be closer to demand. The cost of land and the use of the mine after extraction has been completed "in many cases the value of the sale or rental of the storage space of the mine exceeding the value of the stone removed from it;" are also other factors which encourage mining of rocks.
25% by rail and only 15% is floated\(^1\). (p. 3)

The energy consequences of this should be quite clear from the analysis made in Chapter Three. This timber example is probably typical of the current trends in rationalizing the extractive industries, increasing speed and productivity in form and place related activities through the use of massive fossil fuel subsidies, and this being coupled with the problem of lowering grades of natural resources.

**Material Manufacturing**

Because of the *thermo-chemical* nature of material manufacturing this portion of the production sequence (which only applies to processed materials) is usually the most significant in energy terms. Unlike extraction there are areas for energy savings, in some industries there could be substantial savings. In addition most material manufacturing is controlled by a few very large industrial groups\(^2\), who can devote time and money on energy conservation research and have the potential to carry it out in practice. An idea of the savings possible\(^3\) by available

\(^1\)The wisdom of this energy intensive switch from river to lorry appears somewhat counter-productive after reading further in the report (p. 6). Presumably speed was the main reason for the shift in mode because, "it is important for logs to reach the saw mill quickly", whereupon the logs are, of all things, "either put to lie in water or are stored on land, in which case they are sprinkled with water...to avoid insect or fungal damage..." (p. 6); undoubtedly, to be later dried out by the recently installed kilns instead of the old method of air drying.

\(^2\)Cottrell (1955, p. 207) believes that it is the very fact that large expenditures of energy are normally required in the material manufacturing industries that results in large companies or institutions, "we face the fact that wherever high energy convertors are to be used... large production units will be created."

\(^3\)Steven Berry and Margaret Fels (1973, p. 14) indicate theoretical energies even lower than those indicated by Rose; calculating for example steel at 0.6 kWh/kg, aluminium 5.08 kWh/kg with copper and zinc production actually giving off energy or requiring -0.468 kWh/kg to produce the former and -0.429 kWh/kg.
techniques and those theoretically possible are illustrated for some common materials in Fig. 4.20 which is taken from Sanford Rose's article (1974, p. 111) "The far-reaching consequences of high price oil". When or whether these theoretical values will ever be reached or even approached is an area for speculation only. The majority of conservation reports suggest energy savings in material manufacturing that fall into one of the seven methods listed below and already discussed in Appendix C.

1) Improvements in heat recovery.
2) Economy of scale and integrated plants.
3) The use of continuous processes.
4) Improvements in insulation of heat loss.
5) Improvements in the quality of feed materials.
6) New heating techniques and improvements in instrumentation to improve temperature control, combustion and the use of different types of fuels.
7) Changes in basic processes.

The following few paragraphs will discuss possible savings for some of the more common processed construction materials.

Iron and Steel. – Energy consumption in iron and steel production has steadily been reduced and improvements continue. The coke involved in
producing iron ore in the U.K. has fallen from 1,050 kg per ton of pig iron in 1952 to 930 kg in 1973 (NEDO, 1974b, p. 56), these savings were brought about by the following measures:

1) Improvements in blast furnace burdens including the use of imported ore with a higher iron content, better benification and improved coke.

2) The use of larger blast furnaces.

3) Injection of fuel oil (which would reduce the energy savings implied by the coke figures above) and the reducing gas together with oxygen enrichment of the blast and increased furnace pressures.

4) Improved re-factory linings enabling higher temperatures for longer periods.

5) The improvement of furnace controls to the use of computers and better instrumentation.

As for further energy savings NEDO report (1974b, p. 56) predicts that "taking into account new construction and other developments there could be a 20% reduction in specific energy used in the blast furnace in the next ten to twenty years."

There are alternatives to the blast furnace for the reduction of iron ore and if technically feasible they could by-pass some of the energy consuming steps in reduction. Direct hydrogen reduction of iron chloride produced by leaching the ore with hydrochloric acid followed by fractional crystallization could be employed to produce pure iron powder or melt. Direct conversion of this kind could lead to energy savings of perhaps 40% (Kovach, 1973, p. 8). However, the development of this is not likely before 1990 and is primarily being developed for use with nuclear power.

In steel making the replacement of the open hearth furnace with the
BOS (Basic Oxygen Steel Making) furnace will provide most of the energy savings using 0.183 kWh/kg of crude steel instead of the open hearth's 0.803 kWh/kg of crude steel. Unfortunately, the actual savings are not quite so attractive. When the open hearth which now produces about 63% of the U.K.'s crude steel is phased out, the BOS furnace will only take over a portion of the overall steel making capacity. Because of its limited capacity (30%) to handle scrap the electric arc furnace produces the remainder of steel, whose energy intensity is quite high, about 1.72 kWh/kg. This use of the electric arc furnace could largely offset the savings produced by the BOS furnace, the NEDO (1974b, p. 62) concludes "the direct energy savings in steel making are unlikely to be the largest achieved in the whole steel making process over the next decade."

Transport energy requirements for iron and steel production will probably increase with the centralization of plants and the import of foreign ores, the latter increased energy costs would be offset by the high grade of the imported ore which illuminates much of the energy required in the benification stage and normally associated with lower grade ores. Larger ore carriers with their inherently lower energy intensities might also offset these increased distances.

Aluminium.- The production of aluminium is extremely energy intensive, and major reductions in energy consumption are not that likely. Direct reduction of Bauxite or clays would result in some savings and "are likely to be developed commercially in the 1980-90 period...but it is doubtful that direct reduction processes would be used to produce more than one or two percent of the aluminium needed in the year 1990."

(U.S. Department of the Interior, 1970, p. 460). There appears little room for improving the current electrical efficiency involved in the
Hall-Héroult Electrolysis technique of reducing Alumina. Any savings in the process would most likely occur in increases in electrical generation efficiencies and the reduction of electrical distribution losses. There are several new reduction processes which are being developed to the pilot plant stage. These are the Aloca process, based on the electrolysis of aluminium chloride and the Toh chemical process. It has been claimed that the former would result in energy savings in the order of 30%, the latter theoretically could result in very large savings but in practice "it is not known how much energy will be saved by the process". (NEDO, 1974b, p. 66)

Ceramic Material.- Non-metallic mineral processing offers some potential for energy savings. Structural clay products represent the largest single demand for this category. Firing clay is such an elementary process that the likelihood of any process break throughs are extremely rare. Small economies can be brought about through the application of any of the first six steps of the conservation techniques previously mentioned. Item five, improvements in feed materials holds the most likely reduction in structural clay products, and would lead to a shift in the mix of the basic clays used, highly carbonaceous and stiff clays being favoured.

Most major economies have already been taken in the brick industry for example, the majority of bricks are already fired in continuous kilns and a great deal of consolidation has taken place since the war. Some 1

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1It has been estimated (Buckley, 1972, p. 64) "that there are about 170-190 firms operating 306 brick works at the present time, compared to some 900 works operating during the immediate post war period."
credit must be given for the London Brick Company's recent efforts to transport their product by rail, another exception in transport where a switch has been made to a lower intensity mode. However any energy savings could well be negated by the longer trips involved because of the increased concentration around Fletton clays and the closing down of small plants near the actual demand.

**Cement.** Another mineral product used in construction is cement. The manufacture of cement is very energy intensive in relation to value added with direct fuel costs representing between 20% and 35% of the delivered price (NEDO, 1974a, p. 22). This provides a real incentive for improving the energy utilization within the industry. The Cement and Concrete Association (1974, p. 7) claims:

> That energy consumption per tonne of cement decreased from 2 kWh/kg (7.2 GJ) in 1965 to 1.5 kWh/kg (5.4 GJ) in 1972... [which was brought about by the] adaption of more efficient methods in response to rising fuel prices, and economies of scale through the commissioning of larger and more efficient plant, and phasing out of smaller and less energy efficient production units.

Undoubtedly sophisticated control and instrumentation was a major contribution to the more efficient plant mentioned above along with the introduction of pre-heaters, which use the heat contained from the kiln waste gases to pre-heat feed material before it enters the kiln.

In the future savings in the manufacture of cement could be gained by eliminating any 'wet' processing plants and replacing them with

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1One English cement plant is using a mixture of municipal refuse and oil to fuel their kilns to reduce fuel costs (and eliminate a pollution problem). Manufacturing cements using feed materials from secondary sources can also reduce energy consumption but this option will be discussed in the next chapter.
plants using the 'dry' method of cement making which would result in a saving of 0.27 kWh/kg of cement. This switch from wet to dry is not likely to happen on energy grounds alone; the wet method is far less polluting and some feed materials can only be handled by this method. A more likely candidate for energy savings in the cement industry would be through the application of a fluidized bed in processing, which also would increase the flexibility and speed of the operation. It is hard to say what the effect of these innovations will be on the future energy intensities of cement; but a saving in the next decade will probably be less than those energy savings experienced in the last decade.

Glass.-- The manufacture of glass, an important building material, but not used in the same volume as the others, has quite likely reached the limits in energy efficiency improvement. Berg (1974, p. 266) mentions that "because glass furnaces are generally designed to have extremely long lives, as industrial equipment goes, careful economic justification is applied to their construction. The result is that large glass melting furnaces may already be the most efficient of the large type industrial furnaces...using heat recovery stages which are several times larger than the melting chamber of the furnace itself." With this situation existing today one should not expect many major savings in the glass industry.

Processed Organic Material.-- Mention should be made of organic based synthetic materials or plastics even though it is difficult to go into any detail on energy savings in this area because of the multitude of products. Plastics can range in energy intensity from 12.2 kWh/kg (44 GJ/tonne) for polythene to 45 kWh/kg (163 GJ/tonne) for polyester fibre (both figures excluding the thermal energy of the feed stuff)(NEDO, 1974b, p. 11). It is because of the numerous intermediate steps and the great latitude
for the molecule manipulation of organic substances which provide large scope for potential future energy savings in the plastics field.

The NEDO Report (1974b, p. 74) on energy conservation states that:

Estimates by Du Pont have suggested that 10%-15% of energy consumption in the chemical industry in the U.S.A. could have been saved by adopting measures that are economically viable. However, it is possible that the traditionally higher costs of energy in Europe have left less scope for such improvement.

This figure applies to the entire chemical industry and includes the manufacture of inorganic chemicals where savings are likely to occur, with the gradual substitution of thermal processes for electrolytic ones which are generally more energy intensive (producing aluminium by the Toth process is an example of this in the metal industry).

A development in the future which could have a dramatic effect on the amount of energy required in processing organic materials would be the widespread use of enzymes. Enzymes can break down organic compounds at much lower temperatures and pressures than those usually associated with the processing of organic materials. Consequently saving much thermal energy. Probably the first organic material to be affected by this kind of processing would be paper. Enzymes have been developed (from a form for dry rot) which can attack the lignin in wood, without affecting the cellulose fibres, thus reducing the mechanical, thermal and chemical operations now required to separate these two in the paper making process.

The Effect of Pollution Control on Energy Consumption and the Concept of Thermodynamic Availability

Before going on to possible energy savings and the fabrication sequence of production, some remarks will be made on two items which affect
energy consumption and are common to the majority of processing operations (as well as to other areas of production though not nearly to the same degree). The first item concerns pollution control which is often in conflict with energy conservation; the second involves the concept of thermo-dynamic 'availability' which usually involves utilizing the low grade heat, an area where substantial energy savings could be made.

Over the years controls over pollution have become more stringent particularly with respect to material manufacturing and the generation of electricity; this trend is likely to continue and will undoubtedly have to be paid for in terms of energy. The energy cost of pollution control is a subject in itself\(^1\), but to show the complexity of it, a three dimensional

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\(^1\)The articles which cover this general area of waste products from energy production are Perry and Berkson's (1971) article "must fossil fuels pollute?" and Singer's (1970) "Human energy production as a process in the biosphere". These articles do not mention any energy costs involved in preventing pollution.
matrix (Fig. 4.21) has been constructed. The three variables considered in the matrix concern 1) the source of the pollutant, 2) the form of the pollutant (gaseous, solid, liquid or thermal) and 3) the area affected by the pollutant.

The control of sulphur dioxide (a pollutant defined graphically in Fig. 4.21 as a heavily outlined box) provides an illustration of how energy requirements can vary, even when restricted to the control of a single pollutant. This gaseous pollutant is emitted by burning fossil fuels which contain sulphur, and is normally controlled by one of four methods, all involving different energy costs (the figures quoted are from a NEDO report, 1974b, p. 95).

The first technique for controlling sulphur dioxide involves an almost negligible energy loss and consists simply of using high chimney stacks which are "suitable for the dispersion of emissions". Even though being attractive in energy terms, it is doubtful how effective the system is in practice. There are strong indications (Singer, 1970, p. 186) that sulphur dioxide 'dispersed' in Britain settles in the Netherlands or Sweden as sulphuric acid or accumulates in a layer of sulphate particles in the stratosphere which could even effect global temperatures.

The second method involves stack gas electro-static precipitation cleaning which requires 0.2% of the total energy in the fuel.

The third technique involves the use of 'scrubbers' which require about 0.3% of the total energy; but has a major drawback as described in the 17th June 1974 issue of Newsweek (p. 49):  
most of the (U.S.) scrubbers on line today use pulverized limestone to remove the sulphur. A slurry of rock and water is sprayed into the dirty gas as it passes through the scrubber from the boiler; the limestone combines with sulfur dioxide to form a liquid that settles out as a sludge waste,
while the "scrubbed" gas continues up the stack. The amount of sludge formed is considerable. Scrubber proponents suggest that the waste can be used as landfill and in wallboard. But opponents claim that the waste might create a land and water-pollution problem as severe as the air pollution it is designed to end. According to American Electrical Power advertisements, a large utility system would create enough sludge in one year to cover 10 square miles of land with 5 feet of ooze.

The indirect energy cost to extract limestone and handle the slurry can well be imagined.

The fourth method is that of removing the sulphur from the fuel itself before being fired; an effective system, but one which has to be paid for in energy terms, using between 6% and 10% of the total energy. Despite the variations in energy costs of pollution control its overall effect is suggested in the NEDO Report (1974b, p. 96):

emissions are at present kept to a fairly low level but with energy costs that have not been fully estimated. Taking both air and water protection into account the order of magnitude of industrial energy used for environmental safeguards is likely to be a few percent of the total energy used.

With respect to energy, the ultimate form of pollution is that of thermal pollution, a well known problem in the electrical generation field and one effectively described by Donald Harleman's (1971) article "Heat - the Ultimate Waste". The most likely solution to this problem in the future is through the study and implementation of what Charles Berg (1974a) describes as the concept of 'thermodynamic availability' which is directly related to entropy. In this concept one tries to maintain energy in its highest form and to degrade it (or increase its entropy) gradually in as many steps as possible (a principle which can apply to materials as well, as discussed in the next chapter). To do this one needs to match the energy source to the work required rather than vice versa. It is in these areas more than any other where future energy conservation lies. Like pollution, this is a subject in itself, however
a few examples concerning the concept will be made along with some of the problems restricting its widespread use.

'Combined cycle generation' is an illustration of how the stepped or the sequential use of heat can be applied to improve the efficiency in generating electricity, (which now has a peak efficiency in the U.K. of only 36% and averages 29%). In this system, electrical generators are powered by gas and steam turbines, the latter being driven by steam produced from the waste heat contained in the exhaust of the gas turbines. In the U.S. this system has achieved an overall efficiency of 38%-42% but with higher efficiency turbines the combined cycle generation technique could have efficiencies as high as 55%-60% (Central Policy Review Staff, 1974, p. 33).

In the above example the sequential degradation of energy is contained within the electricity generating system, and closely resembles in-house heat recovery systems mentioned in relation to the brick and cement industries, where kiln gases are used for drying and pre-kiln heating. To date the principle of gradual energy degradation has largely been applied within a production system, the real potential of this concept, which remains largely undeveloped, is the use of low grade heat outside the system which produces it. For example, using waste heat from the generation of electricity for district heating.

Utilizing low grade heat from the power generation outside the generating system is commendable but it should be approached with some caution. Electricity is one of the highest grades of energy and its use to perform low grade functions like heating water is inherently wasteful, a better approach to power generation is suggested by Charles
Instead of building a power plant and trying to find some use for the waste heat, one builds a steam raising plant [for a particular industrial process] and tries to find a use for the surplus electrical power generated, the idea is neither new nor economically unsound. In the 1920's and early 1930's several major paper companies used exactly the idea considered here.

Because of the existing electricity distribution network and the high quality of electricity itself, the chances of finding uses for it would be far greater than that of low grade waste heat from power generation.

**Fig. 4.22** Heat balance for recent British steel making operations. (NEDO, 1974b, p.63)

Often the sequential degradation of energy lies outside the steam and electricity combinations, mentioned so far. Take steel making as an example: the Sankey diagram shown above (Fig. 4.22) for current British steel making indicates a 70% wastage of energy, most of which is lost in low grade heat in the form of waste gases. The potential for energy savings here is great but as the NEDO Report (1974b, p. 63) explains:

> heat recovery from low grade heat is amongst the most intractable problems in steel making as in other areas though the low grade heat might be used for growing crops in greenhouses or for local heating schemes.

The manufacture of ceramics, cement and lime are also examples of processes producing large amounts of low grade heat in the form of stack gases, which have a potential for utilization. The use of stack gases
from the cement industry will be mentioned again in the next chapter.

Fabrication

At present about 3% of all energy released for useful purposes in the world is applied to the production of ingots and casting of virgin metal approximately three times that energy is committed to fashioning and shaping the metal. Thus for every ton of metal fabricated into machinery and equipment about 10 tons of coal or oil are required. (Meier, 1956, p. 25)

Fabrication is an area that consumes large quantities of energy, and as indicated by Meier it is also an area that affects unprocessed materials like timber. Undoubtedly the most important function performed in fabrication is that of forming or shaping and this can be accomplished in one of three ways; first by casting or moulding, thermo setting or chemically setting liquid materials; second by the chipless methods in which semi-solid or solid materials are shaped by applied forces and thirdly by chip cutting solid materials. The NATO report on the efficient use of energy (Kovach, 1973, p. 33) makes the following suggestions about future possible energy savings in relation to these primary shaping techniques:

1) Replace or reduce shaping procedures which involve excessive chip cutting or other shaping methods which produce large amounts of new scrap in relation to the final product. Utilize high yield shaping processes, which produce little if any scrap (extrusion and moulding). Develope the use of laser cutting and break down very complex shapes into simpler elements which can be assembled together to form a whole.

2) Encourage processes in which the final shape is achieved in the least number of stages. The most significant development recently in this area has been the gradual changing over in the steel industry to continuous casting which illuminates using ingots, soaking pits and a primary hot
rolling mill, saving 0.417 kWh/kg of crude steel (NEDO, 1974a, p. 63). Powder compacting technology is another promising development in low energy shaping technology, though its affect on construction materials could be small if limited to metals only.

3) Develop and use low temperature shaping methods by applying high mechanical forces or by Electro-forming where applicable.

Fabrication requiring mechanical activities. - Machining is required either directly or indirectly throughout the fabrication process and its efficiency can vary between 20% and 75% with 50% being common. Machining operations often have a low utilization factor, operating under a variety of load conditions or even idling a great deal of the time. A British survey (CPRS, 1974, p. 52) found that "efficiencies were often low because of the constant speed nature of the standard AC electric motor which drives most machinery" and suggested along with the NATO report (Kovach, 1973, p. 33 and 58) the following ways of reducing the energy requirements of machining operations:

1) The encouragement of full load and continuous machining operations;
2) The use of and development of more efficient motors (generally efficiency is dependent on size, smaller motors being less efficient than larger ones);
3) The development and use of improved cutting tools;
4) Improved maintenance and tribological practices, and
5) Using variable speed drives and motors or hydraulic drives operating from a central hydraulic supply.

The CPRS report (1974, p. 52) suggests "that up to the equivalent of ten million tonnes of coal could be saved by the wide spread use of efficient variable speed drives alone".
It is hard to say what effect on a material's energy intensity would be gained through such suggestions. It would probable benefit unprocessed materials like stone and timber, whose production energy costs are largely involved with mechanical operations more than highly processed materials like steel, whose mechanical operations are usually insignificant in comparison to thermal ones. Cement however could be an exception because of the very fine grinding of clinker involved in its production. The efficiency of electrically driven machinery is especially important, for any electrical losses have to be multiplied by a factor of about three to give a corresponding loss of primary fuels.

Fabrication requiring thermal activities. If fabrication is taken as a whole, most of the energy required would be in heat for use in shaping (e.g. heating required in casting a moulding or applied in chipless forming methods); material heat treating (e.g. annealing, tempering, normalizing and drying) and material coating (e.g. drying). Charles Berg (1974b, p. 267) lists the efficiencies of various types of furnaces used today by industry for shaping and heat treating steel, aluminium, copper, glass and carbon. Furnace temperatures ranged from 37°C. to 1,260°C. with 700°C. being typical. On average 45% of the energy used in these furnaces "goes up the chimney", so the potential for savings are great in this area. The methods for reducing this heat loss would be similar to those already discussed in relation to material manufacturing.

^Rittinger's law of crushing in which energy demands increase directly in relation to the new surface created by crushing would certainly apply to Portland Cement. A cube of cement clinker weighing one gram and having a surface area of about 3 cm² would after grinding produce a Portland cement powder with a surface area of 3,000 cm² having a typical diameter of 1/100th of a mm, and small enough to pass through a metal screen capable of holding water. (Brunauer and Copeland, 1964, p. 86).
However, an appreciation as to the difficulty (and lack of success) in effectively utilizing heat in both fabricating and material manufacturing operations during the last two centuries can be gained from a passage from Count Rumford's *Political, economic and Philosophical Essays* (Vol. 2) written in 1796:

Though it is generally acknowledged that there is a great waste of fuel in all countries, arising from ignorance and carelessness in the management of fire, yet few - very few, I believe - are aware of the real amount of this waste. From the result of all my enquiries upon this subject I have been led to conclude that not less than 7/8's [87.5%] of the heat generated, or which, with proper management, might be generated from fuel actually consumed, is carried up into the atmosphere with the smoke and totally lost. And this opinion has not been formed hastily; on the contrary, it is the result of much attentive observations and many experiments. (Benjamin, 1796, p. 4).

Heat recovery is not restricted to flue gases, waste heat could also be recovered from the heat given off an item after it is removed from the furnace as well as recovered from any exothermic reactions involved with composite fabrication. The idea of supplying a process with the type of energy it requires also appears to be a logical area for saving energy in this type of fabrication. Berg (1974a, p. 22) mentions the use of heat pipes in vacuum furnaces as being one means of accomplishing this. The conventional vacuum furnace uses heat produced by electrical resistance radiation inside the furnace which means that every unit of energy used in the furnace requires about three times as much from primary fuels, and the temperature required in the furnaces may be below that used in raising steam at the power plant. By using a heat pipe to supply energy from a local combustion chamber to the inside of the vacuum furnace illuminates this electrical generation conversion loss. This coupled with autiradiative insulation can reduce energy demands of this type of furnace by 75%.
Another example of matching energy source with requirement is now being recognized with respect to coating operations. Curing of resins and paints often depends on either ultra-violet or microwave radiation. Often broad spectrum infra-red heat and associated with high temperatures, is used for drying paints and resins. By matching the appropriate type of radiation to the ones actually required by the paint or resin can save massive amounts of energy. One industrial firm found that curing resin by ultra-violet radiation used only 1/80 as much energy as that used by direct heat (Berg, 1974a, p. 22). Conductive materials, insitu heating by induction could also save energy and uses the same principle.

These savings may sound impressive, but there are trends in fabrication which are requiring more energy than older and more traditional practices. A particularly relevant example of this to construction concerns timber. The Swedish timber concil's pamphlet Forest, Saw and Handling (1973, p. 11) reports that "air drying, when the timber is left to dry in open air, is rapidly being replaced by kiln drying...a method being quicker than air drying taking barely a week".

The energy ramifications of such substitution need little comment. U.K. timber drying practices for domestic wood which supplies only 10% to 20% of demand, are slightly better than those of Sweden. In the winter 1974-75 issue of the BRE News an article "Timber drying" (p. 13) states that:

the specification for most structural components in traditional houses can be met by air drying alone and a high proportion of soft wood used in the construction industry is not kiln dried in the U.K. (although it may have been through kilns in the exporting country to make it dry enough for shipping).

It goes on to say that the use of refrigerator-type (reversed heat pump) dehumidifiers have increased considerably over the past few years. This method could be more economical in energy terms than kiln drying, and the
condensate could prove a valuable by-product\(^1\). The report mentions that in addition to air, kiln, and dehumidifying methods of drying, other novel methods have been proposed "which include solvent seasoning, vapour drying, press drying and drying by radio frequency heating... none of which seem very likely to supplement the traditional methods of air and/or kiln drying on a commercial scale".

Fabrication activities which create heat.- Of the common building materials Portland cement, lime and gypsum plaster are quite unique, involving exothermic reactions in their fabrication, in which heat is actually created. An idea of the amount of heat generated in just the hydration of lime is indicated by Baynton (1966, p. 287)

\[ \text{hydration of quick lime is a strong exothermic reaction} \]

and it is surprising that the appreciable heat of hydration 490 and 380 (both Btu/lb of quicklime) \([0.317 \text{ and } 0.246 \text{ kWh/kg}]\)\(^2\) for high calcium and dolomitic types respectively, has not been utilized commercially to a greater extent. This means that the heat of hydration of 1 lb of pure quicklime is sufficient to heat 2.3 lb of water from 0°F. to boiling point (212°F.)... Including captive and regenerated limes there are about 12 million tons of lime slaked annually in the U.S. which theoretically evolve 1.0 to \(1.15 \times 10^{13}\) Btu of heat in the aggregate or the heat equivalent of 350,000 to 400,000 tons of high-grade bituminous coat (14000 Btu/lb heat value). This, of course, presupposes 100% pure lime and 100% heat generation efficiency which is impossible, but even of 50 to 75% efficiency the magnitude of this total is staggering. An estimated 98-99% of this heat is dissipated into the atmosphere. As a result, the potential value of this wasted heat offers a challenge to the research ingenuity of chemists and engineers to harness it for useful purposes.

\(^1\) A m\(^3\) of soft wood can have as much as 120 litres of water removed from it in the drying process. If this amount could be collected through a dehumidification system it could be used as distilled water.

\(^2\) By comparison the following is the heat evolved by various Portland cements.

<table>
<thead>
<tr>
<th>Portland cements</th>
<th>kWh/kg</th>
<th>kJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rapid hardening</td>
<td>0.139</td>
<td>500</td>
</tr>
<tr>
<td>Normal</td>
<td>0.136</td>
<td>490</td>
</tr>
<tr>
<td>Low heat</td>
<td>0.111</td>
<td>400</td>
</tr>
</tbody>
</table>
Unfortunately, this unusual property has not been capitalized upon, in fact the reverse is true. Unsatisfied with natural setting time concrete is being steam cured to achieve high early strength. In pre-cast units and light weight concrete blocks high pressure steam is used in an autoclave for 14-18 hours at a temperature of around 185°C.; even steam curing of concrete on site is possible using low pressure steam at 100°C. for periods of about 16 hours. If anything the surplus heat from hydration is looked on as a liability and not as an asset, and low heat cements have been specially developed to reduce this problem and there are cases where ground ice has been mixed with concrete to reduce this problem of surplus energy.
Assembly

Assembly is largely a mechanical operation in which the components are put together to form a final product or sub-assembly. Being primarily a mechanical operation, assembly the last step in the production sequence, largely resembles in energy terms the first step in the production sequence, that of extraction. The mechanical nature of assembly also means that it contributes little to the total formulated energy expenditures in products which are largely made up of processed material, which is the general rule today.

Even though assembly does not make much of a contribution in overall energy terms, it is an area like extraction where energy savings are not likely to occur, in fact if anything the operation will become more energy intensive with time. This is largely explained by the obsession to increase labour productivity or the value added per man hour of labour, which is particularly apparent in assembly operations, though it happens throughout the rest of the production sequence as well. By analogy with labour productivity, there can be described what Aurelio Peccei (1972, p. 426) calls "power productivity" or the value added per unit of energy consumed. It is the historic inverse relationship between these two productivities that leads one to believe that the assembly operation will become more energy intensive in the future. Apart from the substitution of higher intensity materials for lower ones, Peccei points out that:

The reason for the declining power productivity of U.S. industry is the progress of automation in which hand labour is displaced by machines...this revealed in the overall statistics for U.S. industry by the close relationship between the decline in power productivity and the increase in labour productivity. Indeed, the linear relationship between value added and the product of kWh's and man hours expended in industrial production means that the increased productivity...
of labour has been proportional to the increase in the amount of electricity consumed, while the decrease in productivity of power has been proportional to decrease in the number of man hours employed. (Peccei, 1972, p.426).

This is a well known phenomena which fits the old proverb "you do not get something for nothing" and is by no means restricted to assembly operations.

The substitution of machines for men and its subsequent increase in energy consumption has been well documented in the agricultural field. Cottrell (1955, pp 19-22), Slessor (1973, p. 1194), Blaxter (1974, p. 400-1), Pimentel and others at Cornell University (1973, p. 444-6) are only a few who have discussed this phenomena in relation to agriculture. Begg (1960, p. 193) discusses the mechanization problem in a British industrial context; stating that...

...it has been found that in the more progressive factories the continual demand for more and more mechanization and better factory conditions have resulted in a steady increase in the demand for electricity per unit of output - the rate of increase ranging from 2.4 percent per annum despite improvements in the efficiency of the driven plant and machinery [emphasis mine].

Robert Drew (1974, p. 594) in reviewing a Dutch report on national energy policy also mentions in a European context the dramatic increase in energy usage.

...Automation in an industrial society has increased the specific power demand for the production of goods to approximately five thousand watt for each worker-replaced-by-a-machine, as against the fifty watt of power-plus-craftsmanship, dexterity and adaptability. Any further automation can only result from massive further increases in energy consumption...

The changing nature of the Construction Industry

What effect does mechanization and 'pre-fabrication' have on the
energy consumption of the construction industry? Before approaching this question, we must define the 'construction industry' in relation to the production sequence. This is quite difficult when compared to the three other form related major industries i.e. manufacturing, agricultural and extractive (including forestry, fishing and mining). The construction industry resembles extractive industries in that is is not carried out in a permanent factory; it resembles the service industries having to be carried out at the exact location of customer demand (due to the immobile nature of the construction industries' products); but still resembles, in many respects, the manufacturing industry. After all the assembly of an automobile and the 'assembly' of a house both involve bringing together semi finished materials or components and forming these into a useable structure.

The key to the construction industries' definition is locational - it has to take place 'on-site'. It is largely this fact that has lead to misleading claims of increased productivity within the industry, which are not justified. What is really unique about the construction industry is that it is based on location and not the production processes actually involved. Other manufacturing industries are largely defined by material and/or processes. It is well understood, for example, that the coal industry is largely one of extraction while the automobile industry is largely one of assembly. Construction on the other hand can include production processes ranging from extraction through assembly and historically the further one goes back the more steps were included in the 'construction industry'. The on-site feature of construction has remained constant throughout history but the amount and kind of work of on-site production has not, in effect a dynamic system has been described by a static concept. This point is well illustrated by
Fig. 4.23 Percentage mix of on-site and off-site production for various housing types. (Bender, 1973, p.54)

<table>
<thead>
<tr>
<th>TYPE OF HOUSE</th>
<th>OFF-SITE WORK</th>
<th>ON-SITE WORK</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOG CABIN</td>
<td>- MILL LUMBER</td>
<td>- FELL TREES</td>
</tr>
<tr>
<td></td>
<td>- PRODUCE HARDWARE AND PAINT</td>
<td>- SHAPE AND FIT LOGS</td>
</tr>
<tr>
<td></td>
<td>- FACTORY-MAKE FURNITURE</td>
<td>- NEW PLANS FOR ROOF</td>
</tr>
<tr>
<td></td>
<td>- CUT AND FIT LUMBER FOR FLOOR, FURNITURE, ETC.</td>
<td>- FLOOR, FURNITURE, ETC.</td>
</tr>
<tr>
<td>EARLY BALLOON FRAME</td>
<td>- MILL LUMBER</td>
<td>- CUT AND FIT LUMBER FOR STRUCTURE AND FINISH</td>
</tr>
<tr>
<td></td>
<td>- PRODUCE HARDWARE AND PAINT</td>
<td>- INSTALL FACTORY-MADE COMPONENTS</td>
</tr>
<tr>
<td></td>
<td>- FACTORY-MAKE FURNITURE, CABINETRY, WINDOWS, DOORS, STAIRS, WALLBOARD</td>
<td>- PAINT AND FINISH</td>
</tr>
<tr>
<td>CONVENTIONAL FRAME</td>
<td>- MILL LUMBER</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- PRODUCE HARDWARE AND PAINT</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- FACTORY-MAKE FURNITURE, CABINETRY, WINDOWS, DOORS, STAIRS, WALLBOARD</td>
<td></td>
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<tr>
<td></td>
<td>- CUT AND FIT LUMBER FOR STRUCTURE AND FINISH</td>
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<tr>
<td></td>
<td>- INSTALL FACTORY-MADE COMPONENTS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- PAINT AND FINISH</td>
<td></td>
</tr>
<tr>
<td>PACKAGE HOME</td>
<td>- DESIGN AND FABRICATE A SET OF COORDINATED BUILDING COMPONENTS</td>
<td>- ASSEMBLE, PREFABRICATED COMPONENTS</td>
</tr>
<tr>
<td></td>
<td>FOR STRUCTURE/FAÇADE, PLUMBING, INTERIOR DUCTS AND STORAGE UNITS</td>
<td></td>
</tr>
<tr>
<td>MOBILE OR SECTIONAL</td>
<td>- FABRICATE COMPLETE FACTORY-MADE HOUSE WITH ALL FINISHES AND APPOINTMENTS</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4.24 The reduction of on-site production processes involved in U.S. housing. (Bender, 1973, p.53)
Richard Bender's (1973) book on Industrialisation of Building.

The reduction over the years of on-site building processes involved in U.S. housing is schematically shown in Fig. 4.24. It can be seen that if the construction industry existed in pioneering days, it would have included all processing steps from the extraction of trees through the assembly of primitive furniture, whereas the packaged home coming into acceptance today would include only the assembly portion of production with only pre-fabricated components being put together on-site. The reduction of on-site or construction work in relation to off-site work again can be seen in the percentage mix graph, Fig. 4.23 which extends over a larger time span. One can see how productivity might appear to be increasing in the construction industry through the years; it is not that the end product requires any less overall work, whether the workers are working any harder or faster, to a large degree it is merely to do with the work being definitionally moved out of the construction industry and into manufacturing or extractive industries. In addition a great deal of off-site production or pre-production work already exists in what is referred to today as traditional or conventional construction. Cox and Goodman (1956, p. 60) in their study on the marketing of housebuilding materials point this out "in

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1 It is interesting to note that the 'construction industry' only exists in the case of the early balloon frame, conventional frame and packaged homes and is completely absent with respect to the earliest and most primitive form, the log cabin and the most sophisticated form, the sectional home.

2 Off-site work or 'pre-fabrication' was even common in the Middle Ages particularly with wood. Clifton Taylor (1962, p. 40) states that even though: no two houses were framed alike, work preparing the wood skeleton was carried out away from the site and usually carry position marks a supposition that they were prepared in a shop or yard probably during the winters.
an absolute sense, there is already a great deal of pre-fabrication... what arrives on site is not piles of logs, rocks, or clay, sand and the like in their original form. Each of these materials has been processed, if only to the extent of cleaning and sorting".

The drift of work from one industrial system to another is why the plea was made in Chapter One to analyse the constructional system for energy, environmental, labour and other aspects and not the construction industry as defined by the Standard Industrial Code (SIC) system. Fig. 4.24 expands specific areas where the reduction on on-site building processes have been made over the last seventy years or so in U.S. housing efforts and shows quite clearly the evolution of off-site assembly. With the possible exception of poured in place concrete and earth work which are fabricating processes "the contractor is largely an erector or assembler of the products of other industries". (Stone, 19 p. 4). This is why the construction industry is being discussed under assembly.

The Effect of moving production off-site.-- What is the effect of this trend towards pre-fabrication or pre-assembly in building on energy

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1 Categorizing earth work as fabrication might appear odd, the work being better classified as extraction. However, this study has defined fabrication as being largely involved with the shaping of material and in earth work one is in essence shaping the site. On the other hand, if on-site earth work was performed to win a raw material to be used in the building itself, it could be properly classified as extraction. Cob, Plé and even brick making are historical British examples for on-site earth was used in the actual construction process.

2 The term pre-fabrication is widely used today in the building field. When the term first appeared it was referring more to off-site material fabrication i.e. shaping and forming, however as Fig. 4.25 shows this term is and probably continues to be synonymous not with the fabrication of material with off-site pre-assembly which itself would indicate pre-fabrication. Though the term pre-assembly would be more accurate the term pre-fabrication will be used because of its wide acceptance.
demands? There is little doubt that the on-site work that has already
or is likely to be moved into the factory for pre-fabrication would
be subjected to the same general rules that were already described by
Mr. Peccei and others mentioned at the beginning of this section in
relation to mechanization. Indeed, the move off-site is to a large
degree due to the limited amount of mechanization which can practicably
be incorporated on-site. Just to keep the assembly and pre-fabrication
plants heated requires more energy than if the work was performed on-site,
though energy savings could be gained in off-site operation by the
increased utilization and the maintenance of equipment which usually
occurs in a factory situation.

Pre-fabrication not only affects 'form' related energy consumption,
it also affects time/place related energy costs. A report produced by
Cox and Goodman (1954) for the U.S. Housing and Home Finance Agency,
dealt largely with this problem in relation to U.S. housing. Their
conclusions (Cox and Goodman, 1956, pp 60-61) were as follows:

With more extensive pre-fabrication, ton-miles might drop, partly because it is likely that somewhat lighter materials would be used and partly because the waste accumulated in construction would be taken out earlier in the flow. This end result is not certain however, since ton-miles are affected by distance as well as by weight, and transfer of the assembly task from site to factory might entail transportation through longer distances as the goods are moved about among

Reduction in weight frequently has nothing to do with pre-fabrication itself. Many pre-fabricated buildings produced today are classified as temporary buildings and as such do not have to meet the more stringent building regulations applicable to more traditional and permanent type of building. Whether or not a pre-fabricated building requires a foundation or not, makes a great deal of difference in the total tonnage of materials used. Cox and Goodman (1956, p. 60) calculate that a full cellar and cement floor constitute one third of the total weight of a typical U.S. suburban house, though only represent 5% of the total ton-miles, involving the use of relatively local materials.
more factors in the course of processing.\footnote{The effect of pre-fabrication on transport prices is also discussed by Cox and Goodman (1956, p. 61) "The marketing costs might also be substantially increased because higher rates per ton-mile are associated with the marketing of the pre-fabricated unit may well be in addition to, rather than in lieu of, that of marketing the materials."}

What pre-fabrication would do to tonnage and ton-miles cannot be determined without the buildings type and the degree of pre-fabrication being specified...however, if plants served large areas in order to achieve economies of large scale processing considerable back hauling would be likely.

The principles no doubt apply to other types of building besides housing though not to the same degree in Britain due to its smaller scale.

It is worth noting that even though site time is reduced through pre-fabrication "the time elapse between extraction and delivery to the site would presumably increase, so that a substantially larger number of dollar days would have been accumulated by the time the house arrived at the site." (Cox and Goodman, 1956, p. 61). This means in capital terms that all the speed gained by mechanization and production could largely be offset by the finished component or building laying idle while waiting to be sold which makes one wonder whether the same end result could have been accomplished by slower, less energy intensive building techniques on-site, but with the end result being ready when and where required.

A situation appears to be developing with regards to processing and transportation of building materials and components that is similar to the old army boot camp legend about always marching at quick time in order to stand in a queue. The brick industry, for example, has currently
millions of bricks standing in fields waiting to be sold, yet they are no doubt spending or want to spend more and more energy and capital to develop and run processing plants which process more bricks even faster. Once an order is confirmed, the bricks after laying idle for months are quite likely to be placed on a lorry and rushed to the site at 70 m.p.h., to again stand in storage for a few more days. If the distance covered was divided by the time between manufacturing and the assembly of the bricks on site, the speed required could probably be expressed as a fraction of a mile an hour. Smoothing out the relationship between production and delivery and reducing this stop, start, all or nothing approach by planning could reduce energy demands significantly, but whether this will ever be done, even with nationalization is doubtful.

Mechanization of on-site production.- Being largely an assembly operation the material handling of components is becoming a main feature of the construction industry along with the material handling involved with concrete and earth work, the two fabrication processes still carried out on-site. Without a reduction in the actual amount moved on-site energy savings are not likely to occur in this area. A pattern of mechanism is occurring in construction similar to the one already described in relation to extraction and the clothing industry in the U.S. Misch, (1966, p. 287) in his article "The Tendencies of Industrialization in Conventional Building Methods" describes the "tendency towards investment in light and heavy machinery, equipment, and building components to break down the continuous construction operation into a series of identical steps with a view to 'mass' production of these parts of the construction projection with a minimum of skilled man power". (p. 287) He goes on to explain that "all attempts towards increase of productivity through increased mechanization are very difficult..." because of the non-
uniformity of buildings and their sites. Even so "the progress of the idea of industrialization seems quite remarkable" (p. 287). He then describes how the man hours of the German building industry, during a ten year period, remained constant while the volume of buildings produced nearly doubled. These factors were all shown graphically in relation to a 1954 index. Interestingly enough, the most significant factor in the rise in productivity i.e. the increase in tonnage of machinery per worker, was omitted from the graph entirely. Fig. 4.25 plots logarithmically all the factors concerned, to show the rates of change. The fastest growth rate is neither productivity nor volume, but the tonnage of equipment used to produce this increase in productivity.

![Graph of productivity and machinery](image)

**Fig. 4.25 Increase in productivity and machinery in the German building industry.** *(Misch, 1966, p.187, Fig. 1 and Table 1)*

Significantly, at least in energy terms, the trend, tendency or as Misch would say "the progress of industrialization in general" is the increasing divergence between machine tonnage and productivity (the former increasing faster than the latter) which strongly suggests diminishing returns on machinery tonnage. In other words you need ever
increasing amounts of equipment to produce similar increases in productivity. "As a consequence of the adaption of some of the typical features of other branches of heavy or light industry... especially through the progress in mechanization and rationalization... in Germany the building industry is to often called "the industry of the mobile factory"". (Misch, 1966, p. 287). Bender (1973, p. 35) speaks of construction practices in the U.S. being much the same, where "one of the first concerns of the builder has become the supply of power to the site...and if a fuse blows operations cease." The same situation no doubt exists in all developed countries; unfortunately it is gaining popularity in underdeveloped countries as well mostly as a status symbol, there being little need to reduce labour requirements of any kind.

It must be remembered that even though more energy is being used on-site, and its use probably exceeds that of transport, it still only constitutes a relatively small portion of overall constructional energy costs where processed materials are commonly used; a point made by Bullard and Herendeen's (1973) analysis of the construction industry which is shown in Fig. 3.18 (p.129). If committed to such a degree of on-site mechanization, one might reconsider the use of traditional on-site materials. For example mechanizing rammed earth construction techniques, no doubt machinery already developed for road and site work could be easily adapted to this traditional form of construction. On-site mechanization, coupled with the limited use of processed materials, for vapour barriers could make the use of on-site materials viable or at least worth investigating. In other words it could make more energy sense to increase mechanical energy usage on-site to extract and fabricate localised materials than to use much more mechanical and thermal energy
in extracting, manufacturing, fabricating, assembling and transporting materials off-site. Mechanization of on-site work could also encourage individuals to fabricate or assemble their own structures.

The Shift from Direct to Indirect Labour and Energy Costs

Reducing labour or increasing its productivity through either pre-fabrication or on-site mechanization with their resultant increases in energy costs, brings another point up which is not limited to construction but applies to all production processes, and that is what happens to the people displaced through rationalization of mechanization? One could almost look at the displacement of people from industry from a materials (or energy) balance point of view; industries neither creating nor destroying people. People rationalized or mechanized out of one narrowly defined industrial system inevitably show up in another system.

A strong case could be presented that the construction system or the system responsible for the built environment today is as labour intensive as it ever was, irrespective of the rationalization and mechanization that has taken place in the construction industry and supporting industries, which are in some way involved in producing building materials. Of course the constructional system could not be defined in the traditional sense (including only production related industries) it would have to include the portion of trade service industries which support building efforts. For example, Cox and Goodman (1956, p. 61) mention pre-fabrication leading to the likelihood of marketing work "increasing rather than decreasing because of the introduction of one or more additional fabricating plants into the various material flows". It would be quite possible to find people being displaced from the production line
only to be replaced in the sales department.¹

Bullard and Herendeen in their analysis (1973) of U.S. construction, clearly show the energy impact (Fig. 3.18) of the general trend from direct to indirect production activities in the building field especially in relation to their energy requirements exceeding those related to transportation and almost equalling the energy required by the construction industry itself. At a much broader level, administration, education and other professional orientated fields are additional indirect activities which could be related to the construction system. The office of Population Census and Surveys, economic activity figures indicate that between 1966 and 1971 the number of men in manual work fell by 7.8 percent, whilst those in non-manual work rose by 9.4 percent (The Scotsman, 20th January, 1976, p. 11). Generally fewer people were employed in manufacturing industries and more in banking, insurance and finance. This could be expected since the mechanization/rationalization responsible for reducing industries' manpower requirement is also

¹Gerald Leach in his report Energy and Food Production (1975) found a similar trend in the food system. The fall in the number of people employed directly on Britain's farms, largely due to mechanization/rationalization, has been matched by a rise in the number of people in other parts of the food production system. He calculates that "7-8 percent of the 'working week' [Total working population divided by the number of workers in the food industry] is spent on food provision: a performance only about two to three times better than pre-industrial farmers and hunter-gatherers" (p. 12). He also found that the heavy energy inputs into farming, characteristic of modern methods, did yield good returns. However, "while this energy prop has improved the productivity of the land and of labour, the overall improvement when one looks at the entire food system has not been all that dramatic". The gains from energy-intensiveness have been dissipated elsewhere in the food system. Leach mentions that "much more energy is now used to transport, package, sell, cook, store and process (or merely titivate) food stuffs than used to grow it."
responsible for increasing its capital (and energy) intensiveness.

Government is one of the greatest growth industries in Britain today and the recent reorganization of local government in England and Wales resulted in the number of Town Hall executives, chief officers and their deputies and staff in the administration, professional, technical and clerical grades increasing by 14,000. Surely some of these are involved in some way with the building system. The fact that "there has been a hundred fold increase in the number of scientists and engineers in the past 40 years...and an exponential increase in the number of professionals produced each year...along with the number of public and private functions which appear to require professional attention..." (Dumont, 1975, p. 199) also strongly suggests the effect of mechanization and rationalization of basic industry. Again some of these are related to the constructional system.

Fig. 4.26 summarizes the energy forecasts made for the four major production areas. Broadly speaking material manufacture and fabrication, the mid-production activities, not only consume the greatest amount of
energy but also provide the areas of production energy savings.

Extraction and assembly operations, the first and last in the production sequence, which are mechanical in nature, consume smaller amounts of energy and will most likely in the future require energy increases. This suggests a relative energy advantage for processed materials in the future, a point which will be discussed in the next section in connection with the pricing mechanism.

This was Charles Berg's conclusion to his article on energy conservation in industry and it includes a big if: he produced the five following constraints which can inhibit the adoption of energy saving techniques:

1. Lack of awareness and managerial priorities.
2. Technological risk.
3. Institutional, regulatory and legal barriers.
4. Capital Investment and financing policies.
5. Budget policies.

Before going into the constraints in more detail it should be mentioned that all of these constraints coupled with Donnie Schoen's (1973) concept of institutional 'Dynamic Conservation' inevitably lead to lag times between technological development (most of which are only modifications to scientific principles long and well understood), and their actual employment on a commercial scale. The exceptionally fast
Constraints Affecting the Reduction of Energy Consumption in the Production Sequence

There is a wide range of technical measures to improve the efficiency of fuel use in industry. The economic justification for adopting these measures can, as a rule, be readily established. If [emphasis mine] one can resolve the non technoeconomic constraints which affect the adoption of these measures, one can look forward to substantial reductions in the fuel required to operate many important industrial processes. (Berg, 1974b, p. 270)

This was Charles Berg's conclusion to his article on energy conservation in industry and it includes a big if; he mentioned the five following constraints¹ which can inhibit the adoption of energy saving techniques:

1) Lack of awareness and management priorities.
2) Technological risk.
3) Institutional, regulatory and legal barriers.
4) Capital investment and lending policies.
5) Budget policies.

Before going into the constraints in more detail it should be mentioned that all of these constraints coupled with what Donald Schon's (1973) concept of institutional 'Dynamic Conservation' inevitably lead to lag-times between technological development (most of which are only modifications to scientific principles long and well understood), and their actual employment on a commercial scale. The exceptionally fast

¹Even referring to these constraints as 'non technoeconomic' all of the constraints in some degree are related to conventional economic considerations, particularly the last three.
change over in the U.S. glass industry from plate glass plants to the Pilkington float glass process which was attractive from almost every point of view, including energy conservation, still took ten years to accomplish. The application of any major energy saving techniques in most industries has to wait until it can be incorporated into a large scale re-equipment or new plant project which itself is usually the result of labour productivity, marketing, or raw material supply considerations and not energy requirements. A fifteen year time span to re-equip is not untypical, especially when one considers some plant, such as pottery kilns, can have useful lives of up to fifty years.

Lack of Awareness and Management Priorities. - This involves those who are in a position to initiate improvements that save energy, are not aware that improvements can be made, or if they are aware, do not fully realize the economic gains which could be made from such efforts. Even if aware management might not initiate any action because of its ability to deal with only so many items at one time. Faced with a broad spectrum of problems and limited resources to control them, management will deal first with conventional and pressing problems like wages, materials, supply and sales, which if left unattended could lead to crisis. Unless something or someone happens to bring the energy issue (or any number of other issues like environmental ones) to the special attention of management the issue will simply not be attended to. This is particularly true of small industries where the margin of error is very small indeed, on the other hand their ability to take action without

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1 One problem today is that pilot plant or laboratory projects with attractive energy saving potential are often given great publicity leading the public to the impression that the development is in widespread use.
getting involved with bureaucratic inertia is much greater in relation to the small firm.

Technological Risk. — Technological risk presents another factor and is largely involved with the risk involved with scaling up techniques developed in a laboratory to full scale. This is becoming increasingly important because of the increased size of new plants themselves, in order to justify economy of scale. Industrial investors tend to be conservative and investing in a known technique usually implies less risk.

Institutional, Regulatory and Legal Barriers. — These constraints will most likely have the greatest effect on the acceptance of sequential energy utilization. This is unfortunate since it is in this area that the largest future savings could take place, especially between production systems. Take the example mentioned in the material manufacturing section of this chapter, in which Berg suggests the production of electricity in conjunction with paper, he goes on in his article (1974b, p. 286) to say that the U.S. paper companies which produced both paper and power in the late 1920's and early 1930's proved that it could be a very profitable way to generate electrical power.  

- So much so that in the 1930's the Department of Justice took an interest in the matter. In a series of court suits the paper

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1 The same idea was applied in the U.K., combined systems were installed in 1948 at the Llynfi power station in South Wales in connection with the Bridgend Paper Mill. Unfortunately, the end results were the same as those experienced in the States — closure, because of "problems which arose when improvements in the efficiency of newer power stations supplying the grid caused [the combined plant to become] uneconomic to use for supplying electricity at off peak periods". (NEDO, 1974b, p. 77).
companies were required to decide whether they were in the paper business or the electric power business, and most opted for the paper business leaving power generation behind.

Here is an example of a thermodynamically efficient system (which was actually in operation) being curtailed on legal grounds.

One wonders what the chances are in the future for the general acceptance of the sequential use of energy; whose success depends so much on co-ordination between various organisations. In Britain co-ordination even among the nationalized industries (who are theoretically under the same overall management) appears to be lacking. Indeed the industries are more competitive than complimentary, particularly with respect to energy production and transport. What chances are there of a national energy policy emerging that is based on rational energy utilization, which means using each form of energy where it is best suited, when the national coal, gas and electricity boards are engaged in trying to outsell one another? Can this competition be stopped?

Even though the energy saving rewards are great for utilizing low grade heat, the problem still remains one of transferring the waste heat from one system into another. Geographically speaking the systems could literally be only yards apart but institutionally miles apart. Current planning based on simple and isolated zones could in principle provide some opportunity for the interchange between industries of waste heat within their industrial zone; but zoning also results in the physical separation of industry from housing, commercial and agriculture areas, which are quite likely to be even more capable of utilizing this low grade heat.
Capital Investment and Lending Policies.- Lending agencies, generally prefer and give higher priority to loans for expanding plant capacity than for improvements to existing plant which result in no direct increases in output. The NEDO report (1974b,p.9) confirms this point of view:

Technological change usually involves capital investment and is rarely justified by fuel savings alone. The most common exception may be the case of the more sophisticated control systems and possibly the installation of heat recovery systems where this can be done without major changes in plant itself. However, in such cases capital requirements for energy saving measures may be in competition with other demands of capital relating, for example, to an expansion in production facilities.

It is worthwhile mentioning the British Government lending policies on energy saving devices. Recently the government made available to industry an 'Energy Saving Loan Scheme' advertised (The Sunday Times, 15th December, 1974, p. 52) to "encourage the more efficient use of all forms of energy." The loans ranging from £10,000 to £100,000 were for projects that would reduce heat losses in industrial buildings; replace or renovate machinery, plant or equipment; or for the installation of automatic control devices, heat exchanges, pre-heaters or combined heat and power schemes. This would appear to be a government initiative in the right direction, (especially when Britain spends £10 million a day importing oil) but it also points out a major flaw in most lending policies - that is they try to justify them in terms of money and not energy, emphasis should be made on amortization of energy and not money costs, and yet to be eligible for the above government loan "the project must promise sufficient energy savings to cover the capital and interest in four years [emphasis mine]." The scheme makes no mention at all of the amortization of energy costs (the time required for the savings in energy to equal the amount of energy required initially to produce the energy saving device). The energy 'pay off'
time is becoming increasingly more relevant because of the diminishing returns brought about by new energy saving devices, a subject discussed at the end of this section.

Budget Policies. - Industrial budgeting is either directly or indirectly associated with all the constraints which have so far been mentioned. Typical industrial budgets tend to be based on slight modifications of a previous budget, whose base is never questioned. In this situation, areas where costs are rising, will inevitably receive the most budgeting attention, whereas areas whose rate of increase is slower or declining relatively speaking (e.g. energy until very recently) appear to be problems which are solving themselves and require little budget attention. Again the NEDO report (1974b, p. 9) echoes this attitude:

> Energy costs are rarely the most important costs and there may appear to be less need for controlling them than for controlling other costs. It is possible that more efficient overall production can be achieved by greater [emphasis mine] use of energy in many situations.

Budgeting policy is perhaps the best indication of an organisation's attitude towards energy conservation. To get an idea of the real priority given to energy conservation as reflected in budgeting policies, one needs only to review expenditure (particularly government's) on items related to both the supply and use of energy. A comparison of recent U.S. and U.K. energy related expenditures are shown in Fig. 4.27. From the figures represented some general conclusions can be drawn.

Only a terse review indicates at once where the real priorities lie, particularly revealing is the finding of Research and Development (R & D) which, by its very nature, precedes the implementation of any

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1 An article by David Rose (1974) on "Energy Policy in the U.S." and OECD's report Energy R&D (1975) are both good sources for additional information on this topic.
large scale effort. The most notable item in the use of almost all the available economic resources in developing the supply side of the energy equation. The Department of Energy's loans to industry discussed in relation to investment policies are quite insignificant in comparison to the cost of only one nuclear power plant. Even if one thousand of these loans were made averaging fifty thousand pounds the result would still be only about one fifth the cost of a nuclear power plant or equal to the deficit currently incurred by the U.K. by importing five day's worth of oil. The development costs of Concorde, the most energy intensive system of moving people, are about three hundred times greater than the yearly grants for research directly related to the production and use of energy. In addition, it is quite likely that a break down of the SRC grants would, to a large degree, be devoted to

<table>
<thead>
<tr>
<th>U.S. FEDERAL SPENDING ON VARIOUS ENERGY PROGRAMS IN 1974 (Fiscal year)</th>
<th>DOLLARS</th>
<th>POUNDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total federal R&amp;D energy budget</td>
<td>10^9</td>
<td>10^6</td>
</tr>
<tr>
<td>R&amp;D for nuclear energy development, advanced systems, physical research and national defense</td>
<td>10^8</td>
<td>10^5</td>
</tr>
<tr>
<td>R&amp;D on energy related environmental and safety problems</td>
<td>10^7</td>
<td>10^4</td>
</tr>
<tr>
<td>R&amp;D on fossil fuel development</td>
<td>10^6</td>
<td>10^3</td>
</tr>
<tr>
<td>R&amp;D on space applications of nuclear energy</td>
<td>10^5</td>
<td>10^2</td>
</tr>
<tr>
<td>R&amp;D on solar (incandescent) and geothermal energy</td>
<td>10^4</td>
<td>10^1</td>
</tr>
<tr>
<td>R&amp;D for the Office of Energy Conservation</td>
<td>10^3</td>
<td>1.00</td>
</tr>
<tr>
<td>R&amp;D on fuel economy</td>
<td>10^2</td>
<td>1.00</td>
</tr>
<tr>
<td>R&amp;D on electrical power conservation</td>
<td>10^1</td>
<td>1.00</td>
</tr>
<tr>
<td>R&amp;D on end use conservation negligible</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

**Fig. 4.27** Various recent expenditures in the U.K. and U.S. primarily related to energy.

**Sources:**
2. Rose (1974, p.28)
5. The Scotsman (6 Feb., 1975, p.6)
7. The Scotsman (13 Feb., 1975, p.6)

**Total government and consumer spending in the U.K.**

- 1970 Consumer's expenditure on housing
- 1978 Consumer's expenditure on alcohol & tobacco
- 1974 Bill for imported oil
- 1978 Consumer's expenditure on fuel & light
- 1978 Revenue from petrol and oil taxes
- Concorde development costs up to 1975

**Cost of a nuclear power station** 6

**Cost of one thousand 'Industrial Energy Saving Loans' averaging 250,000 each.**

**Daily consumers' expenditure on alcohol & tobacco** 3

**Daily expenditure on imported fossil fuels** 7

**Science Research Council's annual grants directly related to production and use of energy** 6

**Range of short term loans offered through the Department of Energy's 'Energy Saving Loan Scheme'**

**A SRC yearly grant to Cambridge University for a 3 year study on industrial energy consumption**
energy production from fossil or nuclear fuels with production from income sources and conservation efforts receiving only minor amounts. This is certainly the situation in the U.S., in fact government funded R & D for end-use conservation was negligible. And yet end-use conservation as pointed out at the end of this chapter is the most logical point of conservation.

Why should there be such imbalance in energy research and development and is it likely to change? David Rose (1974, p. 28) in his article on energy policy in the U.S. believes there are two basic reasons. The first is due to energy being so plentiful and so cheap that there has been little incentive for people to be frugal coupled with the fact that end users are so diversified that any one saving would have little effect on overall consumption and therefore could be neglected. The second and more significant reason for neglect of energy conservation "is that the industry is richly rewarded for selling energy consuming devices". These are certainly important points, but the figures would also indicate the favouring of research that falls into any combination of the following categories: highly technical, glamorous or defence orientated. Even though research that falls into this category is in itself very complex in nature the overall projects are usually quite easily defined or identified and subsequently budgeted for. Nuclear fusion, breeder reactors and Concorde are all examples of this type of research, highly complex in nature but described and comprehended in merely a few words. Conservation on the other hand is much more diversified making funding difficult.

More importantly, the figures would strongly suggest institutionalization of funds. There appears to be a strong inverse relationship between funds
allocated and organizations or bodies involved;

\[ \text{Energy Supply} \quad \text{Energy Demand} \quad \text{Organizational bodies involved} \]

\[ \text{Funds for energy research} \]

with the production side of the energy equation being represented by a few large and centralized institutions receiving the vast majority of funds at the expense of the consumption and end-use side of the equation represented by a multitude of bodies and even individuals. Donald Schon's (1973) premise that institutions formed in response to a particular set of problems often survive long after the problems have changed dramatically or even disappeared also plays a significant role in the institutionalization of funds. Nuclear research, for example, was to a large degree in response to winning a world war. Once the conflict was over, the research establishment carried on only branching out into civilian applications of nuclear power or 'atom for peace' programmes. By the time this was done funding channels for the particular research organisation had been well established with annual budget fluctuations amounting to only a few percent each year.

The Pricing Mechanism and Energy Conservation

There are some who argue that the conventional pricing mechanisms which are essentially feedback systems, will automatically lead to eventual lower production energy costs, despite the five constraints just discussed. The argument, when applied to production, is based on the belief that as energy becomes scarcer its price will naturally
increase (supply and demand). These increases in turn would be reflected in the price of materials and products in proportion to the amount of energy involved in their production; and consequently pricing high energy products or activities out of existence.

There are certainly some elements of truth with this argument. The close relationship between a material's energy intensity and its demand which was illustrated in Chapter One (Figs. 1.6 and 1.7, p.18) suggest to a large extent building materials are already selected on the ground of energy intensiveness. Indeed this could be precisely the failure of the argument, what materials can we switch to in the future if energy costs go up, in other words what lower energy intensive materials can we substitute for the backbone of the construction industry, those of concrete, brick and wood?

Some technical improvements in reducing energy requirements, as well as some substitution will no doubt occur. The roofing material study in Chapters Two and Three contained an example of this happening with the substitution of concrete tiles for clay tiles. But the roofing material study more significantly pointed out that historically and in the majority of cases substitution was in fact from lower intensity materials to processed materials with intensities that were higher by orders of magnitude; and this substitution was primarily due to the pricing mechanism. Why did the concrete tile supersede slate as well as clay tile? It certainly was not based on lower energy demand or improved performance which could be argued in the case of slate replacing thatch, no, it was essentially due to price¹. The example of roofing

¹Recent measured rates for interlocking concrete tiles and Welsh slate were £4.17/m² and £8.50/m² respectively (The Architects Journal, 17 March, 1976, p. 557).
Figs.
4.28
4.29
4.30
4.31
Material wholesale price index. (Davies, 1974, p.51)

Trends in building material prices. (Buckley, 1972, Fig. 3.1)

DTI building material price index. (Cement & Concrete Assoc., 1974, Fig. 2)

Relative price increases for energy, labour, and excavation by hand and machine.
materials over a long period of time and concerns in place measured rates which as pointed out in the price profile Fig. 4.17 are very sensitive to labour costs.

Correlations between Price and Energy Intensity.- One immediately questions the correlation between energy costs and a commodities' price by merely reviewing the violent price fluctuations so closely associated with commodity markets; ranging from gold to soya beans; neither the amount of energy used in the production of these commodities or its price fluctuate as much as the price of the commodities themselves. What about building material prices? Roofing materials indicated what happened over the long term, but what about recent price trends? Figures 4.28, 4.29, 4.30 represent comparative price graphs for various common building materials taken from three different sources. The results are generally the same - from only a rudimentary review one can see immediately that there is no correlation between material price increases and energy intensity. In fact both long and short price histories of common building materials would indicate that if any correlation existed it was opposite to the price mechanism argument. The Concrete and Cement Association points out in their report on Energy (1974, p. 2) "over a twenty year base period, percentage increases in delivered price for cement, brick, rolled steel sections and imported soft wood timber have been in reverse order to their energy content". Evidence suggests that the prices of low energy unprocessed materials such as gravel and wood have risen at a rate faster than the more highly processed and more energy intensive materials such as plastic metals and ceramics. The reason for the failure of the price/energy argument is simply due to the fact that direct energy costs represent
only a small proportion of the overall value added or price\(^1\).

**Relationship between 'Value' added and Energy added.** - This is so vital in understanding the current energy situation that it deserves further discussion. The production sequence, is made up of various activities which materials and components have to pass through, the more sophisticated, refined and complex the final product the more activities are required, but regardless of how primitive the material or method energy is required for each activity and represents a portion of the value added for that particular activity. Naturally in the case of processed materials, one would expect the highest ratio between direct energy cost and value added to occur in the area of material manufacturing, the most energy intensive stage in production. This is shown to be generally the case, both the NEDO report (1974, a & b) and U.S. Department of Commerce statistics (Cambel, 1965, Tables 1-2 and 1-3). An example from the latter source shows the energy bill as a percent of value added for the metal fabricating industry at about 2% whereas the primary metal manufacturing industries vary between 12% and 27%. It is interesting to

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\(^1\)If it were true that competitive product pricing was largely dependent on energy intensity, one could easily argue for more research in production energy solely on the grounds that it would provide a useful way of analysing and forecasting the economic viability of various materials and methods of construction. Indeed Stephen Berry (1972, p. 9) predicts that in the long range economic and thermodynamic analysis being equivalent. Again if pricing were more sensitive to energy costs the shift to less energy intensive methods of materials would probably be far less rapid than anticipated. An upward swing in the price of energy would force the specifiers of materials simultaneously to a restricted number of lower energy substitutes, which would themselves increase in price most likely to a position only marginally below the price of the higher energy intensive materials; and if the energy price change was rapid enough so as to prevent a corresponding increase in production the price of the lower energy substitute could even exceed the price of the material being substituted for.
note that even when restricted to the energy intensive stages of material manufacture there is no direct correlation between the energy intensiveness of the activity and energy's percentage of value added as shown in the table below (arranged in percentage order).

<table>
<thead>
<tr>
<th>INDUSTRY</th>
<th>Energy Bill as Percent of Value Added</th>
<th>Approximate Energy Added By Industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blast Furnace and Steel Mills</td>
<td>11%</td>
<td>kWh/kg 9 kWh/dm^3 70.</td>
</tr>
<tr>
<td>Primary Copper</td>
<td>14%</td>
<td>kWh/kg 8 kWh/dm^3 71.</td>
</tr>
<tr>
<td>Brick and Structural Slay</td>
<td>19%</td>
<td>kWh/kg .5 kWh/dm^3 .9</td>
</tr>
<tr>
<td>Primary Aluminium</td>
<td>21%</td>
<td>kWh/kg 70 kWh/dm^3 189.</td>
</tr>
<tr>
<td>Cement</td>
<td>22%</td>
<td>kWh/kg 2 kWh/dm^3 2.8</td>
</tr>
<tr>
<td>Primary Lead</td>
<td>22%</td>
<td>kWh/kg 10 kWh/dm^3 113.</td>
</tr>
<tr>
<td>Primary Zinc</td>
<td>27%</td>
<td>kWh/kg 11 kWh/dm^3 78.</td>
</tr>
</tbody>
</table>

The lack of correlation exists whether the energy added is expressed in relation to mass or volume. What is striking is how small the percentage is even in the most energy intensive area of production. Aluminium, the most energy intensive common material used today, energy costs only represent about 20% of the value added in its manufacture which is even less than the ratio found for the manufacture of cement.

1 A more striking example of how insignificant fuel costs have been can be seen in the electrical generation industry, whose sole product is energy itself. 1962 direct fuel costs in generating electricity in the U.S. represented a mere 14% of the final delivered price of electricity (U.S. Congress, 1970, Table 42). It is this fact that should dispel the idea of free energy in the future with the development of income sources of fusion power.
The Dilution Factor.—The lack of correlation, particularly between the metals and non-metals, can to a large degree be explained by the dilution factor stemming from the highly significant relationship between the number of activities or stages required in manufacturing a material and the proportion of value added directly related to energy. This relationship is most apparent in petro-chemical based synthetic materials and is described in the NEDO report (1974,b, p. 73):

Even though energy requirements of related products tend to be highest for those that involve the largest number of stages in their manufacture...it is essential to relate energy costs to other manufacturing costs, and it is a general rule that the ratio of energy costs to total cost tends to be higher when the number of manufacturing stages is smaller. Thus the energy cost to total cost ratio is...lower for the polymers such as PVC than it is for intermediates such as ethylene or Benzene.

Similarly a New Scientist (5 September, 1974, p. 600) review of an ICI report speaks of the effect of a 300% increase in crude oil prices resulting in only a 30% increase in the cost of polythene bags the percentage being progressively reduced through the manufacture of intermediate products including ethylene, polyethylene, and polyethylene fill. The NEDO report (1974 a, p. 9) on the implications of increased energy costs calculates the effect that a rise in oil prices to ten dollars a barrel would have on various products. The processed building materials most affected by the increased oil prices was cement whose cost increased 29.3%. This was followed by bricks (16.5%), iron and steel (12.1%) and finally plastics (11.6%). These results would again show the effect of additional stages lowering the ratio between energy costs and value added.

Moving from material manufacture to the area of fabrication and initial assembly operations where the energy bill is a percentage of
value added is smaller, there still seems to be little connection between the energy intensiveness of the material being fabricated and the value added. For example, in the U.S., the percent of value added allocated to energy in the lumber and wood products industry amounted to 4%, whereas the industries producing rubber and plastic products and those producing fabricated metal products had percentages of roughly 3% and 2% respectively (Campbell, 1965, Table 1-2). The diluting effect of additional activities or production stages is not restricted to material manufacturing, but applies throughout the production sequence. Sanford Rose, in his article on "Consequences of High Priced Oils" (1974, p. 111) uses the apparel industry to show the effect throughout production.

Fortunately the impact of a rise in the cost in energy becomes progressively diluted as we move to higher stages of fabrication. If, for example, the chemical industry spends 20 percent of each sales dollar on energy, and if the cost of crude oil represents one-half the total cost of providing that energy, then a doubling of oil prices would raise the cost of chemicals by 10 percent. In turn, if chemicals in the form of fibres account for 20 percent of the cost of producing fabrics, then fabric cost will rise by only 2 percent (0.20 times 0.10). And if fabrics account for 30 percent of the cost of apparel, then apparel costs would rise by only 0.6 percent (0.30 times 0.02).

Unfortunately, what the above example and the example of the polythene bag really show is not so much the diluting effect of progressive steps on the ratio between processing energy costs and value added but the dilution effect that progressive stages have on raw materials costs. The same effect could be shown with regards to the price of iron ore in relation to a steel column, or raw clay costs in relation to a brick wall, it is only that the raw material for plastics are based on petro-chemicals which can be used equally well as fuel, that they are associated with energy. Even so, the principle of dilution applies to all products whether or not they involve processed, unprocessed, organic
A production activity's direct energy costs (\(E\)) as a portion of value added by that activity.

A production activity's direct energy costs (\(E\)) as a portion of total cost or value added.

Cumulative direct energy costs (\(E\)) as a portion of total costs of value added.

Direct energy costs as a \(\%\) of total costs: Approximate Energy Intensity:

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A production activity's direct energy costs (\(E\)) as a portion of value added by that activity.

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Direct energy costs as a \(\%\) of total costs: Approximate Energy Intensity:

Direct energy costs as a \(\%\) of total costs: Approximate Energy Intensity:

Fig. 432 Relationship between value added, direct energy costs (\(E\)) and energy intensity for various in-place materials.
### Material and Fabrication Costs

#### Table: Material and Fabrication Costs

<table>
<thead>
<tr>
<th>Process</th>
<th>Value Added</th>
<th>Energy Costs</th>
<th>Cumulative Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% of Total Value</td>
<td>£/t</td>
<td>% of Total Value</td>
</tr>
<tr>
<td>Gravel, 20mm crushed, washed and delivered.</td>
<td>N/A</td>
<td>N/A</td>
<td>1.00</td>
</tr>
<tr>
<td>EXTRACTED HARDWARE, using gravel as specified above.</td>
<td>55.5</td>
<td>1.81</td>
<td>53.5</td>
</tr>
<tr>
<td>FABRICATION</td>
<td>100.</td>
<td>3.58</td>
<td>46.5</td>
</tr>
</tbody>
</table>

#### Notes:

1. Final prices or total value added were prepared by Davis, Felsfield & Everest chartered quantity surveyors (Architects Journal, 1973b, p. 1322 & 1326). The values added for on-site work for each material was deduced from the same source by subtracting the final price or measured rate the market price of the material concerned. In the case of steel the value added for extraction (iron ore only), material manufacture and fabrication activities were determined by applying the following price ratio to market price of structural steel: Raw Steel price @ 65.7% of Structural Steel price, Pig Iron @ 4.3%, Beneficiated Ore @ 9.6% and Raw Ore @ 2.2%. These relationships were based on figures assembled by Jack R. Miller of the Battelle Memorial Institute (Alexander, 1967, p.262). Raw materials involved with Cement manufacture were assumed at 20% of the market price for finished cement.

2. The NEDO Report (1972b, p.21) states that the fuel element percentage of delivered price for transporting aggregate is ranging between 4% and 8% and for processing aggregate between 4% and 6%. The value assessed was 5% for transport and 5% for processing. This breakdown was also applied to the extraction of raw materials to produce cement. For on-site fabrication or assembly, the direct energy costs were assumed at 2% of the value added on-site. This percentage was based on the average for industries (Cambel, 1965, TABLE 1-2) primarily involved with producing and processing for final consumption (mostly assembly industries). In steel production the values of direct energy costs to value added for the material manufacture and fabrication stages of production were based on U.S. Department of Commerce statistics (Cambel, 1965, TABLE 1-3) for the 'Steel rolling and finishing' and the 'Blast furnace and steel mill' industries. In processing raw ore direct energy costs were used, based on aggregate figures, and 20% was assumed for beneficiation because of the possible sintering involved.
or inorganic materials. This can be explained in relation to steel (Fig. 4.17). In the energy profiles the highest gains occur on the early stages of production extracting and manufacturing materials. In the price profile, the largest gains take place in the later stages of production effectively diluting the costs incurred in earlier stages.

To illustrate the dilution effect in a construction context, fig. 4.32 has been constructed. It contains four sets of graphs each set showing the relationship between value added and direct energy costs for a particular in place material. The examples have been chosen to represent different degrees of processing and are based on mass alone (1 ton) their performances are in no way comparable. The most elementary material concerned was that of delivered gravel, literally dumped on site. The assumed ratio of fuel cost to delivered price was based on figures from the NEDO report (1974a, tables 3.4 and 3.5) amounted to 5% for both transport and extraction, resulting in a combined ratio of 10%. The next example uses exactly the same assumption as the first, but includes site compaction of the gravel into hard core. This one addition, which is labour but not energy intensive, reduces energy's portion of total value added to just under 6%. The third example uses the same gravel as in the first two but this time as an aggregate to produce one ton of unreinforced concrete mixed and poured on site. Significantly, even with the addition of energy intensive cement the ratio between value added and energy costs amount

\[ \text{Transport fuel element as a percentage of delivered price for aggregate was 4 to 8% whereas for brick it was 3 to 5% and for cement 1 to 3% showing that even in transport the more sophisticated or complex the further along the production sequence the transport takes place the less effect fuel prices have on overall costs.} \]
to just under 10%, less than gravel alone. In place structural steel, a highly processed and energy intensive material provides the last example and actually produces the lowest ratio of the entire group at roughly 5\%\%\%\%. Once again revealing the paradox that while the energy usage as a percentage of material cost for steel is the lowest the total energy content is the highest, with gravel the reverse is true\(^1\).

Is the comparison between gravel and steel fair, after all we have been discussing this whole issue of value added and energy costs on a percentage basis. In absolute terms steel's energy content, the cost of the energy content and the cost of the inplace product simply dwarf those of gravel. The price of energy alone for a ton of structural steel could be in the range of £15 a ton while gravel's total cost amounts to only £1.81 a ton and the portion of that related to energy would be about 18 pence. If the two materials were substitutable for each other, one could see that in a condition of increasing energy prices that it would be years before gravel's total or energy costs would even approach those of steel irrespective of the latter's higher ratio of energy to total value added, making the substitution viable on both energy and economic grounds. Unfortunately, the two materials cannot be substituted for one another, the materials which are suitable for substitution for structural steel i.e. wood and reinforced concrete are already economically competitive so if the price of energy goes up equally among the truly

\(^1\)The NEDO Report (1974a, Table 3.1) on the implications of increased costs of energy confirmed to a large extent this situation. An assumed increase in the cost of oil to ten dollars a barrel resulted in cost increases for "stone, slate, chalk, sand, etc." of 13.8\%, while iron and steel and plastics would have increases of 12.1\% and 11.6\% respectively.
competitive system it will favour the system whose energy cost of value added ratio is lowest and generally speaking these are the more processed and energy intensive systems.

Other Direct and Indirect Factors Affecting the Pricing Mechanism. - There are three more factors which directly affect the relationship between processing energy costs and material prices which benefit the highly processed and energy intensive materials over low energy or unprocessed rivals. The first concerns the areas where future energy savings are likely to occur. As discussed in the last section and shown in Fig. 4.26 extraction and assembly operations will probably increase in energy intensity in the future with reductions in energy intensity through technology, occurring in material manufacture and to some degree fabrication, a situation which definitely favours the highly processed material over an unprocessed material like wood. In other words the unprocessed material misses entirely the area where the most savings are likely and has little opportunity to dilute the increased energy cost likely in extraction.

The second reason for processed materials being favoured deals with the price of energy itself. Energy prices are by no means uniform and differences in them can be related to energy type, i.e. coal, gas, oil or electricity, or different tarriffs within a particular type the rates and amount of change over time can for these two factors vary enormously, (as shown in Fig. 4.36). Processed materials, by the very fact that they usually involve large amounts of energy can benefit from bulk energy tarriffs which are usually reduced as consumption increases. Large plants running on a 24 hour basis can also take advantage of off-peak rates in the case of electricity, and if very large amounts of energy are required
in a particular process the plant location itself will be usually based in relation to a cheap source of energy. Unprocessed materials like wood largely require relatively small scale mechanical operations in their extraction, fabrication and assembly, can benefit little from any of the pricing conditions mentioned above. In fact these operations often use the most costly forms of energy like heavily taxed motor fuels and electricity; and because of the simplicity of being unprocessed cannot easily dilute the higher energy cost incurred.

The final reason that processed materials are likely to be favoured in the future is by far the most important and concerns value added by labour a subject which has only been touched upon so far but whose effect on material choice, especially in construction, is of extreme importance. It is the large disparity between a labourer's energy demand and his wage demand and the relationship between labour, wage and fuel costs which invalidate the argument about the price mechanism leading to large scale substitutions from high energy to low energy systems.

Any significant attempts to change the energy content of current forms of construction through substitution of materials would inevitably lead to the use of unprocessed materials with their corresponding high labour content. Therefore we have to look at the cost relation between accomplishing something by hand as opposed to accomplishing it by machine to see whether this can be done. In order to isolate just these two factors excavating costs, which are not dependent on material costs in any way, are analysed. The cost of machine and hand excavation has been indexed to 1958 and plotted logarithmically in Fig. 4.31 (p. 217) which clearly show the costs for hand excavation have increased more rapidly than that
of machine excavation and the difference is continually widening.\(^1\)

Can we expect this situation to change? A comparison of the labourer's wage rate against various forms of energy over the same period of time and also shown in Fig. 4.31 would suggest that this is unlikely. Labour wages have been increasing at the highest rate and again the difference is widening especially when compared to industrial gas whose price actually decreased. To appreciate the difference in absolute terms that already exists between the cost of energy produced by man and that produced by fossil fuels, it should be pointed out that if a London labourer were to operate a pedal powered generator for ten hours the electricity he would produce would cost roughly £33 per kWh (at 1975 wage rates). The same amount of electricity bought from the generating board at domestic tarriffs (the most expensive form of energy) would be under five pence per kWh.

Future differences in price between labour and commercial sources of energy will surely be detrimental to systems that are labour intensive, which usually are the low energy ones as well (a point which the roofing study should have made clear).

the most ubiquitous energy increase in industrial processes is believed to have occurred via automation - that is, the displacement of labour from the production process. The ratio of production workers' wages to the cost of electricity increased steadily by 225 percent from 1951 to 1969. During that time the wholesale price index for electrical machinery increased by 50 percent. These factors indicate the pressure on the industrial decision makers to eliminate the increasingly expensive worker from the process and to substitute machines, which increase the energy intensity of the process (Hannon, 1973, p. 142).

\(^1\)Recent rates for excavation work (the Architects Journal, 17 March, 1976, p. 556.) show hand excavation to be £4.34 per m\(^3\) or eight times more expensive than mechanical excavation which costs about £0.52 per m\(^3\). In the same set of figures for 20 November, 1974 (AJ, p. 1235) the mechanical excavator exceeded hand by a factor of about 7.
The gap between labour and fuel costs is so fundamental to the western way of life that a significant closing of this gap would likely require change in society as fundamental as that brought about by the introduction of fossil fuels which powered the Industrial Revolution.

Financing and land costs are two indirect factors which are contradictory to the ideas that market forces will lead to lower energy architectural solutions. Both of these items resemble labour in that their effect on overall construction costs bears no relation to their actual energy demands, if they could even be thought of as having energy cost. In the U.K., for example, land represents from 9% to 25% of a new dwelling's total cost (O'Neill, 1974, p. 747); and the increase in land cost can far outstrip those of building materials or labour costs. Between 1967 and 1972, the cost of an average building plot in the U.K. rose by 80% while building materials and earnings rose by 30% and 58% respectively (Buckley, 1972, p. 24); and the differences in the rate of change had very little if anything to do with energy. Land and its development cost together can represent between 30% and 40% of a U.K. dwelling's total cost (O'Neill, 1974, p. 747) but the actual energy cost for such development would be nowhere near this figure. Even though land, by itself has no direct energy demand its price can indirectly increase energy demand. Higher land values especially in urban and commercial contexts, lead to higher buildings, which usually involve more sophisticated materials whose energy requirements are higher. The reciprocal of this situation is to build in an area of low land value, which usually means building on a site further from the centre of town, this then leads to the possibility of using less energy intensive materials but requiring additional energy for site work, infrastructure and transport requirements when the building is completed.
The cost of borrowing or holding capital in relation to stock or plant is another market force which often results in the demand for more energy. Speeding up any operation in order to increase or maximise return on money generally results in additional energy requirements, similar to those already discussed in relation to productivity; although the best example of this condition can be found in the area of haulage which was covered in Appendixes E and G.

![Graph](image)

Fig. 4.33: U.K. Output and money supply. (Money Which?, December 1974, p. 195)

No doubt the pricing mechanism will reflect increases in both labour and energy in the future and prices will rise but it is highly unlikely that this mechanism will lead to substitution of low energy systems for those of higher energy in the conventional construction industry.

The pricing mechanism could in fact produce the absurd result of increasing demand on energy resources rather than conserving them, and producing a vicious circle that already seems to be emerging between rises in energy costs and rises in labour costs. Labour costs rising faster than energy costs result in substitution of more energy to reduce labour this in turn puts more demand on energy resources and their costs go up. Couple this with the achievement curve problem of diminishing returns on energy investments and many like Howard Odum believe does produce a highly inflationary situation. The resolution of this problem seems to lie with one or a combination of the following: stop building, lower standards, or increase the supply (print) of money. Judging from Fig. 4.33 and from recent building statistics Britain has indulged in the first and last choice.
Diminishing Returns of Energy Saving Technology and the Need to Develop End-use Energy Conservation

The efficiency of energy convertors has risen sharply from 1850 to 1950, but from here on improvements will be much harder to win, partly because of thermodynamic limitations...

The above remark by Starr (1971, p. 40) made in his article on "Energy and Power" highlights a more fundamental constraint in reducing the energy consumption in the production sequence, especially in the conversion and fabrication stages through the application of technology. The tapering off of the efficiency of energy convertors is logarithmically shown in Fig. C-1 (duplicate below) which was also adopted from Starr's article.

![Graph showing efficiency of energy convertors over time](Starr, 1971, p.40)
The increases in fuel economy in the generation of electricity gained during the first half of this century represent a typical improvement pattern (Fig. 3.34) for a conversion process - it shows steady initial efficiency gains which gradually diminish as the thermodynamic limits are approached. This pattern conforms closely to Starr's estimate of efficiency improvements. From Fig. 3.34a hypothetical efficiency 'achievement curve' can be constructed (Fig. 4.35). It is evident that energy savings will be harder and harder to win in both capital and energy terms in the future. The relationship between the X and Y co-ordinates on the achievement curve becomes critical when approaching maximum efficiency, at some point in development, net energy savings disappear when the energy required to achieve the efficiency increases (X) are greater than the savings incurred by the increased efficiency itself (Y), regardless of the capital costs involved. When this happens it would be a waste of money, as well as energy to invest in additional efficiencies.

Bearing this in mind let us again consider where the present efforts are being directed in the energy field. As indicated in Fig. 4.27 most
Energy system efficiency of a conventional light bulb, and the effects of improving the efficiency of end-use and intermediate conversion activities (efficiencies from Sunners, 1971, p.151 and Ayres & Scarlott, 1952, Table 7)

Fig. 4.36
financial resources are devoted to finding 'new' sources of energy. Intermediate energy conversions, such as the gasification of coal, or the development of a 'hydrogen economy' also receive attention. The intermediate energy conversion receiving most attention in Britain is in the production of electricity. Increases in efficiency in this area no doubt match those experienced in the U.S., shown in Fig. 4.34. However, in the U.S. and Britain, future gains in efficiency will require increasing amounts of energy and capital to achieve the same results. We are reaching a point of diminishing returns. Ironically, this very fact provides an argument for diverting more resources into this area instead of areas of conservation with greater potential for energy savings. From a rational point of view is this the most logical place to concentrate national financial resources in an attempt to reduce energy consumption? Will this institutionalization of research funds lead to value for money or, more importantly, energy in resolving the overall energy problem, what is the cost effectiveness of continuing present policies?

To bring into question current policies let us take as an example the production of light from an incandescent bulb. Fig. 4.36 indicates graphically the energy conversions likely to occur in producing radiant light from crude oil which has an overall efficiency 1.2%. Represented in tabular form are three hypothetical options which could be pursued for increasing the overall efficiency for the same series of conversions. Option (A), which resembles most closely present day policies, would concentrate all efforts on increasing the efficiency of the intermediate conversions involved in a conventional steam generation plant, and assumes that such effort could double the generation efficiency from 40% to 80% (an assumption which is quite unlikely to ever occur). The
The comparison of Option (A) and (B) points out how misleading efficiencies, when expressed as percentages can be. This confusion can be compounded by the fact that producing various forms of energy, materials or components, rarely involve only one energy conversion or activity, but consist of a series of conversions or activities, each one having an individual efficiency, which when compounded together produce a cumulative overall efficiency of the entire production process considerably below any of the individual convertor efficiencies involved in the production of materials (as shown in Fig. 4.36).
utilization sequence. In the example given this can easily be appreciated by comparing the saving in energy at the point of improvement with the savings in primary energy. Option (A) would save 34.7 units in the intermediate conversion processes related to electrical generation, ultimately saving 42.8 primary units of energy; in Option (B) only 12.5 (end-use) units need to be saved to produce the same results (the saving of 42.8 primary units). Option (C) would save 22.5 (end-use) units of energy. This saving is 12.2 units less than the 'point of improvement' saving gained in Option (A). However, it produces a primary energy savings of 77.1 units which is 34.3 units more than primary energy savings of Option (A). To carry the example to extremes, a savings of one half unit of energy in the extraction of crude oil at the beginning of the total energy conversion system would save one half unit of primary energy, whereas a half unit of energy saved at the end of the total sequence would in this example save 42.8 units of primary energy. The examples provided in Fig. 4.36 emphasize the need to concentrate on end-use energy conservation whether in transportation, industrial, commercial and domestic fields. Unfortunately current interest in the energy question seem to be applied in a completely opposite manner.

A summary of Chapter Four, concerning production energy from primary sources, indicated that there have been historical increases in the amount of production energy used in producing construction materials, as well as shifts in where it is used within the production sequence. It also showed that many technical means exist to reduce production energy requirements and when applied these tend to benefit highly processed energy intensive materials more than the less sophisticated ones. In addition, since production processes are in themselves the end-use of energy, the savings in primary terms could be far greater than the direct energy
savings especially if electrical power is involved. Despite the potential energy savings possible through technology, it was also pointed out in the chapter that major constraints exist which inhibit their realization. The constraints included the lack of interest, even resistance, to energy conservation in general by organizations; pricing mechanisms which actually encourage more energy intensive production methods; and the likelihood of steadily diminishing returns in energy savings of new and more efficient equipment.

Production from Secondary Sources

The application of new technology to the production sequence is not the only way of achieving savings in material or energy. In the example of the light bulb we were looking at the end-use of an energy conversion system only and the effect of saving energy through improved technology. On can easily see that the multiple effect in which 42.8 primary units saved by doubling the efficiency of the bulb would apply equally as well if the light were left on for only half as long. An analogy can be similarly made with respect to the production of materials and components from primary sources; as materials pass through the production system the 'energy investment' in the material accumulates (along with by-products), so that saving a unit of material in the last stages of production would save both the unit of finished material and the accumulated energy, which would otherwise be invested in it in the proceeding stages of production. This idea would also apply to by-product generation. As in the example of the bulb the most effective material saving is at the end of the production sequence. Using less material though in more efficient design would be more effective than improving efficiencies of intermediate production process, though both should be strived for. Of course, doing without the end product is the
ultimate way of saving material and energy. However it is doubtful whether this would be acceptable by society.

Another approach in reducing: 1) the amount of material requiring processing, 2) the amount of by-products generated and 3) the energy involved in the production sequence, would be to base production not on materials from primary sources but those from secondary sources, in other words to use materials or components completely or partially processed by man which have been discarded during production or after their consumption, but which have a certain amount of processing energy invested in them. The following chapter is concerned with production from these secondary sources.
CHAPTER FIVE
PRODUCTION FROM SECONDARY SOURCES

Interest in the environment and ecology over the past decade has produced vast numbers of papers, articles and books related to what could generally be referred to as 'waste management', which includes both control and utilization of wastes. This literature is usually devoted to technical descriptions of specific equipment or procedures or to the description of proven or possible uses of particular wastes or by-products. It is not the intention of this study to go into either of these areas which are adequately covered in reports such as A Survey of the locations disposal and prospective uses of major industrial by-products and waste materials, (Gutt et al, 1974) which is perhaps the most comprehensive document on the subject of both primary and secondary methods of utilizing British by-products in the construction field.

Unfortunately little direct attention has been given to the energy savings possible through the use of secondary materials and components, the intent of this chapter is to investigate these possible energy savings and to establish a framework permitting such an investigation.

1The following are some useful references dealing with the control and utilization of waste from both 'new' and 'old' sources: Bower et al (1968), Department of Environment (DOE, 1972), Secretary of State (1974), OAP Journal (1969), Swartz (1972), U.S. Environmental Protection Agency (1971), U.S. Department of Interior (1971).
Before discussing by-product utilization, material recycling and component re-use, it should be mentioned that often the efforts to find some use for what would otherwise be waste, actually leads to the artificial creation of a demand; in this situation no energy is really saved. It should also be noted that energy savings through the use of secondary products can only be established by knowing the energy costs of alternative methods of production from either primary or other secondary sources; the savings being determined by subtracting the former from the latter, naturally if the former uses more energy than the latter it could not be justified in energy terms, though it could very well be justified on environmental grounds, mainly by reducing both the need to sterilize ground by extractive operations or by the disposal of the by-products or waste themselves.

**Secondary Sources**

In Chapter Four the discussion on energy savings has been restricted to production from primary or natural sources of material. Potential energy savings can be realized through the use of secondary sources of materials or components in the production sequence. However, the type of secondary source and the methods for utilizing them vary enormously, and range from using common industrial by-products such as asphalt from the petroleum industry, to the recycling of refuse.

In discussing the energy implications of such a diverse field we must look at the possible pathways or material flows through the PUD cycle diagramatically shown in Fig. 5.1 and identify general types of secondary products on which we can base a discussion. As mentioned in Chapter One production activities' inputs are \((P_i)\) equal to outputs \((P_o)\) in mass.
Fig. 5.1 Material, component and end product balance and flow diagram.
Production outputs can be divided into the broad categories, primary products be sought in the process \( P_u \) and by-products \( B \). By-products can be further divided into two groups, those which remain in the production sequence where they are utilized \( B_u \) and those which return to the natural environment as waste \( B_w \). By-products can also be classified as non-scrap \( B_n \) or scrap \( B_s \). Scrap refers to materials or substances which are similar to the primary product be produced. Non-scrap is largely generated during extraction, material manufacture or conversion processes and differs substantially from the principle product being sought.

By combining the two by-product classifications, four categories of by-products can be defined. Scrap \( B_u \) and non-scrap \( B_n \) by-products which are utilized and scrap \( B_w \) and non-scrap \( B_n \) by-products which are wasted. The first two represent 'new secondary sources' of materials.  

Like production, de-production also has an input \( D_i \) and output \( D_o \) which are equal. The output can be divided into two general areas, those products which are not re-utilized and become waste \( O_w \) and those which are re-utilized. The products re-utilized in the production

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1 It should be noted that the term utilization has been used in relation to by-products; often the term re-use or recycle is used when discussing by-products, but in this study the prefix re- will be essentially restricted to those products which have been used or 'consumed', in their designed capacity by man. Industrial or production by-products do not fall into this category and are therefore considered as being utilized and not re-utilized.

2 By-products can occur in any state i.e. solid, liquid or gas, but this study will be largely restricted to solids, and their use in relation to construction.
sequence (as well as those wasted) can be broken down into two types; material or old 'scrap' \((O_{rs})\) which is recycled, and components \((O_{rc})\) which have been removed from an assembly and are 're-used' in another assembly or by themselves. Together these represent 'old secondary sources' of material or components. It is the two 'old' sources and two 'new' sources of secondary products which will be discussed in this chapter.

Figure 5.1 also allows for the functional re-use of end products \((O_{rp})\). This type of re-use does not involve production processes and will be dealt with in Chapter Six. The end products re-utilized \((O_{rp})\) combined with the components and materials re-utilized from the deproduction system \((O_{rc} \text{ and } O_{rs})\) make up the total recovered \((O_r)\) which society might otherwise have discarded as 'obsolete'.

**Methods of Utilizing Secondary Sources**

In addition to the analysis of pathways within the PUD system, involving the careful differentiation of secondary sources of material or components which may be re-utilized. An appraisal of energy consumption requires consideration of the methods of utilization or re-utilization which may be involved. It will be necessary to distinguish primary, secondary and tertiary methods, between which there are significant differences in energy consumption.

By combining secondary sources of material components and end products \((B_u \text{ and } O_r)\) with the three methods of utilization produces a matrix of fifteen categories graphically shown in Table 5.1 (fold out, p. 517).
The remainder of this chapter will be divided into sections covering the twelve categories concerning materials and components only. Chapter Six deals with the three methods of using end products. The significant difference between end product re-use and component re-use or material recycling, is that the end product is normally re-utilized in a 'functional' sense, without returning to the production system.

Section One

Primary Utilization of By-Products

By-products are produced incidentally with little by-product planning, quality or subsequent processing or use. Generally, however, they are intentionally produced in integrated processes where they can substitute, save energy produced as co-products and act as co-processing. The last chapter dealt with reducing production loss, the energy that energy produced as co-products and act as co-processing and co-processing and co-products will again be discussed in the next chapter. What effect do by-products have on energy costs of by-products and co-products?

Firstly sharing is the first method and consists of dividing the total energy of a process among all products. Secondly, there are two ways in energy terms. The first method allocates energy costs of by-products and co-products while the latter being more effective. The idea of energy budgeting is fairly new but...
Section One

Primary Utilization of By-Products

By-products are produced incidentally with little or no regard as to quantity, quality or subsequent processing or use. Co-products, on the other hand are intentionally produced in integrated plants with quantity, quality and subsequent use in mind. Co-production was briefly mentioned in the last chapter as a means of reducing production energy. Materials and energy produced as co-products are not, strictly speaking produced from secondary sources; the distinction however between primary co-products and secondary by-products is often difficult to define; because of this co-production and co-products will again be included in this chapter. The consequences of whether a product is produced as a co-product or as a by-product does have an effect on energy costing. There are two ways in which the energy costs of by-products and co-products can be determined. Energy sharing is the first method and consists of dividing or pro-rating the total energy of a process among all products which are effectively utilized. The second method allocates energy costs only to a primary product with the remaining useful by-products or co-products being free in energy terms. The former method is probably more appropriate for co-products while the latter being more appropriate for by-products. The idea of energy budgeting is fairly new and the
costing of by-products and co-products is still very ill-defined. This is especially true of the by-products or co-products in the meat industry as well as the heavy distillers such as tar and pitch from the petrochemical industry. The energy content of organic materials also presents a problem in energy costing. (Currently an inconsistency appears to be developing in the energy budget field with regard to this matter. Products from natural organic materials such as wood, seldom include the calorific value of the material itself whereas synthetic organic materials such as plaster usually do.)

The majority of by-products are generated during the extraction or manufacturing stages of production though some can be generated during fabrication, and most require subsequent processing before becoming useful. The energy costs of this subsequent processing would be handled in the conventional way or as though the product were coming from primary sources. As mentioned earlier, any savings realized through the use of by-products can only be determined by actually comparing the total energy cost required by their utilization with the cost of competing products from either primary or other secondary sources. There are situations where production for by-products could involve more energy than those from primary sources particularly with respect to secondary methods of utilization.

The distinction between primary and secondary methods of by-product utilization can be fine, especially in the case of cellulose based fibres. The criterion on whether a by-product is used in a primary or secondary fashion is based on the quality, refinement, application potential and the amount of processing involved to meet these criteria. Secondary methods usually involve simple cold mechanical processes, with the by-product or waste being selected primarily for its physical or bulk properties which are suitable in a constructional context only. For example, paper produced from cellulose by-products would be an example of primary by-product utilization for the end product is of a high enough quality to be used for many applications outside the constructional field, on the other hand, fibre board being restricted to the constructional field would be considered a secondary method of utilizing such waste even though it is identical in nature to that which produced the paper and the processes involved are similar as well.

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In the construction field the best primary utilization of by-products is in relation to the production of cementitious or matrix materials used in the fabrication of composites; and the discussion of primary product utilization will be largely restricted to those cements based upon calcium compounds and including lime, portland cement, high alumina and calcium sulphates or gypsum cements. Potential energy savings can be realized in three production areas; those of transport, extraction and material manufacturing. The discussion of primary by-product utilization and its effect on energy savings will be based on these three general areas. In principle, if a by-product is effectively utilized

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1 These calcium compound cements can be grouped in categories in a number of ways. In this chapter calcium compound cements will be classified in two ways, the first classification being based on whether a cement is simple or complex, and the second method of classification based on whether it is an active or passive cement. Simple cements are those whose manufacture normally involves only the expulsion of combined water of carbon dioxide from a raw material by the application of heat. Expelling H₂O from hydrous calcium sulphate, usually gypsum, to produce a calcium sulphate cement such as gypsum or Keene's cement; while expelling the CO₂ from calcium carbonate or a mixture of calcium and magnesium carbonate produces a non-hydraulic lime (C₂O). The setting properties of both cements are due to the re-absorption of the compounds expelled to form the original compound from which it was derived. In other words the simple cements are reversible and capable of being recycled, a subject to be discussed later. Complex cements are those whose setting properties are due to the formation of entirely new chemical compounds during manufacture or use; the set cement being different in chemical composition from the raw materials or mix of raw materials from which it is derived. These cements are based largely on calcium silicates and/or aluminates and would include hydraulic limes, natural cements, portland cement and high alumina. Active cements have cementitious values in themselves and can be used alone and can be simple or complex in nature. Passive cements on the other hand are made up in part by natural or artificial materials which have no cementitious values in themselves but when used in conjunction with many of the active cements produce workable cements. Slag and pozzolanic cements are the two types of passive cements. Passive cements are all complex in nature even though many employ a simple cement as the active ingredient; super sulphated and lime pozzolanic cements are examples of this.
energy credit should be allowed for the energy that would have otherwise been required in its disposal and would include mechanical, chemical or thermal operations. Most by-products, however, with potential of being used in the manufacture of cements have little if any treatment before their ultimate disposal; so energy credits will most likely be small or non-existent. This disposal credit is likely to be more significant in the future when the public will demand tighter controls over all forms of waste disposal. Most disposal energy savings would be in the area of transport and here again only marginal energy credits can be expected. Most bulk industrial wastes such as by-product calcium sulphate\(^1\) are either dry-dumped in the immediate vicinity of the plants producing them or are pumped into estuaries or the open sea; either method involves short distances and transport systems having very low energy intensities.

Transport and Extraction Energy Savings Possible From By-Product Utilization

Apart from the slight disposal transport energy credit, the primary utilization of by-products normally offers little if any savings in transport energy over that required for natural materials. If any transport energy savings were to occur, they would likely be in a situation where the by-product constituted a large portion of the final product and was

\(^1\) Calcium sulphates can be used in the production of both simple and complex cements. In Britain by far the largest source of waste calcium sulphate is phosphogypsum, about 2M tons of which are produced annually. This tonnage is equal to about half the total U.K. annual consumption of calcium sulphates currently being supplied from natural deposits of gypsum and anhydrite virtually none of the phosphogypsum being produced in Britain is used, 80% of it being pumped into the sea or estuaries with the remainder being dry-dumped on land. Similarly, 93% of the 80/90 k tons of fluoroanhydrite produced in Britain annually, the next most abundant source of by-product calcium sulphate, is either dry-dumped or pumped to sea (Gutt et al, 1974, chapter 5).
generated in an area closer to the final demand than competitive natural materials. These conditions are more likely to be satisfied when by-products are being used in a secondary fashion as aggregate but could exist in Britain in relation to the primary utilization of those products and would most likely occur with the use of calcium sulphate waste, pulverized fuel ash (PFA) and blast furnace slag in the manufacture of both active and passive cements. On the other hand, the primary utilization of by-products could actually involve more transport energy than that required for raw materials from natural sources. Examples of this would be the use of either waste slate or china clay waste as an argillaceous feed material in the production of portland cement (PC) both by-products being remote from areas of demand as well as being removed from any large source of calcium carbonate which is the main constituent in the manufacture of PC.

An area with more potential for energy savings is in the area of extraction i.e. winning and dressing. The excavation energy costs would be largely eliminated by the use of by-products and reduced in the case of co-products; especially if the deposits of the natural minerals being replaced require blasting and/or overburden removal. The energy costs of dressing could, in some cases, be reduced or eliminated as well. The amount of energy savings depends on the degree of dressing involved, the largest savings occurring with the reduction or elimination of comminution i.e. crush and grind. A good example of this occurs in the production of alpha-hemihydrate gypsum cement using either the Gruline or ICI continuous processes (Gutt et al, 1974, p. 43) which use slurried gypsum as the basic raw material. Natural gypsum must be finely ground and slurried whereas phosphogypsum the most common source of calcium sulphate in Britain, is generated as a slurry and would only require minimal
mechanical treatment. Despite the potential elimination of grinding, the use of slurried calcium sulphate by-products in the production of alpha-hemihydrate is non-existent\(^1\) in Britain, though there is increasing interest in research in this technique.

Since comminution energy depends on the fineness of grinding and the hardness of the material ground, the best example of comminution energy savings would be in the use of pulverized fuel ash (PFA), the ash produced by burning pulverized coal. It is an extremely fine material having a specific surface area of between 2500 and 5000 cm\(^2\)/g which is finer than ordinary portland cement. PFA can be used as either a raw ingredient in the manufacture of portland cement supplying the silica and alumina portions of the raw material usually provided by mud or clay. Since both these materials are soft and could be by-products themselves\(^2\) the savings in comminution energy by the use of PFA would be fairly small. If, however, the argillaceous feed materials were as hard material such as slate the use of PFA should be considered. More significant comminution energy savings can be realized by the use of PFA as a substitute pozzolana, used with PC or lime. Both artificial pozzolanas such as burnt clay and natural pozzolanas such as volcanic ashes from Pozzuoli, Italy, or Trass from the Upper Rhine all require grinding to some degree which could be eliminated through the

\(^1\)The practice of using calcium sulphate by-products in the production of beta-hemihydrate, the most common form of gypsum cement, is also non-existent in Britain since the close down in 1971 of the gypsum plaster and plasterboard plants operated for over 30 years by ICI at Billingham and Severnside.

\(^2\)Cement plants which use chalk and limestones as a source of calcium carbonate often use the quarry overburden, which could be considered a by-product, as a source of argillaceous feed material.
Thermal Processing Energy Savings Possible by the Primary Utilization of By-Products

The transport and extraction operations discussed so far are largely restricted to mechanical operations; the greater scope for energy savings by the primary utilization of by-products is in the area of material manufacturing where thermal energy can be saved. There are three main ways in which thermal energy can be saved by the use of by-products. The first deals with the principle of energy sharing through co-production, the second involves the use of those by-products which intrinsically require less thermal energy and natural materials normally used in their place by containing either less water or less carbon dioxide or both, and the third involves the use of mechanically processed by-products as passive cement in place of thermally processed active ones.

Thermal Energy Savings Through Co-Production

Probably the best example of co-production where energy costs can be prorated on various products, occurs in the distillation processing of fossil fuels. Tar and pitch are both produced as co-products to such refining operations and are the most common cements outside the calcium compound family being used in vast quantities in flexible pavements. Unfortunately these co-products which could have a fairly

\[\text{Transport and balance of payments problems could also be reduced or eliminated by the use of PFA in place of natural pozzolanas for all require importation.}\]
low energy intensity are currently restricted in building to non-structural functions used as a mastic or a coating material, but the use of such co-products as the binder in flexible concrete floors or stabilized soil-cement blocks should be developed to a greater extent.

Another co-product likely to be produced in conjunction with the production of fossil fuels is elemental sulphur. Already about 20% of the world's sulphur production is from the desulphurization of natural gases, and oil. With stricter pollution laws this percentage is bound to increase. Various organizations such as the U.S. Sulphur Institute, the Canadian Government and the Brace Institute at McGill University are investigating various ways of utilizing elemental sulphur in building which so far is undeveloped. Its use as a binder or matrix material is seriously being considered\(^1\). Another attractive feature of using sulphur is the low amount of thermal energy required to recycle it, a subject to be discussed later in the chapter in the section dealing with primary material recycling.

In the British context the use of sulphur on a large scale in the construction industry will most likely remain very limited. Britain has no natural source of elemental sulphur and the domestic production of sulphur from calcium sulphate, once the most common source is disappearing. Britain currently imports most of its sulphur which is

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\(^1\) Other opportunities for using sulphur in construction include its use as a foamed insulation, a protecting and/or structural surface coating and as an impregnant in porous materials. It is claimed (Hornbostal, 1961, p. 504) that pulp and paper articles impregnated with sulphur become very strong, dense, hard and water resistant materials and soft wood impregnated becomes phenomenally hardened "almost as if petrified" and resists insect and bacterial attack. Impregnating hardened portland cement with elemental sulphur, as reported (Thaulow, 1974) has increased the compressive strength by a factor of 2.7. The south west Research Institute has been studying the use of glass fibre impregnated sulphur coatings over mortorless concrete block walls, the result was an impervious wall with the tensile strength across two joints being stronger than a wall made with conventional mortor (Dale, 1965).
produced from both primary and secondary sources; and it is unlikely that sulphur will ever become a co-product of the fossil fuel industry in Britain, for North Sea Oil and gas contains little sulphur and the coal which does contain sulphur is not de-sulphurized before burning. The SO₂ produced from burning such unsulphurized coal is currently being dispersed in the atmosphere through the use of tall flue stacks at power and industrial plants. If the extraction of SO₂ from flue gases were required in the U.K., it would probably be done by scrubbers using pulverized limestone (described in Chapter Four). The resulting by-product of this procedure would not be elemental sulphur but vast amounts of calcium sulphate slurry, which could be utilized as a secondary source of calcium sulphate for the manufacture of calcium compound cements, a subject discussed later in this section.

The energy sharing principle can also be applied to the production of various calcium compound cements. The co-products with the most potential of being produced in conjunction with calcium cements are iron, sulphur oxide and carbon dioxide. Various methods have been proposed for the simultaneous production of iron and high alumina cement (HAC) from iron ore and bauxite, or aluminous iron ore and limestone. Currently HAC is produced in Germany in an ordinary metallurgical blast furnace, the charge consisting of low silica bauxite, limestone and coke together with scrap metal. The slag produced from this furnace has a chemical composition similar to that of HAC and is run off, cooled and ground to cement fineness. The ratio of slag to cast iron for this German plant is about 0.65.

Pig iron and portland cement can also be produced together by the Bassett process which is used in a number of countries outside the U.K.
Limestone, coke and iron ore are burnt in a special rotary kiln, in which a reducing atmosphere is maintained, shaped in such a way as to collect the molten iron on every revolution. The slag produced has the chemical composition of portland cement clinker and only requires grinding to the appropriate fineness.

Sulphuric acid is another co-product currently being produced with portland cement in a combined portland cement/sulphuric acid plant. The process consists of roasting ground calcium sulphate, instead of the usual calcium carbonate, clay and coke to temperatures of between 1200° - 1400°C. At these temperatures the calcium sulphate is reduced to lime which combines with the rest of the charge containing silica, alumina and ferric oxide to form the portland cement clinker which requires the normal grinding. The gases from the kiln are processed for their sulphur content. A plant at Whitehaven, which uses natural anhydrite as a source of calcium sulphate at present is the only remaining combined cement/sulphuric acid plant in the U.K. The chances of more such plants producing only sulphuric acid and cement is unlikely in the future, for the long established practice of extracting the sulphur values from natural calcium sulphates is itself disappearing in the U.K.

1 In principle a lime/sulphuric acid plant could be designed in which lime were produced by burning calcium sulphate instead of the usual limestone or calcium carbonate. It is doubtful that such a plant would save any energy since the temperatures and energy required for the dissociation of SO₃ from the CaSO₄ is higher than that of dissociating carbon dioxide (CO₂) from calcium carbonate (CaCO₃). In addition the calcium sulphate would most likely be a dihydrate (CaSO₄ 2H₂O) or hemihydrate (CaSO₄ ½H₂O) which would require additional energy to drive off the combined H₂O, a subject to be discussed later in this section.

2 Argillaceous by-products could be used instead of natural clay; (Gutt et al, 1974, p. 8), for example, have successfully utilized colliery spoil for this purpose.
Ironically the decline has been brought about in part by the fact that sulphur itself is becoming a co-product or by-product, as discussed earlier.

Expanding the idea of the combined plant further might provide a new opportunity in Britain for providing portland cement as a co-product. The idea would be to combine the cement/sulphuric acid plant with either a hydrofluoric or phosphoric acid plant which produce calcium sulphates as by-products, i.e. phosphogypsum and fluoroanhydrite, which would provide feed materials for the cement/sulphuric acid operation. Most of the sulphuric acid produced would be used in the production of the primary acid, i.e. hydrofloric or phosphoric. Gutt et al (1974, p. 193) describe such an "integrated phosphoric acid/super sulphate/cement/sulphuric acid plant". A plant similar to this description actually exists in South Africa and such totally integrated plants would divide energy costs among even more co-products.

Carbon dioxide (CO₂) is another potential co-product which could be generated in conjunction with those cements produced largely from calcium carbonate (CaCO₃) i.e. limestone, chalk and marble. The complete thermal decomposition of pure CaCO₃ results in a loss of weight amounting to 44% due to evolved CO₂. This loss in weight is called loss on ignition. Thus for every kilogramme of quicklime produced from limestone there is approximately 0.8 kg of CO₂ produced. The CO₂ dissociated from limestone in the manufacture of PC is only about 0.5 kg due to the lower CaCO₃ content in the raw materials. Since most

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1 Even though producing lime from limestone is carried out at lower temperatures, i.e. 1000°C, than those required to produce PC, i.e.
calcareous cements use CaCO\textsubscript{3} as a source of lime, the amount of CO\textsubscript{2} generated annually in the production of such cements is enormous. In the U.S. in 1968, for example, roughly 17 M. tonnes of CO\textsubscript{2} was released from the calcium carbonate used in the manufacture of portland cement alone; none of this CO\textsubscript{2} however was recovered\textsuperscript{1}. The absence of any CO\textsubscript{2} recovery in the cement industry is due to abundance of other sources of CO\textsubscript{2}. It is often found in conjunction with natural gas or as a co-product in ammonia or sodium phosphate plants or as a by-product of the fermentation industry.

Integrating a cement or lime kiln with glass-house agriculture is one possible way of utilizing CO\textsubscript{2} which needs further exploration. The CO\textsubscript{2} contained in the flue gases would be absorbed by the plants and assist in their growth; and if a wet process were utilized in the manufacture of cement the gases would also contain a fair amount of moisture as well and also help in growth. A combination of electrostatic precipitators, cyclone separators, scrubbing towers and bag filters would have to be used to trap the dust contained in the flue gas of cement kilns before

1500°C.; the theoretical energy requirement to produce PC is slightly lower than required to produce an equivalent amount of lime. This apparent contradiction is largely due to the lower carbonate content of the portland cement feed material, which results in both lower calcination energy requirement and less loss on ignition. In practice lime usually requires less energy than portland cement because of the more efficient kilns normally employed.

\textsuperscript{1}One early British PC plant produced CO\textsubscript{2} as a co-product but the practice was abandoned after only a brief period of time. Currently there are plants outside Britain producing lime suitable for building which do recover CO\textsubscript{2} as a co-product, but the practice of CO\textsubscript{2} recovery for use in the chemical process industries is most frequently found in large captive lime plants associated with the alkali and beet sugar industries.
it could be used for such agricultural use. Cleaning the stack gases would remove the pollution potential and dust removed could contain a large percentage of alkali salts, especially potash, a substance which could be used as a fertilizer. There are already some cement plants which recover these alkali salts and sell them as profitable by-products though most flue dust recovered is returned to the kiln. What is particularly attractive about the use of by-product potash is that the crops that have a particular need for potash are those likely to be grown in glass houses i.e. market garden crops, tomatoes, beans and soft fruits such as blackcurrants.

Waste heat is a cement kiln co-product of far more importance than either CO₂ or potash in relation to such an integrated agricultural/cement plant. In 1972 the average U.K. PC kiln used about three times more energy than the theoretical heat requirement, with most of the heat being lost in the stack gases, which even in the most advanced kilns discharge at temperatures of over 150°C. Page (1973) suggests that excess heat, CO₂ and moisture produced in offices and industry be used in conjunction with glass houses to improve crop growth; but does not specifically mention cement manufacturing plants.

Utilizing By-Products which Intrinsically Require Less Thermal Energy To Produce

The second fundamental way of saving thermal processing energy in the manufacture of calcium compound cements is by using those by-products which intrinsically require less thermal energy than those natural materials used in their place by containing either less water or less carbon dioxide or both.
Utilizing By-Products with minimal water content

Using feed materials would be an obvious way of saving thermal energy; an example of this would be the use of dry PFA instead of moist, or clay or mud in the manufacture of PC using the 'dry' process. Using such dry feed material eliminates the energy which would otherwise be required to evaporate the free water. Unfortunately, many by-products are produced in a slurry or precipitated form and could involve additional thermal energy requirements for evaporation of excess moisture. The best example of this is in the use of by-product calcium carbonates as a raw material in the production of either lime or PC. Calcium carbonate is a fairly common by-product being produced in the beet sugar, kraft paper, soda ash, alkali and synthetic ammonium sulphate industries as well as in some sewage and water treatment plants. The carbonates from these industries are usually produced as a sludge or in a precipitated form. Boynton (1966, p. 272) estimates that to produce quick lime from precipitated CaCO$_3$ with a 40% moisture content (fairly typical), 0.75 Kg's of water must be vaporized for Kg of lime produced and the additional fuel requirements would be around 0.49 kwh/Kg which alone corresponds to about 55% of the theoretical heat of calcination.

Far more effective in saving thermal energy would be the choice of by-products containing minimal amounts of combined water. Unlike uncombined or free water, combined water cannot be separated by mechanical means alone nor can it be evaporated at low temperatures. The minimum temperature required being 100°C. or higher. The release of combined water from clay for example, in the production of portland cement only becomes appreciable above 500°C. Even though greater energy savings usually result from using by-products with minimal
amounts of combined water the best by-products from a thermal point of view would be those minimal amounts of both combined and uncombined water.

Calcium sulphate by-products.- the greatest possibility of using by-products containing less or no combined water is found in relation to calcium sulphate by-products. These by-products usually come from one of four sources: the first source would be discarded products made from simple calcium sulphate cements. Obsolete plaster moulds used, for example, by the ceramic industry would provide an almost pure source of gypsum (CaSO$_4$.2H$_2$O). Since this by-product is a dihydrate containing as much combined water as natural gypsum no thermal energy would be saved by its use.

The second source are those calcium sulphate by-products produced from the neutralization of sulphur based compounds with lime. The sludge produced by neutralizing "pickle liquor" from steel fabrication plants with lime is an example of this type of by-product along with the sludges mentioned earlier in relation to the "scrubbers" used to remove sulphur oxides from flue gases. Occasionally the by-product calcium sulphate produced in this fashion can be crystalized as either a hemihydrate (CaSO$_4$.1/2H$_2$O) containing only one fourth as much combined water as the dihydrate form or anhydrite which contains no combined water, but by and large calcium sulphate by-products generated by neutralizing sulphur compounds are dihydrates which again prevents any savings in thermal energy based on lower combined water content. In fact additional thermal energy could well be required by their use in order to remove free water for these by-products are frequently produced as sludges or slurries.
The third source of calcium sulphate is related to the production of hydrofluoric acid, used mostly for metal treatment and by the expanding fluorocarbon industry. The most common method of providing this acid is by reacting fluorspar with sulphuric acid under heat
$(H_2O\text{SO}_4 + CaF_2 = H_2F_2 + CaS_2)$
the resultant being hydrofluoric acid and a by-product anhydrite containing no combined water and referred to as fluoroanhydrite. A dihydrate or fluorogypsum (but not a hemihydrate) can also be produced by the direct hydration of fluoranhydrite.

The fourth source of by-product calcium sulphate (results) when calcium phosphate rock is treated with sulphuric acid to produce phosphoric acid. This acid is used mainly in the manufacture of fertilizer and detergents. The calcium sulphate by-product produced is often described by the prefix "phospho-" and can be crystallized as a dihydrate, hemihydrate or anhydrite, depending on the pressure and temperature of the process used and whether it is a 'dry' or 'wet' process. In Britain only the 'wet' process is utilized and produces about 12m tonnes per year of phosphogypsum, which is more than the U.K. yearly demand for natural calcium sulphates used in the production of both plaster and plaster boards. However, being a dihydrate prevents any opportunity for saving energy on the grounds of lower combined water content. Even though most by-product calcium sulphates are dihydrates, both hemihydrates and anhydrite can be produced as a by-product and their lower combined water content would result in thermal energy savings in the production of calcium compound cements. The amount of energy saved would depend on the crystalline form of the by-product as well as what it was replacing.
Cements produced from calcium sulphates. - As mentioned earlier the, calcium sulphates could be utilized as a raw ingredient in the production of complex cements such as portland cement (PC)\(^1\) and high alumina cement (HAC) preferably in an integrated sulphuric acid/cement plant. Used in this fashion any combined water in the calcium sulphate would be detrimental to energy savings since it is only the calcium and oxide and sulphuric oxides that are being sought. Naturally, replacing dihydrate with a hemihydrate would save the heat which would otherwise be required to drive off 75% of the combined water and the use of anhydrite would save even more energy by eliminating the need to drive off any combined water. In Britain such energy savings are not likely because PC plants which utilize dihydrate as a raw material have closed and the only one remaining, which is also on the verge of closing uses mineral anhydrite as a source of calcium sulphate.

A more appropriate use of by-product hemihydrate and anhydrite would be in relation to any one of the sample calcium sulphate cements\(^2\) which

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\(^1\)By-product calcium sulphate could be utilized as a cement retarder; however, since natural dihydrates or gypsum is quite satisfactory for this use no thermal energy savings can be realized by using by-products. However the use of waste gypsum as a cement retarder in the U.K. could be a good outlet for such waste products. The gypsum required as a PC retarder (740k tonnes in 1970) outstripped the amount of gypsum used in plasterboard (712 k tonnes in 1970).

\(^2\)Calcium sulphate cements usually depend on the partial or complete expulsion of combined water from neutral or by-product hydrous calcium sulphates, in most cases mineral gypsum (CaSO\(_4\).2H\(_2\)O). Heating gypsum at between 150°C. and 180°C. drives off 75% of the combined water to produce a hemihydrate or CaSO\(_4\).1\(_2\)H\(_2\)O usually referred to as plaster of Paris (BS 1911, class A plaster) this type of cement sets too fast for ordinary use and a protein retarder is usually added to produce a retarded hemihydrate (BS 1191, Class B). Both of these cements are "beta-hemihydrates" produced by the direct calcination of gypsum at atmosphere pressure. By converting a dihydrate in to a hemihydrate in the presence of water and various aqueous solutions at carefully controlled temperatures and pressures (usually in an autoclave at a temperature of about 130°C.) produces an alpha-hemihydrate containing large dense and
are almost entirely manufactured from gypsum. The potential energy savings from using waste calcium sulphate as simple cements, or in their manufacture, would be far greater than the use of such by-products as raw material in the manufacture of complex cements, even though lower temperatures are involved and less combined water removed; the reasons for this are that only a fraction of complex cements use calcium sulphate as a raw ingredient (a situation which is unlikely to change because of the abundance of calcium carbonates) and calcium sulphates that are used are already anhydrous.

On a quantity basis the best use of waste calcium sulphates would be in the direct use of by-product hemihydrates as hemihydrate cements eliminating the need to calcinate gypsum. The most likely source of by-product hemihydrate would be related to the production of phosphoric acid from calcium phosphate rock; plants producing such by-product:phospho-hemihydrate instead of the more usual phosphogypsum are non-porous crystals. Being less porous lowers the cement/water ratio and consequently leads to greater density, strength and durability than would be expected from beta-hemihydrates. In Britain alpha-hemihydrates are in limited supply and cost about three times as much as good quality beta-hemihydrate. All water of crystallization is lost when gypsum is heated above 190°C at atmospheric pressure and anhydrite (CaSO₄) is formed calcinating at temperatures between 190°C. and 300°C. produces a soluble anhydrite, the solubility decreasing inversely with calcination temperatures. Anhydrous gypsum plaster (BS 1191, Class C) is based on soluble anhydrite and is usually produced at temperatures between 190°C. and 200°C. This type of cement is very hygroscopic and in absorbing water vapour forms a hemihydrate. Calcinating gypsum or soluble anhydrite over 300°C. produces insoluble anhydrite or deadburn gypsum which sets very slowly and usually has an accelerator incorporated in to it. Keene's cement (BS 1911 Class D) is this type of cement and is produced between 315°C. and 700°C. Calcination at temperatures between 1100°C and 1200°C produces some dissociation into sulphur trioxide (SO₃) and lime (CaO). Calcium sulphates burnt at this temperature produce slow setting product used in Germany and known as Estrich Grips. Calcination temperatures over 1400°C result in the complete dissociation of calcium sulphate into CaO and SO₃.

Phospho-hemihydrate could be considered as co-product if the phosphoric acid plants were designed specifically as integrated plaster/phosphoric acid plants.
becoming more popular throughout the world. In Britain, the direct use of by-product hemihydrates would appear to be practical, barring any impurity problems.

Of course by-product hemi-hydrates would have an energy advantage over gypsum in the production of anhydrite cements, but could not match those resulting from the direct use of by-product anhydrite such as phospho- or fluoro-anhydrites. The latter, to a very limited degree, is already being used in this fashion; about 7% of the fluoroanhydrite produced in Britain is being utilized in the manufacture of 'synthanite' a proprietary binder used in floor screeds. It is surprising that there is not more use made of anhydrite by-products or for that matter mineral anhydrite in relation to anhydrous cements, instead of producing them in the more conventional way from natural gypsum which occasionally involves thermally extravagant methods of calcination.

The use of anhydrite cement in general appears to be under-utilized. From an energy saving point of view its potential of being produced directly as either a by-product or as a natural mineral is totally unexploited. In fact anhydrite cement is unique, being the only one which occurs naturally and requires only mechanical operations in winning and dressing. In addition the performance of anhydrite cement exceeds that of standard hemi-hydrate cements in certain areas. The principle advantage being due to the lower water/cement ratio which results in greater strength and hardness with better resistance to impact and indentations. The use of anhydrite cements in conjunction with

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1For years the method of producing Keene's cement in the U.S. required two kiln operations; natural gypsum being first calcined to a hemihydrate which was soaked in a solution of alum then recalcinated at about 500°.
by-product light weight aggregates could produce interior building units along the lines of wood wool with good thermal performance and very low energy inputs. The use of anhydrite plasters and cements presents a possible energy saving loophole seldom found which should be pursued in both practice and research.

The relatively slow setting properties and low tolerance of impurities appear to be the major obstacles to the wider application of these cements. Hemihydrate cements are capable of being produced from gypsum deposits containing as much as 30% impurities commonly in the form of limestone, dolomite, shale, clay and, ironically, the most common impurity anhydrite. Impurity levels of this magnitude would be quite unacceptable with anhydrous cements. The slow setting could well be more of a deterrent to anhydrate cements than the impurity problem, requiring hours instead of minutes. For site work this slow set could actually be an asset allowing more time to work the plaster to a smooth surface. However this slow set is a liability in the manufacture of plaster board which is replacing most on-site plaster work. To achieve the maximum output of a capital intensive plaster board plant speed is essential and in modern operations an accelerator is actually added to hemi-hydrate cements in order to quicken the set time of the plaster board which is immediately kiln dried. But is such speed really justified? Cox and Goodman (1956, Table I) in their case study on the marketing of house building materials in the U.S. found that 54 days evolved between the extraction of the raw materials involved in its production and the application of gypsum lath. Anhydrite usually involves hours instead of minutes to set but surely the pre-fabricated lath produced with anhydrite, if handled correctly, would be ready for use by the time of application. One must ask, is this speed really worth the
energy subsidy involved? It can no doubt be justified by the conventional accountant but it is clearly another example of the conflict between time/capital and energy, it would also suggest the weakness in the argument that the price mechanism will reduce energy demand discussed in chapter four.

Utilizing By-Products with Minimal Carbon Dioxide Content

By-products which provide non-carbonated sources of calcium would intrinsically require less thermal energy to process into both complex and simple calcium based cements, than if these cements were produced from common calcium carbonate feed materials. By-product calcium oxide (CaO) or lime, is a non-carbonated source of calcium which can be used directly as a simple cement much in the same way as calcium sulphates can be used directly as simple calcium sulphate cements. Non-hydraulic lime does however differ from gypsum cements in that it does not occur naturally in any form. The only significant source of relatively pure by-product lime is carbide lime, a by-product generated in the manufacture of acetylene from calcium carbide and may be in the form of a paste or dried so that it is indistinguishable from normal hydrated lime. Carbide lime is included in BS 890 Building Limes and experience has shown that it is a satisfactory substitute for lime produced in a more conventional fashion, i.e. burning limestone. The thermal energy savings which result by eliminating the calcination would be substantial for even a modern limekiln requires about 1.6 kwh/Kg of lime produced.¹

¹The theoretical net energy required in heating up calcium carbonate and disassociating the CO₂ is about 0.89 kwh/Kg; the most advanced lime kilns upgraded today are German vertical mixed feed kilns which are about 85% efficient and require about 0.97 kwh/Kg of lime.
Non-carbonated sources of calcium oxide would also save energy in the production of most complex cements especially PC. However, the savings would not be as great per unit of cement as those realized through the direct use of the by-product as a simple cement for two reasons; first the lime content of portland cement is lower than that of quick lime i.e. 65% versus 100% consequently less CO₂ would have to be dissociated from the raw materials; and secondly the use of CaO in the production of complex cement would in no way eliminate the high temperature kiln operations which are essential in the formation of the required aluminates and silicates. Even so, the thermal energy savings by the use of CaO as a raw ingredient instead of CaCO₃ would be substantial for dissociation absorbs about 46% of the theoretical amount of heat required in producing 1 kg of cement clinker using dry CaCO₃ and clay as raw materials. The savings would be actually greater since only about 0.65 kg of CaO would have to be heated up to the dissociation temperature of limestone, i.e. 900° to 1100°C., instead of approximately 1.12 Kg of CaCO₃, to produce kg of clinker. Despite these potential savings the use of by-product lime in the manufacture of portland cement is limited, only a few PC plants in Germany¹ use carbide lime at all and then only blended with

¹The use of by-product lime is somewhat limited by its availability, but the technique of using non-by-product lime is gaining some acceptance. One Japanese firm produces PC using two kilns; the first, a vertical kiln, produces quick lime from limestone, which is mixed with silica and alumina and burned in a conventional PC rotary kiln. The firm claims nett savings in fuel, though the figure given (Boynton, 1966, p. 267) of 1200 cal/kg (1.396 kWh/kg) is about the same as would be expected from a more advanced continental cement kiln using CaCO₃ as feed material. Other advantages claimed include: 1) less comminution, the limestone only requiring rough crushing before calcination while the resulting quick lime, being softer than limestone is far easier to grind to the fineness required for good kiln feed, 2) greater cement kiln capacity, due to the low loss of ignition brought about by the use of lime, 3) improved cement quality because of the more gradual formation of crystals. A few West German lime producers have solved the problem of imbalance in demand between the various types of limes by manufacturing portland cement as a co-product mixing the surplus lime with waste clay of shale overburden from the limestone quarries. The advantages claimed are similar to those made by the Japanese firm.
limestone. Its widespread use is limited by the availability of by-product lime.

Another source of uncarbonated calcium is found in blast furnace slag along with other chemical compounds. A typical slag is composed of about 40% CaO, 30% SiO₂ and 18% Al₂O₃, the remaining 12% being various other compounds. This composition bears a strong resemblance to the raw materials necessary in the manufacture of portland cement which is composed of about 65% CaO, 25% SiO₂ and 10% Al₂O₃. The silica and alumina content contained in the slag is usually adequate to satisfy the argillaceous requirements of PC feed materials, but unless the slag is intentionally produced as a co-product cement clinker, as in the Bassett process, the lime content has to be supplemented. Even so producing PC from a combination of slag and limestone would probably require only half as much dissociation in energy as portland cement produced from a limestone and clay mixture. These energy savings would be somewhat offset by either increased comminution energy costs if an air-cooled slag were used or by increased thermal energy costs if granulated slag were used because of its water content.

**Thermal Energy Savings by Utilizing By-Product Passive Cements**

The last technique of reducing the thermal energy intensity of cement is by the use of by-product passive cements which are of two general types: those based on ground granulated blast furnace slag (GGBS) and those based on pozzolanas. In either case the thermal energy savings are indirect, essentially a low energy passive cement replaces a portion of

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¹GGBS is often referred to as a pozzolana, because it can be used in conjunction with lime in portland cement in much the same way as a pozzolana; however GGBS is not a pozzolana and both substances react to free lime in quite different ways.
a higher energy intensity active cement, usually PC. The use of passive cement as a means of reducing the energy intensity of complex cements is probably the most easily implemented; and the use of such cements in Britain has been suggested most often by Gutt (1971 and 1974) and Clayton (1975).

Pozzolana Cements

Pozzolanas are largely silicious materials containing active silica, i.e. amorphous and (generally) hydrated, which in a finely divided form and in the presence of moisture at ordinary temperatures chemically combine with calcium hydroxide used alone or liberated from the hydration of portland cement to form calcium silicates possessing useful cementitious properties. Pozzolanas may occur naturally as volcanic tuffs and pumicites. Artificial pozzolanas can be manufactured from calcinating, between 600°C and 950°C, suitable natural clays or shales, or by-products such as spent oil shale or waste clays.

Artificial pozzolanas can also be produced directly as a by-product and requiring no calcination. The use of this latter type of pozzolanas would obviously save thermal energy, and their use in place of natural pozzolanas more of which are found in Britain, would reduce transport energy requirements as well as eliminating the need for importation. The main pozzolanic by-product of this nature are PFA and powdered ceramics. The use of the latter has been known for centuries, crushed potsherds, tiles and bricks have been found in mortar of the middle Minoan period. Surkli, the waste produced by small scale brick and tile kilns in India is still widely used with lime to produce hydraulic pozzolanic cements in that country.
In Britain the practice of mixing waste ceramics was used by the Romans because of the absence of any natural pozzolanas. They were primarily used to increase the strength and hydraulic properties of building lime, but the substitution of waste ceramics also had the effect of reducing the amount of lime required. One wonders whether the Romans were not also aware of the energy savings resulting from this reduction in lime. It is quite likely that they did, for they were using inefficient batch kilns fired by quantities of timber or peat. Even some of the British batch kilns described by Brunel a century ago required 1.9 tonnes of fir, to produce 1 tonne of quick lime; the volume of this timber would be roughly equivalent to two fir trunks a foot and a half in diameter and thirty feet long.

The practice of using pozzolanic cements died out with the Romans but was re-introduced to Britain in the 16th and 17th centuries with the importation from Holland of mixtures of lime and natural pozzolanic trass from Germany. The use of these natural pozzolanas declined with the introduction and manufacture of 'Roman' cements early in the 19th century and disappeared for all practical purposes with the acceptance of portland cement in the latter parts of the same century.

As the use of natural pozzolanic cements disappeared interest reappeared in the utilization of by-products in the manufacture of passive cements\(^1\). This was mostly brought about by the large amounts of slag and

\(^1\) Calcium compound cements have always been expensive because of the calcination required and the practice of eking out such expensive materials, by diluting them with cheaper materials some of which could be considered by-products, has long been practised. Sand, tile, brick or potters dust, ashes, animal hair, even road scrapings and cow dung have all been incorporated into plaster and mortar cement mixtures. It is doubtful whether these dilutes were intentionally picked because of their cementitious values, an indication of this being the use of crushed brick and tile in gypsum cement where their pozzolanic properties would be of no value.
and pozzolanic by-products such as furnace ash and ceramic dust which were being produced in large quantities as a result of rapid industrialization. But the use of these by-products was very limited, as indicated by the Eleventh edition of the Encyclopaedia Brittanica (Blount, 1911, 'Cement') which describes the use of pozzolanic cements as "of only local importance...largely depending on the nearness and abundance of suitable slags and pozzolanic materials".

The advent of power stations fueled by pulverized coal in Britain has resulted in the production of massive quantities\(^1\) of a pozzolanic by-product in the form of pulverized fuel ash (PFA). Faced with the ever increasing amount of PFA the Central Electricity Generating Board (CEGB) has spent much effort trying to encourage its use as a pozzolanic cement using PC as the active ingredient instead of lime. A proprietary portland pozzolanic cement is made in Britain consisting of a post-kiln mixture of PC and PFA but normally PFA is added to the concrete mix as a separate ingredient. Pozzolanic Limited are now marketing in Britain a high quality PFA under the trade name 'pozzolan' for this purpose.

Slag Cements

 Ground granulated blast furnace slag\(^2\) has no cementitious value

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\(^1\)In 1970/71 about 80% of coal consumed by power stations in the U.K. was pulverized and produced about 9.8 M tonnes of PFA.

\(^2\)Granulated slag is a glassy substance produced by the rapid quenching of molten iron blast furnace slag. Slag cooled in any other fashion would be crystalline and unsuitable as a passive cement, though they would be acceptable as either the raw ingredients in the manufacture of portland cement or as aggregates.
until it is ground into a powder and mixed with an activator. Cements based on GGBS can be classified by the three main activators used:
lime, portland cement and calcium sulphate. Cements based on slags were only developed in the 19th century with the increased production of iron. Initially GGBS was considered a pozzolana and mixtures of it and slaked lime in the proportions of about 75% slag to 25% lime by weight were the earliest slag cements. These were first produced in Germany and their use soon spread to many other countries. Today the use of such cements has practically died out, though in France and Belgium specifications exist for its use as a masonary cement. In Britain this type of cement was referred to as slag cement or 'cold process cement' and it never gained much acceptance; and was already losing its appeal at the beginning of this century.

...Slag cement set slowly, but ultimately contains strengths scarcely inferior to portland cement. Although it is cheap it is suitable for many purposes its use is not large and tends to decrease. (Blount, 1911)

As slag cement based on lime were declining those based on GGBS activated by PC were emerging. The two types currently covered by British Standards are Portland blast furnace cement (BS 148) which

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1. Sodium hydroxide, potassium hydroxide, sodium carbonate, calcium chloride and sodium sulphate can also be used as activators.

2. Standards for Portland blast furnace cements in the U.S. are roughly similar to those of the U.K. Germany specifies two varieties of blast furnace cement, which are fairly representative of the blast furnace cements produced in other European countries. The two cements specified are Eisenportland cement which contains a maximum GGBS content of 40% and Hochofen cement which contains between 41 and 85% GGBS. The use in Europe of portland blast furnace cements appears to be greater than that in either Britain or America. In Russia 15 to 20% GGBS is added to portland cement clinker almost as a matter of course.
contains between 20 and 65% slag but is generally produced with contents of between 30 and 40% and low heat portland blast furnace cement (BS42 46) which has a slag content of between 50 and 90%. Like pozzolanic portland cement clinker before grinding or added to the concrete mix as a dry powder; such a GGBS additive is being marketed in the U.K. under the trade name 'Chemsave'. A more efficient way of making blast furnace cement was developed in Belgium and known as the 'Trief' process. In this process slag is granulated in the normal fashion, then ground wet and stored as a slurry until being mixed with PC and aggregate to form a concrete. The energy savings are due to the elimination of slag drying and better grinding efficiency in a wet state. The latter permits much finer grinding than could be expected from dry grinding using the same amount of energy. With increased surface area good strengths can still be obtained using lower proportions of portland cement. 'Trief' cements produced in Europe usually contain more than 10% slag.

Energy Savings and the Use of Passive Cements

Portland cement can be used in conjunction with either GGBS or PFA\(^1\) to form passive cements and there is some question as to which is the most effective in saving thermal energy. There appears to be no clear cut answer, both having certain trade-offs. The amount of energy saving is dependent on two factors, the energy cost of the passive cement itself and the degree to which it can be substituted for the

\(^1\) A Ternary cement is manufactured in France which contains both GGBS and PFA as well as portland cement whose strength is comparable to that of ordinary portland cement.
active cement, in this case portland cement.

PFA has a distinct advantage over GGBS in the first case, requiring about 0.05 - 0.1 kWh/kg (185-320 MJ/tonne) against 0.2 - 0.3 kWh/kg (740-1100 MJ/tonne) required for GGBS (Clayton, 1975, p. 31); PC by comparison requires 2.1 kWh/kg. This is simply due to the fact that PFA requires no grinding an important factor since PFA and GGBS both require a fineness of between 3000 and 6000 cm²/g (PC is about 2500 cm²/g) before being effective. Even though PFA requires only about a third as much energy to produce than GGBS on average twice as much PC has to be used to activate it. Consequently we might expect a portland blast furnace cement containing 40% of GGBS to have an energy intensity of about 1.36 kWh/kg (assuming an energy intensity of GGBS of 0.25 kWh/kg) while a portland pozzolanic cement containing 20% PFA would have an energy intensity roughly 1.7 kWh/kg ¹ (assuming an energy intensity for PFA of 0.075 kWh/kg). However, the order would be reversed if both cements had a substitution of 50%; in this case the portland blast furnace cement would have an energy intensity of 1.75 kWh/kg ² whereas that for the pozzolanic cement would be about 1.08 kWh/kg.

¹ In 1970 9.9 tonnes of PFA were generated in Britain. If 3.3 M tonnes of this PFA were to have been used as a 20% replacement of the 16.5 M tonnes of PC consumed in Britain that same year, the energy savings would have been equivalent to roughly 0.74 M tonnes of coal, assuming an energy intensity of 0.07 kWh/kg (250 MJ/tonne) for PFA and 2.1 kWh/kg (760 MJ/tonne) for PC (Clayton, 1975, p. 21) and a calorific value of coal of 9.04 kWh/kg.

² In 1970 a portland blast furnace cement of such a percentage could have been produced in a quantity equal to the amount of portland cement consumed in Britain that year if the annual production of blast furnace slag had been granulated and used in the blast furnace cement. If such a substitution had occurred it would have resulted in the energy savings roughly equivalent to 1.85 M tonnes of coal, assuming an energy intensity of GGBS of 0.25 kWh/kg (900 MJ/tonne) and PC at 2.1 kWh/kg (7600 MJ/tonne) and a calorific value of coal at 9.04 kWh/kg.
Of course replacements of this nature are only hypothetical and probably will never be accomplished in practice, but certainly an improvement can be made in the primary utilization of both slag and PFA. In 1970 just over 1% of the blast furnace slag generated in Britain was actually granulated for use in cement. Even worse was the use of PFA of which about 0.6 M tonnes out of the 9.4 M tonnes produced in England and Wales (representing about 6%) was utilized in the manufacture of cement with only about half that amount being used as post-kiln passive cement. Far greater energy savings could be realized by the primary utilization of slag and PFA especially, as passive cements, than by their more conventional secondary use as aggregate, fill and, in the case of slag, road stone and rail ballast. These uses could be easily met by rock or by-products such as waste slate which do not have such unique cementitious properties.

In either case the proper substitution of PFA or GGBS portland cement by no means hinders this performance; in fact, distinct advantages have been claimed by their use including improvement in workability and finish; increases in strength and resistance to chemical attack, and reductions in permeability heat of hydration and cost. Despite these advantages, the idea of substituting PFA or GGBS for portland cement receives cool reception from the cement and concrete association in their report Energy and the Construction Industry.

1 No doubt PFA's pozzolanic properties would benefit in its secondary utilization as an aggregate in concrete, especially in light weight aerated concrete blocks. In 1970 about 67% of the PFA generated in England and Wales was used in a secondary fashion, roughly 50% as fill and 16% as aggregate (Gutt et al, 1974, Table 5). Of the total amount of PFA, 4.8% was used in light weight aerated concrete blocks, which is a good use for it in energy terms because of the insulative properties of such a product.
The partial substitution of PFA or ground blast furnace slag affects the rate of strength gained in concrete. This slower gain in strength seriously affects the economies of concrete construction; in the majority of construction work labour costs and capital investment place a much higher premium on faster gain of strength and the resulting improved utilization of labour and other resources than is ever likely to be regained by the partial substitution of one cheap material for another. (1974, p. 8)

Here again is a classic example of a conflict between money and energy economics discussed in the last chapter and in relation to calcium sulphate cements. In fact this high early strength criteria, to reduce labour and capital expenses is largely responsible for the use of HAC which is causing so much controversy in Britain today. HAC itself is more energy intensive than ordinary portland cement and achieving ultra high early strength from portland cement can only be achieved by additional inputs of energy required for ultra fine grinding.

1 The method of manufacturing HAC is far from standardised and a variety of furnaces are in use. However, in England and France the most common is the open hearth furnace fired with pulverized fuel or oil at between 1550°C and 1600°C. The fuel consumption is about 25% by weight of the cement produced or about 2.03 kWh/kg (Lea, 1970, p. 493) assuming the calorific value of the fuel to be 9.04 kWh/kg. By comparison the energy intensity of a British portland cement kiln is about 1.5 kWh/kg. Grinding energy costs are also higher with respect to HAC. Instead of a clinker, HAC is poured from the furnace and cools into a very hard fused pig which is harder than clinker and requires finer grinding (3000 cm²/g for HAC as opposed to 2250 cm²/g for portland cement). The high temperature and finer grinding have an effect on cost as well, HAC being about three times more expensive than ordinary portland cement and most of it has to be imported.

2 For comparison the specific surface areas in cm²/g for other complex cements are as follows:

- 2250-3200 for OPC and Portland blast furnace cement
- 2300-3000 for HAC
- 2500-3600 for sulphate-resisting PC
- 2800-3600 for low heat PC
- 3250-4200 for rapid and extra rapid hardening PC
- 3500-5000 for super sulphate cement and PFA
- 7000-9000 for ultra high early strength PC (Taylor, 1967, p. 9)
In Britain the slag cement with the lowest PC content is supersulphated cement (BS 4248) which contains between 1 and 5%, the main activator being anhydrous calcium sulphate\(^1\). The minimum slag content is 75% but the usual British proportions are GGBS, 10% anhydrite and 5% portland cement. Supersulphate cement can be substituted in most cases for PC and has a very high performance. It is more workable than portland cement at the same water/cement ratio and is not prone to 'false sets'. Its general performance can even be compared with specialized portland cements; it exceeds the performance of low heat portland cement producing about half as much heat of hydration, its inherent resistance to chemical attack is superior to sulphate resisting portland cements, and its bond tensile and compressive strengths are equal or better than rapid hardening portland cement after only three days. Orchard (1958, p. 61) states that "...if a particularly good slag is available, strengths nearly as high as those of high alumina cement concrete are available from supersulphated cement at both early and greater ages". The principle disadvantages of this cement seem to be the additional grinding needed to obtain the required 3500-5000 cm\(^2\)/g

\(^1\)Another cement closely related to super sulphate slag cement is sulphated HAC, the major product of hydration being calcium sulpho-aluminate for both. They are normally made by grinding or mixing together 20-25% by weight of calcium sulphate with HAC and are mostly produced in the USSR. It is claimed (Robson, 1962, p. 137) that this type of cement is "capable of gaining early strength not much lower than the original HAC and does not suffer the same loss of strength when hardened at high temperatures....while having a lower heat of evolution during hardening....and great immobility". These cements would no doubt be less energy intensive than HAC alone, because the energy required to process the calcium sulphate would be substantially less than that required for HAC, especially if a by-product anhydrite were used. It would appear that, from an energy point of view, these cements should be further investigated. Non shrink or expansive cements are also being developed which are usually based on a mixture of calcium sulphate, HAC and PC though the calcium sulphate content is lower than that of sulphated HAC.
the unsuitability for either lean mixes i.e. those below 1:6, or mixes containing HAC or PC, and the greater curing care required, especially in cold weather to prevent a soft skin or small shrinkage cracks. Considering the number of good qualities exhibited in this cement and the minor nature of the bad ones the use of supersulphated cement seems to be totally underdeveloped; especially when one considers that it is the only high performance cement capable of being produced by cold processes alone and entirely from by-products (PC is not essential in its manufacture and it could be produced entirely from by-product calcium sulphates and slag). It presents perhaps the greatest undeveloped opportunity for saving thermal energy by the primary utilization of by-products in the construction field.

Problems Encountered in the Primary Utilization of By-Products

In summary, the primary utilization of by-products to reduce energy consumption has potential, particularly with respect to reducing thermal energy. Pullitt (1964, p. 31) points out however, "that in fact the use of by-products for the manufacture of portland cement is extremely small compared with that of natural occurring materials." This is also true of other calcium compound cement. This lack of by-product utilization in manufacture is partly an issue of producing by-products in the right quality, quantity and location, which in practice largely determined profitability, and partly an organizational/institutional issue.

The quantity of by-products presents a major problem; and a large mis-match exists between by-product generation and possible primary by-product utilization. The major raw ingredient of calcium compound
cement are those containing calcium with minor demands for argillaceous materials. Unfortunately the by-products actually produced are in opposite quantities, argillaceous by-products being produced in the greatest quantities while calcareous ones are produced in the least quantities. For example, in 1970 total demand for CaO of all calcium compounds cements used in Britain was probably in the neighbourhood of 12 - 14 M tonnes being based mainly on demand for 16.5 M tonnes of portland cement and 2 M tonnes of gypsum plaster and plaster board. It is doubtful whether half this amount was generated in all U.K. by-products. Blast furnace slag which has an average CaO content of about 42% would have provided the largest source of CaO and in 1970 9M tonnes were produced which would have contained about 3.8 M tonnes of CaO far short of that required in the manufacture of portland cement alone.

Even if all the slag that was produced were used in either supersulphated or portland blast furnace cements, maximum replacement of PC would have amounted to about 50%, which is below the theoretical limits of substitution. On the other hand, in 1970 the maximum British demand for argillaceous material in Britain in the manufacture of cements would not have exceeded 6.5 M tonnes \(^1\), and was probably about 4 M tonnes (Gutt et al, 1974, p. 9), while the production of argillaceous by-products in that year amounted to over 83M tonnes and the amount already contained in stock piles amounted to well over 3580 M tonnes \(^2\). Unfortunately, the most

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\(^1\) The maximum use of argillaceous materials that could possibly be expected would have amounted to around 6.5 M tonnes; about 3.3 M tonnes would be required if 20% of the total of 16.5 M tonnes of PC produced in 1970 were replaced by pozzolanas based on argillaceous by-products and 3.2 M tonnes would be required as the sole source of argillaceous feed materials for the manufacture of the remaining 13.2 M tonnes of PC.

\(^2\) Gutt et al (1974, summary table) gives the following 1970 figures on the four major sources of argillaceous by-products in Britain:

1) colliery spoil - annual production 58 M tonnes, stock piled 3000 M tonnes
abundant types of by-products are also those providing the least potential energy savings. As mentioned earlier, the use of most argillaceous by-products as pre-kiln feed materials in the manufacture of complex cement would not likely reduce the energy requirements necessary in extraction, transport or calcination. PFA would be the possible exception and the amount generated in Britain annually exceeds the amount of argillaceous materials which could possibly be utilized in the production of complex cements.

The question of quantity, however, is not restricted to merely matching gross annual production with possible gross demand; the number, size, and output of the plants producing by-products is also an important consideration. The use of PFA as a possible raw ingredient in the manufacture of PC in Britain provides a good illustration of the problems. Associated Portland Cement, the largest producer of PC in Britain went through a plant rationalization programme in the early 1970's which included the building of a new PC plant at North Fleet, Kent designed to replace a number of smaller plants in the Thames area. The plant, operating 6 kilns, has an annual capacity of close to 4 M tonnes. The

(of which 0.6 M tonnes were used for the manufacture of bricks and 0.13 M tonnes used in the manufacture of PC), 2) China clay waste — annual production 22 M tonnes, stock piled 280 M tonnes, 3) slate wastes — annual production 1.2 M tonnes, stock piled over 300 M tonnes, 4) PFA and furnace bottom ash — annual production 9.9 M tonnes, stock piles not known.

Colliery spoils and PFA can contain various amounts of unburnt fuel, which is normally considered an impurity and can affect the performance of any cement produced from it. However under certain conditions the unburnt fuel can also assist in reducing the fuel requirement of a kiln operation, but this feature has more potential in the secondary utilization of such by-products as either artificial aggregates or bricks, where quality control is not so essential but kiln operations are necessary.
argillaceous raw materials required by such a plant would be in the
neighbourhood of 1M tonnes. If PFA were used to supply the raw argil-
laceous materials for this plant it would probably use the entire output
of PFA from all 18 CEGB power stations within Greater London and the
60 miles surrounding it\(^1\). Even the Ferry Bridge Power Station in central
England which produced the largest amount of PFA in Britain in 1970,
generated 0.565 M tonnes of PFA or about half the North Fleet demand
(Gutt et al, 1974, Appendix A)\(^2\). The problem of matching by-product
output with production input seems to be increasing with the progression
towards larger rationalized plants. In Britain the major source of by-
products capable of being used in the manufacture of cement i.e. slag,
PFA and calcium and colliery spoils, are all produced by nationalized
industries which are themselves trying to rationalize production into
bigger units\(^3\); the problem is that the private firms producing cement

\(^1\)These stations produced 1.01 M tonnes of PFA in 1970, averaging
out at 0.056 M tonnes of PFA per plant. Eight power stations produced
less than 0.025 M tonnes of PFA and the two largest stations in the London
area produced 0.21 and 0.18 M tonnes respectively, or about a fifth of
the North Fleet PC plants demand for raw argillaceous materials.

\(^2\)This mix-match problem could be overcome by well planned stock
piling by which a reserve could be built up of enough adequacy to operate
a large scale plant over a limited number of years. An easier solution
to this problem with PFA and slag would be in their use as post-kiln
passive cements instead of pre-kiln feed materials. This is because kiln
or furnace operations usually require very large plants to achieve
ultimate efficiencies, whereas those plants producing passive cement involve
only mechanical operations which can achieve the same sort of efficiency
but at a much smaller scale.

\(^3\)The consequences of a by-product from a remote source are obvious
in energy and economic costs especially with such low value material.
Location though would have less effect on by-products being used in a
primary fashion than they would by those being used in a secondary way.
Even so, transport requirements for slag or PFA will be adversely affected
by rationalizing trends taking place in the industries producing them.
This is especially true of slag which will be located not adjacent to the
market for cement but adjacent instead to deep water.
have rationalized before the nationalized corporations and have rationalized in such a way that their source of raw materials for their new plants are based on primary or natural sources and not secondary ones.

Another problem affecting the possibility of by-product utilization is institutional in nature. The CEGB, for example has a Charter that does not allow them to operate any commercial enterprises other than generating electricity. The quantity, quality and subsequent use of by-products or possible co-products such as PFA and waste heat are therefore only secondary considerations when compared to that of generating electricity, despite the fact that the CEGB actively pursues customers for its PFA. Likewise the National Coal Board is concentrating all its efforts on fuels alone and is selling off the brick and cement works which were previously operated by former private coal mining firms in all probability British Steel will be closing down the small iron plants which are currently producing cement as a co-product¹. These mono-product corporations tend to sacrifice the use of by-products in an effort to maximise the efficiency of the prime product with little consideration as to the quality or quantity of the by-products being produced; and they largely depend on private firms to utilize these by-products. However firms who could utilize these by-products in a primary fashion would be very hard to establish because they would have no control over their major sources of raw materials; consequently, if by-products such as PFA or slag are utilized at all they are utilized in a secondary way as bulk material because this method of utilization requires far less capital intensive equipment and quality control.

¹This trend also seems to be appearing in relation to cements in private industry as well. ICI for example, has shut down the plants which produced PC and plaster from by-product calcium sulphates.
Section Two

Secondary Utilization of By-Products

In the secondary utilization both non scrap and scrap by-products, the materials are utilized basically for their physical properties for structural and non structural purposes. Non structural secondary utilization of by-products would include their use as abrasives, filter mediums and loose insulation. However, secondary utilization of by-products in a structural sense is far more common and the discussion will be limited to this aspect. Indeed, secondary utilization of by-products is almost restricted to basic construction materials. Because of this, it is particularly relevant to architects and engineers, who should not only be aware of this type of by-product utilization but should actively pursue its use on ecological, energy and quite often conventional economic grounds.

The suggestions for using by-products in a secondary fashion for structural purposes are numerous. Unfortunately, the proliferation of

1 For elaboration on this subject one should refer to Bridger and Sellick-Smith (1973), in their thesis "waste not", which concentrates on secondary methods of by-product utilization in the construction field, (although referring to it as material recycling).
ideas stem mainly from the question of "what can we do with this or that waste by-product?" and not with the question of "whether such use would save energy".

The structural secondary utilization of by-products fall into two main categories. The first is the indiscriminate use of by-products as fill. This method of secondary by-product utilization offers the greatest scope for absorbing by-product tonnage but offers the least scope for saving energy. The second category involves the use of by-products as aggregates or simple building units. This method of utilization offers far more potential for energy savings and consequently the following discussion will concentrate on this area.

For the purposes of discussion the by-products utilized as constructional bulk materials will be divided into three broad groups:

1) unprocessed by-products, i.e. those requiring only mechanical operations,
2) processed by-products, i.e. those requiring mechanical and thermal operations,
3) scrap by-products.

Unprocessed By-Products

The successful use of by-products as aggregate depends on a number of factors such as the matrix or binder used; as well as the density, strengths and the size of the end product required. The energy intensity of the composite which uses an unprocessed by-product as an aggregate is not determined so much by the aggregate as by the binder or glue used and the heat required in its fabrication. The fact that the by-products we
are speaking of are unprocessed and require only mechanical operation means that they are likely to have very low energy intensities, but the same can be said for the natural aggregates for which they are being substituted; so the source and nature of the natural aggregate or fill is vital before any kind of energy savings can be determined.

Natural inorganic aggregates such as sand and river gravel, in which nature had done the work of crushing and sorting, require very small amounts of energy in the extraction, so it is doubtful whether or not, by-product utilization would require any less energy (especially if the by-products require less dressing) even if extraction energy costs could be allocated to the primary product. On the other hand, if the natural sources had to be blasted and crushed the use of by-products would clearly be favoured on energy grounds.

Transport energy requirements are always critical when considering bulk aggregates from either primary or secondary sources because of the sheer weight involved. Even in conventional costing, locational considerations are vital because of the low value of the material and high cost of transport. It is the relationship between the by-products point of generation and its final use that has greatly reduced its attractiveness as a means of saving energy.

Inorganic Extractive by-products.- recollecting the by-product 'profile' (Fig.41) we can see that most of the inorganic solid by-products are produced during the extractive operations, i.e. winning and dressing. Since the location of extractive operations producing most of the solid by-products are based on geological considerations and not on the final demand of the material or its by-products, areas of greatest by-product
generation are frequently the areas of least demand, and transport
costs could offset any energy savings incurred by their use.

This dislocation factor between generation areas and demand is
getting progressively worse; small extractive operations scattered about
the country are being replaced by fewer and larger operations. In
addition, as the grade of ore lowers, the by-products increase, while
the most logical demand i.e. the extractive industry and its supporting
community, is getting smaller because of mechanization. In fact, in
Britain, history indicates that most ores that have historically been
extracted domestically are being increasingly imported from abroad,
making secondary use of inorganic by-products impractical, though
plenty of bings from previous industrial periods remain to be tapped.

Inorganic conversion by-products.- Solid inorganic by-products produced
from conversion operations (particularly ashes and slags) have a great
deal more potential for secondary utilization as heavy aggregates or fill
than those inorganic by-products produced from extraction activities.
Conversion activities are much more likely to be nearer population and
demand; this is especially true in Britain whose present demography
stems largely from the development of metal production, the industry
which produces slag. Power stations and incinerators by their very
nature are fairly close to population centres making their ash readily
available for secondary utilization in geographical terms. Because
conversion by-products are produced closer to the public there is also a
greater likelihood that more stringent disposal measures would be
required than for those involved with extractive by-products, and when
dealing with unprocessed bulk materials such as slag and ash, the energy
costs of disposal need to be considered; if this type of by-product is
utilized an allowance should be made for the disposal operations eliminated by their use. Winning and some dressing energy costs would also be eliminated by their use; thus it is quite likely that some energy could be saved by the substitution of slag and ashes for natural aggregates and fill.

Special mention should be made of clinker or furnace bottom ash. This is the only major by-product from a conversion operation which produces a lightweight aggregate (820-1000 kg/m³) without special cooling techniques or high temperature roasting, and it has been used in the production of concrete blocks since the turn of the century. If clinker is considered free in energy terms it could easily compete with natural lightweight aggregates that do not require heat treatment such as pumice; and clinker would also require far less transport than these since they are imported. Ironically, the switch to pulverized fuel and oil in power stations in Britain has eliminated the principle source of clinker and in the South East of England this shortage has been solved largely by importing pumice. Clinker would also involve much less energy than those processed (manufactured) lightweight aggregates from natural sources and most by-products, with the possible exception of foam slag and fuel bearing colliery spoils or PFA. Unfortunately clinker is the heaviest of the lightweight aggregates and due to the impurities which are normally found in it it is restricted only to use in unreinforced concrete.

Organic By-Products.— Agriculture is an extractive industry which generates vast amounts of cellulose based by-products which can be utilized in a secondary fashion. By their very nature, agricultural by-products are not nearly so concentrated as those involved with mining
and quarrying operations. Thatch is an excellent historical example of a secondary utilization of an agricultural by-product in which a dispersed demand and a dispersed source were matched on a small scale. This situation was effectively destroyed in the industrial revolution and the development of the city, but it points out the current problem of utilizing agricultural by-products arising from the conflict where conventional economics have demanded large specialized production units fed by large concentrated sources of materials, while agricultural plants need vast areas to utilize dispersed solar energy. In addition the type of agricultural by-product may change over time, even with a limited area, due to a change in the primary crops in response to market conditions.

Despite these problems the secondary use of extractive organic by-products from agriculture is possible; for example 'Strawit' a building board made from straw is already produced in Britain, along with others. It is easy to see that these could be attractive in energy terms, especially when agricultural by-products, are often self building; and because of their natural cellular structure they have good insulation properties which could save operating energy.

Forestry is another extractive industry producing vast amounts of organic by-products; indeed only 18% to 20% of the tree by weight is used in the final product (Hughes and Jones, 1975, p. 707). Since forestry tends to be a more integrated industry than agriculture and the distinction between product and by-product tenuous, secondary utilization of its by-products is becoming common practice, as is seen in chip- and fibre-boards of various densities. As far as energy saving is concerned they, like agricultural by-products, are quite attractive, often
requiring no energy intensive binders and having good insulation properties, but for energy accounting costs they should be probably considered as co-products in which energy costs are pro-rated, rather than as true by-products, in which energy costs could be considered free.

It should be mentioned that the organic by-products produced by forestry or agriculture do not present the same type of environmental problem as those of the inorganic type for they are already dispersed over a large area and more importantly they are biodegradeable (unfortunately this feature is also the primary problem encountered with the products produced from them).

**Processed By-Products**

Inorganic extractive by-products such as slate waste and colliery spoil can be processed, usually through the application of high temperatures i.e. above 1000°C., into dense 'synthetic' aggregates or bricks or into expanded light weight aggregates. Because of the high temperatures involved in the processing, transport and extractive energy became relatively insignificant, unlike the unprocessed bulk by-products discussed above; therefore, if any energy savings are to be realized, one has to compare the processed by-product with similar materials produced from primary sources.

**Processed Extractive By-Products**— Manufactured dense aggregates produced from extractive by-products, could well involve the consumption of more energy than comparable natural aggregates and should be considered only if they are self fueling or truly superior in performance. In the case of producing bricks from extractive by-products, it is also very unlikely
that any energy savings would be realized over bricks produced from primary sources unless it contains natural fuel as in the case of some colliery spoils. Similarly there is little likelihood of energy savings in producing light-weight aggregates from extractive by-products instead of from primary sources. For example, 'Solite' produced from slate waste requires roughly the same amount of energy as comparable light-weight aggregates produced from natural shale or clay such as 'Leca'. On the other hand, 'Aglite', which is produced from colliery spoils is largely self-sufficient in fuel and could be competitive in energy terms with pumice and clinker. Organic fibrous by-products from forestry and agriculture can be processed by chemical and mechanical pulping into light-weight,(i.e. insulation board,) or dense products,(i.e. fibre boards) with energy savings similar to those already discussed in relation to chip and straw boards.

Processed Conversion By-Products.- Inorganic by-products such as slags and ash from conversion operations can be processed by grinding the by-product into granules, mixing them with other constituents, and firing them at high temperatures, to produce bricks or synthetic dense aggregates but like those manufactured aggregates produced from inorganic extractive by-products it is doubtful whether energy savings can be realized over similar products from natural sources. This would also be true for the recent methods of processing slags, clinkers and ashes into 'castable' or glass ceramics which have the potential of being fabricated

1 'Glass ceramics' regardless of the source of raw materials, have so far only been commercially applied to kitchen ware and table ware by U.S., Japanese and West German manufacturers. The Soviet Union, however, is producing building units from glass ceramics produced from slags.
into fibres or wools, dense building units of foamed blocks.

The best secondary use of processed by-products conversion activity lies in the area of providing high quality light weight aggregates, which become even more important with increasing thermal insulation standards. 'Terlite' and 'Lytag' are both trade names for light weight aggregates produced by pelletizing PFA and heating it rapidly to 1200°C. Because the fly ash contains a fair portion of unburnt coal very little additional fuel is required for this procedure, making it competitive in energy terms to those light weight aggregates produced from both clinker or those aggregates produced from fuel bearing clays.

Blast furnace slag is the other major conversion by-product from which light weight aggregates are manufactured. With respect to energy the process is even more attractive than that of roasted pulverized fuel ash (PFA) described above. It is the only major by-product generated from a conversion operation which can actively utilize the high temperatures involved in producing the primary product from which it is derived; unlike any of the other synthetic processed aggregates which require heating or re-heating to achieve their desired light weight properties. Slag comes from the furnace at about 1500°C. and; if allowed to cool naturally produces an unprocessed heavy aggregate (already mentioned). If, however, the molten slag is quenched with water, steam is trapped inside the slag which expands to produce a foamed slag.

1 Clinker is also a light weight synthetic aggregate, but it should not be considered as being manufactured or processed, for its properties are both unintentional and uncontrollable.
Work on lightweight concretes in general carried out at BRE, has shown that with most aggregates the thermal conductivity is unaffected by the amount of aeration, given constant density and moisture content. However with foamed blast furnace slag aggregate, the concrete has a lower thermal conductivity (75% that of the others). In addition by modifying the foaming process it is possible to produce a foamed aggregate with extremely low densities (approaching 100 kg/m$^3$) making it the only inorganic by-product capable of reaching the ultra light weight aggregate densities (0-300 kg/m$^3$). In the case of ultra light weight aggregates, foam slag has a very pronounced energy advantage over the two major ultra light weight aggregates produced from primary sources, those being Exfoliated Vermiculite and Expanded Perlite (which require 1200°C and 1800°C. to produce respectively). Transport energy savings could also be significant as well, since vermiculite is imported from South African and Perlite from the U.S.

### Scrap By-Products

So far the by-products we have been discussing come from extraction and conversion operations and differ from the materials being sought. 'New' scrap by-products are similar to the materials being produced and can be divided into two types - home scrap consisting of scraps generated during material manufacturing operations and 'prompt' industrial scrap which is generated during fabrication or assembly operations.

New thermoplastic scrap (metal, glass, thermo-plastic plastic) and paper scrap is not likely to be recycled in a secondary fashion at all. This type of scrap being normally utilized in a primary fashion by
remelting or re-pulping. In fact, from an energy point of view, secondary utilization of such scrap would be unwise, for so much more energy could be saved from its primary utilization than from its secondary use, a subject which will be discussed in a later section.

On the other hand concrete and ceramic materials so closely associated with the construction industry lend themselves to secondary utilization since their very nature prohibits primary utilization. Wood scraps, even though capable of being pulped and used in a primary fashion also fall into this category.

The actual energy saving likely to occur by the secondary use of such materials would on the whole be similar to those realized through the secondary utilization of non-scrap by-products. The discussion here is not one of possible energy savings but of the generation patterns of these construction materials and the difficulties of trying to use them in a secondary fashion.

The type, location and size of the activities producing new-scrap by-products has a great affect on the potential for secondary utilization. Generally speaking, if a by-product profile were made, the generation of new scrap would start gradually in material manufacturing activities; reach a peak in the fabrication stages of production and, with the possible exception of the construction industry, gradually diminish through the assembly operations. Kneese, Ayres and D'arge (1972, p. 56) when discussing residuals from the production of wood based products, point out this scrap generation pattern and go on to suggest that even though scrap production is highest during fabrication, the actual waste by-products are lowest at this point because of the large scale and
Sawmills, plywood plants, and veneering plants do not contribute large amounts of processing waste, but there are substantial residuals in the form of sawdust, chips and scraps. Again, in large, efficient integrated plants most of the material can be utilized either as "pressed wood" [secondary utilization] or as chemical raw materials [tertiary utilization] or as inputs to pulp and paper manufacture [primary utilization]...in smaller local sawmills the residuals are disposed of or simply burnt (and not utilizing the heat). At every stage in the utilization of wood products - notably in furniture manufacture and construction - there is a substantial wastage, the amount tending to increase inversely to the size of the operation [emphasis mine]. Thus, residential and commercial construction is a major source of residuals; subsequent demolition also contributes substantial quantities.

(Kneese, Ayres and D'arge, 1972, p. 56)

Evidence bears this out; the construction industry, whose fabrication and assembly work has to be comparatively small for the very fact that it takes place on site, does produce large quantities of scrap as Skoyles (1974) in his report on Wastage of Materials on Building sites clearly illustrates. The report showed that scrap was by no means limited to timber; on the seventy two building sites investigated, it was found that the average wastage amounted to 10% for carcassing, second fixings and walling materials, and 15% for boarding materials. Concrete blocks had wastage rates in some cases as high as 20%. It is not likely that these scrap by-products will be utilized by any method. Specialization and plant size economies have totally separated material manufacture and fabrication from assembly, and transport which would be required to return construction by-products back into the production system would be prohibitive in conventional and energy costs, especially

Laverick (1974, p. 81) mentions a Royal Institute of Public Administration report on the industrial wastes in the Manchester/Salford area which found that the "brick and building" industry produced 16 tons of refuse per employee per year, the highest amount of any of the major industrial groups included in the report. The second highest was the heavy chemical industry. Unfortunately, it is impossible to distinguish which portion of the by-product were from construction activities and which portion from the production of the construction materials themselves.
when one considers that construction scrap is mostly non-thermoplastic, would probably be utilized in secondary manner as unprocessed bulk materials, which require little energy in the first place.

This situation would suggest the encouragement of more pre-fabrication in the building field and many advocates of pre-fabrication or system-building have justified it on the grounds of reduced wastage. Pre-fabrication might curb the problem but it by no means eliminates it, as Dunung's (1972) article "A Study of Wastes in Industrialized Building Systems" clearly illustrates. In fact the scrap produced from pre-fabricated reinforced concrete units is likely to be much more difficult to utilize than on-site broken brick or blocks, being a complex composit of great weight and size.

The proposition that the potential to utilize by-products varies inversely with the size of the operation is probably true in a highly industrialized nation\(^1\), but is it really an issue of sheer size or is it one of physical and organization separation brought about by the use of highly specialized, capital-- and energy--intensive machinery, which itself justified the increase in size?

Examining earlier methods of construction one wonders whether the on-site scrap problem ever occurred at all. The 'scrap' stone from the mason, for example, was automatically incorporated as rubble in the

\(^{1}\text{It should be emphasized that the potential for utilizing by-products is probably higher with large operations rather than smaller ones, but bigness alone by no means guarantees the utilization of by-products. Laverick (1974, p. 78) in discussing a report from the Royal Institute of Public Administration on industrial wastes for the Manchester area mentioned that "the survey showed most of the waste as produced by a few large firms (i.e. employing over 500 staff) and, in general, larger firms produced disproportionately more industrial waste."}
middle of the stone wall, (secondary utilization of a by-product) and surely wood scraps were used as fuel (tertiary by-product utilization) and not left on site\(^1\). This utilization had nothing to do with the scale of the operation, it had to do with such things as the limited number of products, the total knowledge of their potential uses, man's dexterity, the small geographical areas involved in the generation and use of by-products and the lack of organizational barriers. A craftsman was far more attached and responsible for his particular material\(^2\).

The generation of scrap was dispersed and small, but so was the demand, the two could easily be conceived and matched.

Today total specialization exists at every stage of the production process. The physical and organizational distances between the areas producing by-products, the areas capable of utilizing them, and the final areas of demand seem to be continually increasing, thus making by-product utilization, especially those from construction, more difficult on a commercial basis. By-products can be matched up to production requirements but only at large scale because of the current degree of specialization.

\(^1\)Knoop and Jones (1933, p. 54) specifically refer to the revenue received from the sale of bark and "lop and crop" from felled trees, required in connection with building work carried out on Eton College in the fifteenth century and recorded as "foreign receipts" in the College's 'Compotus Rolls'. Innocent (1971, p. 102) mentions also the common practice during the sixteenth and seventeenth centuries of using bark from timber production in the tanning of leather, another example of tertiary reuse.

\(^2\)A craftsman's responsibility spread over a much greater portion of the production system than his counterpart today. In relation to wood Salzman (1967, p. 32) mentions that "speaking generally, every type of [medieval] wood craft from felling timber to making tile-pins was done by the carpenter"; and Bowyer (1973, p. 79) mentions in relation to brick that in the "late sixteenth century brick layers organised themselves into Tyler's and Brickmaker's Companies; most of whose members produced and laid their own bricks"; Innocent (1971, p. 120) mentions in relation to stone that "stone, for earlier wall and foundations were obtained by breaking up boulders on the surface, masons usually being quarrymen and wallers, the two trades not being separated".
### Section Three

**Tertiary Utilization of By-Products**

In the tertiary utilization of by-products, the by-products are utilized for their chemical properties and used in one of three general ways:

1. **By-products utilized as an intermediate substance requiring substantial processing before emerging as a constituent part of a processed material**, e.g. natural cellulose by-products used as feed materials in the production of synthetic plastics.

2. **By-products utilized as an intermediate substance in a production process which does not appear in the final product**, e.g. by-product iron used for the chemical recovery of copper.

3. **By-products utilized as food or fuel.**

Because of the total nature of the by-product being changed by tertiary utilization the distinction between scrap and non-scrap can be largely ignored. In addition, the methods of by-product utilization have little direct application to construction per se, consequently the following discussion will be based on natural organic by-products since they provide the greatest opportunities for utilization, especially
Changes in the Methods of By-Product Utilization

A very brief historical perspective of the changes between primary, secondary and tertiary methods of by-product utilization which can occur, is given in a report prepared by the National Industrial Pollution Control Council (NIPCC, 1971, p. 7) concerning wood based by-products in the U.S.:

The story of anti-pollution effects is inseparably related to the [forest products] industry's capability to utilize its own waste products in some fashion. In the late nineteenth century, mill trimmings and sawdust were in wide demand as domestic and commercial heating fuel; this demand declined when coal and oil came into favour. [Tertiary utilization].

Before 1900, sawmills began using the heat resulting from the burning of mill residue to drive machinery and generate electrical energy. Well into the twentieth century, mill generators provided electrical energy for hundreds of lumber communities.

About 1920, the industry began to develop methods of taking the log apart and putting it back together again in various forms. Plywood and laminated lumber were followed by hardboard and particle board which enabled the industry to utilize all low grade logs formerly left in the woods as well

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1. Because of the chemical composition of natural organic by-products the potential for their tertiary utilization is great. The methods can be grouped into the following broad categories:
   1) utilization through hydrolysis and/or fermentation to produce sugar, organic acids, polyals, yeast and protein.
   2) utilization through pyrolysis to produce charcoal, distillates and gas.
   3) utilization through hydrogeneration to produce char and oils.
   4) utilization through combustion to produce work, heat and ash.
   5) utilization through biological oxidation to produce humus and compost.

Animal by-products can also be rendered into glue, soap, fertilizer, oils and fats.
as coarse manufacturing residues [Secondary utilization].

The expanding pulp and paper industry at the same time began to find value in sawmill residues. Enterprising operators erected pulp mills adjacent to lumber and plywood plants where they found a ready source of raw materials for pulp digestors [Primary utilization]. With advancing technology, particularly since World War II, paper makers have been able to use fine residues\(^1\) from both lumber and plywood mills in significant volumes.

The swing from small scale tertiary methods of utilization, to secondary and then to primary and secondary methods brought about through large scale integrated production units can clearly be seen. Recently, with the increase in fossil fuel prices, there has been pressure in the U.S. paper industry (who already meet 37% of their energy requirements by burning their flammable wastes) and in the British chipboard manufacturing industry (who also generates steam from wood waste) to increase tertiary utilization of their by-product as fuel at the expense of primary and secondary methods.

More appropriate to Britain are the various methods of using cellulose based agricultural by-products in particular straw. Traditionally straw was an agricultural by-product which created little if any problem; indeed, on small mixed farms, it was considered an asset, some being used in a secondary fashion as thatch or earth walls but most being used as a matter of course in a tertiary fashion as feed in cattle production. Here is a case of very small operational units dispersed over large areas producing and utilizing by-products, again showing that size alone has

\(^1\)The use of such residues must be put into perspective. In Oregon, for example, in 1953 only about 6% of the sawmill residues were used in the manufacture of paper and composition board, but this increased rapidly to 60% in 1967 (NIPCC, 1971, p. 74).
little to do with whether a by-product is utilized or not. As in early forms of construction, it was the lack of specialization and the knowledge of the product that made the use of straw an accepted practice.

Gradually the situation changed, farming units became specialized. Farms in East England for example, have largely abandoned dairying and cattle rearing to concentrate on mechanized barley and wheat production, making straw, previously a useful by-product, into a useless one; currently burning is the fastest way of getting rid of it, costing much less than baling and carting straws to regions which can use it. Again this is not an issue of scale it is one of specialisation and simplification of the production unit itself. Recently, due to the increase cost of feed, interest is again being revived in the utilization of straw.

Choice of By-Product Utilization

So which method of utilization would be most appropriate in the future for a by-product such as straw? Producing paper from it, an example of primary utilization, would reduce the balance of payments problem in Britain, but it would probably require almost as much energy as producing paper from any other sources. Using it in a secondary fashion to produce building boards would save energy if it were used in place of synthetic organic materials and most of the processed inorganic materials. However, it might be more appropriate to use inorganic by-products for such secondary uses, for they have few opportunities of being utilized at all outside the constructional field and are not susceptible to vermin and rats.
From a strictly energy point of view, and if material sequential recycling is not considered the obvious choice would be tertiary utilization — using the organic by-product as a fuel. Conventional combustion, however, might not be the most effective way to utilize it; improving its digestibility and using it as cattle feed replacing high energy intensive grain could be a better method. In the future a micro-biological route from cellulose to ethanol or methanal, while producing protein at the same time, would be an even better method. These products could be utilized on the farm where the by-product is generated, thus saving transport energy as well.

But is the choice between methods of utilization that critical at present? Surely the selection of method would be only a relevant problem if all the straw or other organic by-products produced were, in fact, utilized by any method. Presently by-products are not being fully utilized; in the case of straw for example, it has been estimated that in Britain alone, farmers burn off between 2 and 5 million tons of straw each year, the energy released exceeding the total put into British agriculture from petroleum sources in a year (Heslop-Harrison, 1975, p. 266); and wastages of this magnitude are by no means restricted to straw.

1 If sequential recycling (a subject discussed later in this chapter in the section on tertiary recycling) is considered the type of by-product utilization most appropriate would probably be secondary. This method usually results in the minimum material degradation which is essential in realizing the full potential of sequential recycling.
Section Four

Primary Utilization of Scrap

Primary scrap utilization only applies to manufactured or processed new materials which are repulpable or thermoplastic in nature and include paper, glass, all common metals and their alloys, most common plastics. Being processed this scrap is fairly refined and already has a substantial amount of energy invested in it, and to dispose of such high quality scrap would be ridiculous in energy terms, for the amount of energy to re-melt or re-pulp would be far less than that to produce the same quantity from primary sources.

The obvious or primary method of utilizing this type of new scrap is by recirculating it within its own material production system. This is standard practice in industry today and is commonly referred to as recycling, no distinction being made as to the origin of scrap, i.e. 'old'.

1. The more common thermoplastics include: polythene, polypropylene, polymethyl methacrylate, polystyrene, nylon and derivatives of polyvinyl and cellulose.

2. The savings in energy occur largely because of the reduction in winning and dressing as well as in basic conversion operations. These savings by using secondary sources of metals should increase proportionally to the decrease in ore grade.
<table>
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<th>Processing energy required from primary sources</th>
<th>Units from secondary sources</th>
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</table>

Fig. 5.2 Variations in energy intensities of a thermoplastic material due to differences in the utilization of 'new' and 'old' scrap (processing energies are those for iron taken from Bravard et al., 1972, Table 1)
or 'new'. Technically the procedures are similar but new scrap has in no way benefitted society and is merely an industrial by-product. It is quite understandable why manufacturers of thermoplastic materials tend not to stress the difference of scrap type. To give the impression that their operations are "environmentally sound", the manufacturers naturally want to emphasise the proportion of this product which is already produced from "recycled" materials, with the implication that the more recycled, the more efficient the operation. In actuality this would only apply to old scrap, in the case of new scrap recycled the reverse would be true, the portion of new scrap being inversely proportional to the overall efficiency of the production process, assuming the new scrap is recirculated, which it is to a large degree (usually exceeding 85%). The percentage of total production that is 'recycled' new scrap for six common materials is shown as a percentage mix in Fig. 5.5 (p. 308). The proportion varies from about 40% for iron and steel to about 10% for plastics and glass. The proportion of new scrap appears to be largely based on the fabrication techniques currently employed for each material; a low proportion of new scrap is produced by the more efficient chipless methods (i.e. casting and moulding), common to glass and plastic fabrication, and a high proportion of new scrap is produced by materials requiring chip cutting as in the case of steel.

The energy consequences of new scrap generation and the portion of it recirculated is illustrated in Fig. 5.2 representing six hypothetical material flow patterns. Material flows (A) through (C)

1 The energy calculations associated with the various flow patterns illustrated are based on energy figures for iron produced from primary and secondary sources as calculated by Bravard et al (1972, Table I). The flow patterns and energy calculations in Fig. 5.2 are much simpler than those found in actual practice. New scrap is seldom handled separately but
clearly show that if new scrap is produced the more that is recycled, the more the energy cost per unit of production and consumption. Flows (C) and (D) indicate that if the same proportion of scrap is recirculated (in these examples 100%) the system producing less scrap has a lower per unit of consumption energy cost, whereas the system producing more scrap has a lower unit of production energy cost. In a scrapless production system, pattern (E) this paradox is carried to extremes. It has the lowest energy cost per unit of consumption, while at the same time having the highest energy cost per unit of production, of the first five examples. Flow pattern (F) indicates a closed and balanced material flow system in which production, consumption and scrap generation are all equal. In energy terms this is by far the best solution with respect to both production and consumption unit energy costs. Pattern (F) is the ultimate example of the primary recycling of obsolete scrap which is the next category to be discussed.

is used as a constituent feed material in conversion and alloying operations. A good example of this occurs in the glass industry where up to 30% of the furnace feed is coloured the addition of which greatly reduces the energy requirements of producing glass from primary sources by improving the heat conduction through the otherwise low heat conducting powdered raw materials within the furnace. Obsolete scrap also normally requires more energy to recycle than new scrap because of the additional sorting, dressing and transport operations required, even so, the principles developed in Fig. 5.2 are still valid.

Attention must be paid when estimating material energy costs, particularly when using the statistical method, to the new scrap and wastage involved in the production sequence. Using crude production figures instead of the actual materials consumed or used could lead to artificially low energy intensities. For example, if the brick industry produced and reported one million bricks and consumed one million units of energy, the energy intensity would be one unit of energy per brick, but if the construction industry could only effectively utilize 0.8 million (a wastage rate of 20%, which is not uncommon) the actual energy intensity would be 1.25 units per brick and not 1 unit per brick.
Section Five

Primary Recycling

Earlier sections have dealt with opportunities for utilizing "new" scrap and non-scrap by-products arising in the production of new materials. Remaining sections of this chapter are concerned with the recycling of materials or the re-use of components which have already fulfilled some function but which are to be rejected as 'old' or obsolete. Consideration must be given to the possibility of extending the usefulness of such materials or components by exploiting their material properties or adapting the form of components to new uses.

As with the discussion of "new" by-products, the purpose is to identify factors which must influence decisions on the nature of recycling or re-use, and in particular to emphasise the importance of energy conservation.

Considering first the primary re-cycling of materials it is clear that the critical property of suitable materials is that they are thermoplastics (or re-pulpable in the case of paper). Obviously when discussing primary recycling the energy that is required to melt various thermoplastics should be known. The energy required is dependent on the melting temperature, specific heat capacity and the latent heat of
Figs.
5.3
5.4
5.5
fusion in the case of crystalline solids. These factors have been used to calculate the energy required by more common thermoplastics on a unit of mass (kg) and volume (dm³) basis. The results are compared in graphical form in Fig. 5.3.

On a unit of mass basis glass would require the most energy with aluminium and steel next in order both requiring about the same amount of energy; followed by copper, polystyrene and sulphur. On a unit of volume basis the order is somewhat changed with glass and aluminium requiring about half the amount of energy to remelt than either steel or copper; but plastic and sulphur still requiring the least amount of remelting energy. Because of the low amount of energy required to remelt sulphur, on both a unit of mass or unit of volume basis, its potential for recycling with respect to energy appears good. This low remelt energy requirement plus sulphur's potential to be produced as a by-product or co-product, with corresponding low energy intensities, should provide justification for its development as a matrix or material in the construction field.

In reality, the energy costs to recycle thermoplastics are much greater than those shown in Fig. 5.3. The actual energy required to recycle steel, aluminium, copper, glass, plastic and paper are indicated by the hatched areas in Fig. 5.4. A comparison of this graph with Fig. 5.3 indicates that on a per unit of volume basis; theoretical and actual recycling energies fall into the same general order even though

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1 Aluminium and copper alloys usually have slightly lower melting temperatures than their elemental form; and the melting point of an amorphous material such as glass does not necessarily have to be reached in order to reshape them.

2 The other common thermoplastics fall roughly into the same energy range.
the actual energy costs are much higher. However, on a unit of mass basis, there is a marked switch in the ordering between steel and glass, steel requiring the most recycling energy instead of glass; the recycling energy costs of glass being roughly comparable with those of aluminium and copper.

Differences in Energy Costs Between Producing a Material from Primary and Secondary Sources

The difference in energy costs between producing a thermoplastic from secondary sources by recycling instead of producing them from primary sources is more important than the recycling costs alone. Since recycling thermoplastics is often done in conjunction with primary production, the amount of energy saved by recycling a given percentage of production is directly proportional to the difference in the energy cost of producing the material from primary and secondary sources.

The energy savings possible through recycling have been investigated by various researchers. Bravard et al (1972) calculates the energy cost of producing magnesium, aluminium, iron, copper and titanium from both primary and secondary sources in the U.S. Chapman (1973b) does the same in a U.K. context for aluminium and copper; while Berry (1972) and Berry and Fels (1973), discuss the energy saving implications of recycling metals used in the automobile production system. Berry and Makino (1974) also investigate the possible energy savings by recycling steel, aluminium, plastic, paper board and glass with relation to the packaging industry.

The energy costs to produce from primary and secondary sources the materials which are commonly recycled are shown in Fig. 5.4. The difference
between these energy costs are also expressed on a percentage basis and as a ratio. On a percentage basis there are great variations between the materials, ranging from a 96% energy saving in the case of aluminium and plastics down to 0% for glass. Expressed as a ratio, this would mean the amount of energy to produce one unit of aluminium from primary sources would required about 28 times more energy than that required to produce it from secondary sources. Glass on the other hand would require equal amounts of energy whether being produced from primary or secondary sources.

The percentage of energy saved by recycling can bear little relation to the actual energy saved in absolute terms. Obviously the potential for absolute savings would be greater for materials requiring higher energy costs to produce from primary sources. This can be seen by comparing paper and steel. Both of these materials have similar recycling energy saving percentages (about 50%) but recycling steel instead of producing it from primary sources results in an energy saving of 7.7 kWh/kg\(^1\), while recycling paper results in a saving of only 1 kWh/kg. Despite this difference the general order of absolute energy savings (aluminium being the highest followed by copper, steel, paper and glass) corresponds to the order of energy savings expressed as a percentage or ratio (with the exception of plastics). Material energy intensities (from

\(^1\) The difference between recycling energy costs and primary energy costs for metals could increase in the future with the development of direct hot rolling or compaction of scrap metal into finished shapes, thus eliminating the energy intensive re-melt operation. The United States Steel Corporation and General Motors in a joint research effort have reportedly developed a process whereby quality hot rolled steel products can be made directly from scrap iron (Polt, 1970, p. 5) and the NATO report on the technology of efficient energy utilization (Kovach, 1973, p. 33) also suggested the development of scrap recycling processes which by-pass the re-melting stage, for example the direct compaction of turnings into reinforcement bars.
primary sources) also follows the same general order.

With respect to energy one would hope to find that the material systems with the greatest potential for energy savings through recycling would also be the material systems with the highest percentage of absolute scrap recycled. Unfortunately a review of Fig. 5.5 reveals this only to be true in the extreme cases of aluminium and glass and the difference in the amounts of obsolete scrap actually recycled (20% for aluminium versus 2-3% for glass) is nowhere near the energy saving percentages brought about by recycling (98% for aluminium versus 0% for glass). Between these extremes there is little correlation between the percentages, for example, plastic with a percentage energy saving 96%, the second highest of the group has the lowest percentage of obsolete scrap recycled. This lack of correlation raises the whole question of the flow pattern of materials within their PUD material system.

Material Flow Patterns and Their Effect on Energy Costs

When discussing primary recycling and its energy consequence, one needs to study the flow patterns of material within their particular system. Meadows and Randers (1972, p. 20) in their excellent article on "The dynamics of solid waste" point out that:

To speak precisely about controlling the flow of materials from resource to waste we need a quantitative expression for its magnitude in tons/year. If we call the number of products in use $P$, and the average lifetime of the products (i.e. the number of years it is used) $L$, the number of products discarded per year is $P/L$; and if the average amount of waste from each product is $W$, the solid-waste generation rate is $PW/L$ in a steady state.

From this equation we can see that the amount discarded is inversely proportional to the life of the product, the shorter the life
Material flow patterns

NOTES
- All examples (A–P) assume a net stock gain (S_i) of 1 unit.
- Assumed energy intensity (kWh/kg) for processing from:
  - Primary sources (E_{p0}) = 5.21
  - Secondary sources (E_{s0}) = 1.84 (except for P)

- Total energy costs to produce a net stock gain of 1:
  - Energy costs = (P_p x E_{p0}) + (P_s x E_{s0})
  - The formulae used in (E, P and P') only apply if:
    - Material efficiency is less in period 'A' than period 'B'
    - E_{p0} is less than E_{p0}

- Total processing energy costs to produce a net stock gain of 1:
  - Energy costs = (P_p x E_{p0}) + (P_s x E_{s0})

- The selection factor (m^) for (E, P and P') is
  - Secondary to primary energy ratio (m^) for (E and P)
    - m^ = E_{p0} / E_{s0} = 5.21 / 1.84 = 2.83
    - Selection factor = (m^ x E_{s0} / m^ - 1) / m^ = (1 x 2.83) / 2 = 1
  - Energy costs = 1 x 1.84 = 1.84

- Assume recycling energy increased from 1.84 to 3 kWh/kg
  - Secondary to primary energy ratio (m^) for (E and P')
    - m^ = E_{p0} / E_{s0} = 5.21 / 3 = 1.74
    - Energy costs = 1 x 3 = 3

<table>
<thead>
<tr>
<th>Material flow patterns</th>
<th>Total processing energy costs to produce a net stock gain of 1 (kWh)</th>
<th>Units of primary source (P_p)</th>
<th>Units of recycled source (P_s)</th>
<th>Units of material recycled (P_r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>Energy costs = 2 x 5.21 = 10.41</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b)</td>
<td>Energy costs = (1.5 x 5.21) + (0.5 x 1.84) = 8.74</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(c)</td>
<td>Energy costs = (1 x 5.21) + (1 x 1.84) = 7.05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(d)</td>
<td>Energy costs = 1 x 5.21 = 5.21</td>
<td></td>
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</tbody>
</table>

Assume a technical efficiency factor (m^) of 2 for (E, P, P') i.e. 1 unit produced in period 'B' performs the same function as 2 units of material from period 'A'.

<table>
<thead>
<tr>
<th>Material flow patterns</th>
<th>Total processing energy costs to produce a net stock gain of 1 (kWh)</th>
<th>Units of primary source (P_p)</th>
<th>Units of recycled source (P_s)</th>
<th>Units of material recycled (P_r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E)</td>
<td>Energy costs = 1 x 5.21 = 5.21</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Assume a secondary to primary energy ratio (m^) of 2.83 which is more than m^ of (2) therefore recycling requires less energy, i.e. 1.84 vs 2.6

Energy costs = 1 x 1.84 = 1.84

Selection factor (m^) for (E, P and P')

Secondary to primary energy ratio (m^) for (E and P)

Assume recycling energy increased from 1.84 to 3 kWh/kg

Fig. 5.6 Variations in the energy required to increase a hypothetical material stock by one unit, between two periods of time, for various material flow patterns.
the more is discarded; but the more that is discarded the greater the potential for recycling. Examining Fig. 5.5 bears this out; glass, plastic and paper have the highest proportion of obsolete scrap, and it is these materials that are commonly used in short life non-durable products particularly packaging.

The inverse relationship between a product's useful life and its potential to be recycled, coupled with the primary/secondary energy cost relationship, produces an interesting choice of production strategies. To meet the same demand, one can either produce a shorter life product which could contain a higher proportion of low energy recycled materials or produce less, longer life products which contain more higher energy materials produced from primary sources.

To illustrate this and the general effects that recycling has on energy costs within a materials system Fig. 5.6 which consists of a series of flow diagrams has been produced. This figure resembles in many respects Fig. 5.2 which was related to the primary utilization of scrap by-products. The six hypothetical material flow patterns all indicate the same increase in material stock from two units in a time period A to three units in a time period B. Flow pattern (A) shows the situation where one unit from period A becomes obsolete and is discarded as waste, the net gain in this example being produced entirely from primary sources. The situation represented in (B), which is perhaps the closest example to the "real world" is basically the same as (A) except that a portion of the obsolete material is recycled. Pattern (C) is the same again except all of the obsolete material is recycled, and (D) indicates a situation where the net gain is provided solely from primary sources with none of the original stock being discarded or recycled.
The simple energy calculations (Based on Bravard et al, 1972 figures for iron) of each of these flow patterns indicates energy requirements descending in the same order as they are presented. It clearly shows that, if material does become obsolete, the more of it recycled the lower the overall energy requirements will be. However, the system which has no obsolescence and hence no recycling potential demands the lowest energy requirement of all.

Returning to the two options mentioned earlier we can see that the longer life approach should result in lower energy costs, especially when one considers that in the short life, high recycling option a high percentage of recycling is mandatory to achieve low energy demands. In reality, the short life option would lead to a situation similar to example (A) where short life has been achieved but virtually no recycling. The plastic material systems are a good example of this happening today, and are wasteful in both energy and material terms.

It is worth considering the energy consequences of the proposition that man can extend his resources by continually recycling material, every cycle incorporating a new and more efficient technology which would permit the use of less material to accomplish the same general tasks. This idea of doing more with less, normally in a structural sense, is associated mostly with Buckminster Fuller. If energy is considered a resource, it could be argued that to "do more with less" in a material sense might not be so in an energy sense, even if one were to assume that all material becoming obsolete was recycled and that a more efficient technology had been developed. (E) and (F) in Fig. 5.6 and the accompanying calculations illustrate this point.
The determination as to whether or not energy would be saved by such recycling is dependent on two factors; the first is the improvement in technical efficiency within a particular time frame. This technical improvement factor \(m_i\) \((E)\) and \((F)\) is assumed to be two; in other words one new unit at period 'B' using new technology would have the same performance as two units of material using the earlier technology of period 'A'. The second factor to consider is the ratio between the energy required to recycle a materials and to produce it from natural sources which can also be expressed as a multiple \(m_e\). Aluminium for example had an \(m_e\) ratio of 28; in other words, 28 units of aluminium could be produced from recycling the same amount of energy as one unit could be produced from primary sources.

By knowing both the nett increase in stock \((S_i)\) in period 'A' units and the technical improvement factor \((M_i)\) the amount of material required from primary sources \((Pp)\) can be calculated by the formula \(S_i / M_i\), assuming there is no recycling. Likewise the amount of recycled obsolete scrap required \((Ors)\) could be calculated by the forumula \(Ors = (S_i \times \frac{m_i}{m_i - 1})\cdot m_i\) assuming that all production is from obsolete or secondary sources without any wastage. Dividing \(Ors\) by \(Pp\) provides a factor \(m_{es}\) which, when compared to the \(m_e\) factor, can establish whether recycling a particular material at higher material efficiency uses more or less energy than would otherwise be required if the original material were to have been left in its less efficient form and if the net increases in material were provided from primary sources alone. If \(m_{es}\) is greater than \(m_{es}\), energy would be saved by recycling, if however \(m_{es}\) is less than \(m_{es}\) more energy would be required.

In flow patterns (E) and (F) (Fig. 5.6) the \(m_i\) factor was
assumed to be 2 which resulted in a $m_{es}$ of 2. The example also
assumed an energy intensity for recycled material at 1.84 kWh/kg and
5.21 kWh/kg for materials from primary sources (figures for iron from
Bravard et al, 1972, table 1) which produces an $m_e$ of 2.83 which is
greater than $m_{es}$ so recycling should in principle save energy. In
this case increasing stock by one unit from primary sources using
improved technology (in a material performance sense) would require
2.6 units of energy while $m_e$ 1.84 unit of energy would be required if
material were removed from the system and recycled with an increased
material performance. Suppose, however, as in example (F1) that both the
energy to produce the material from primary sources and the technical
improvement factor ($m_i$) (and consequently the $m_{es}$) remained the same
as those presented in (E) and (F), but the energy required to recycle
was increased from 1.84 kWh/kg to 2 kWh/kg. In this situation the $m_e$
would amount to 1.74, which is lower than the $m_{es}$ of 2, indicating that
more energy would be required to increase stock by applying
improved technology to recycled material (3 units of energy) than if the
stock were increased from primary sources (2.6 units of energy) using
the same improvements in technology.

Of course this is a greatly simplified model, but we can see
that, if production and recycling energy costs are not considered,
increasing technical efficiency ($m_i$) would lower the selection factor
($m_{es}$) thus increasing the opportunity of saving energy through recycling.
But increasing the $m_i$ is very likely to be offset by a corresponding
increase in the $m_e$. This is due to the fact that increasing the
performance of a material usually means the use of additional heat
treatments or more specialized and sophisticated materials (particularly
composites and alloys which would require more energy to manufacture and
Kiessling (1974, p. 113) in an article about the future of steel points out the current and future trends likely to occur in material systems:

The producer is no longer the only one who designs the steel and puts it on the market. But it is the customer who wants to have more and more say about the materials he intends to use for different application... the change has been accelerated by the nuclear and aero space industries with their specific material requirements... but big material consuming industries like transportation, ship building; and even household appliances have followed the trend... steel has to become more versatile - we already see many examples of the new way of designing with this material, in for example, polymer coated steel for building, composite steel products, improved alloys such as stainless/carbon steels and steel fibre composites.

Kenannan (1972, p. 8) speaks of the consequences of these trends:

Each year, vast tonnages of prime metals and alloys are trapped in discarded manufactured products. Many of the ever increasing variety of alloys that end up as scrap continue to accumulate in junk piles for lack of extractive methods to separate and reclaim the valuable metals they contain. This problem is compounded by the irony that many of these alloys - some of which are in critical supply - were developed to resist just such conditions as are used by the extractive metallurgist in making separations to recover them.

He also goes on to suggest (p. 9) that more use of pyro- and hydro-metallurgical methods will have to be adopted in the future to separate such sophisticated metals along with the mechanical methods already used today in recycling as well as in the preparation of virgin ores. The energy to recycle will undoubtedly go up as a result of these additional efforts, reducing the potential of saving energy through recycling. If the energy costs of producing a particular material from primary sources remains the same or increases because of a lower grade ore, the effect of the increase in recycling energy would not be as critical as if the primary energy costs were to decline. Unfortunately, in the near future the difference between recycling energy costs and those
involved in producing materials from primary sources is likely to increase. Using British steel manufacturing as an example, the steady substitution of higher grade foreign ores and integrated plants will reduce primary energy costs while those involved in recycling will either remain the same or increase. These trends will effectively reduce the amount of energy savings which can be realized through recycling.

So far the discussion on recycling and material flow patterns technical improvements has been based on the assumption that when materials are recycled in products would be used in much more efficient ways; this is by no means always true, but even if it were, doubling the efficiency would progressively produce diminishing material savings. The other assumption, which is of far more importance is that all materials would be recycled, which is certainly not the case in practice.

Problems Encountered in Primary Recycling

The factors which prevent obsolete scrap being recycled more effectively are numerous but can be generally grouped into legal, economic, organization or technical, i.e. quality, quantity and location. Of course these are often inter-related and legal, organizational and technical factors can frequently be translated, either directly or indirectly into economic terms which ultimately affect the viability of recycling.

Legal and Economic

Legal discrimination against recycling usually involves restrictive local zoning or licensing requirements on scrap processing plants. These restrictions are common in most developed nations and
Levy (1969, p. 705) describes these problems in a U.K. context while Bengston and Regan (1972) refer to them occurring in the U.S. From an economic standpoint recycling should be encouraged in Great Britain on the balance of payments issue alone. However, current economic factors are mostly detrimental to recycling. Scrap price fluctuations, for example, are even more violent than those witnessed with natural raw materials. This makes any capital investment on scrap processing equipment extremely risky and most governments are not willing to guarantee minimum prices as they often do with respect to agricultural products. The only way to encourage obsolete scrap recycling is by either increasing the cost of producing materials from primary sources, or reducing the cost of recycling, or both. Meadows and Randers (1972, p. 28) mention that:

numerous authorities have stressed the immediate importance of initiating or increasing recycling efforts and there have been suggestions as to how one should go about it...but in principle all the different proposals reduce to one question: do we wish to enhance recycling by subsidies or discourage extraction by taxes?

Presently the opposite is happening. Three economic policies commonly discriminate against the recycling of both 'old' and 'new' scrap:

1) Fiscal measures may, for example, permit depletion allowances on exploration and extractive operations, while denying such allowances on material processing.

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1 It is estimated that the annual import bill to Britain could have been cut in 1974 by £500 million if paper, metals, glass and plastics had been recycled. Recycled paper alone would have saved £200 million (Jerman, 1974, p. 5). This is extraordinary when one considers that historically paper was almost exclusively produced from secondary sources; as pointed out in the Encyclopaedia Brittanica "Paper was made in Europe until the middle 19th century almost entirely from rags, either linen or cotton" (Fisher, 1911).
2) Development or research grants are often given to the extractive industries, but these are denied to the secondary material industries.

3) Freight rate structures which favour ore over scrap.

An economic factor which is not often discussed in relation to recycling but which could have far more effect on recycling is the failure of the market-orientated economy to deal adequately with external or non market costs, Victor (1972b) and Barkely and Seckler (1972) discuss the 'externality factor' and trace many of the most common environmental problems to it. Simply stated, the payment made for an item does not cover all the cost of producing and disposing of it. Costs can be eliminated by releasing by-products or the obsolete products themselves on land or in the atmosphere or in bodies of water which are communal in nature. If the cost of pollution suffered by the community could be effectively passed on to the consumer by regulatory intervention (i.e. taxes, subsidies, laws or regulations), recycling would immediately become more economical.

**Technical and Organizational Factors**

Scrap quantity, quality and location are technical factors which have a great effect on recycling opportunities. As with most secondary material sources, matching up supply and demand is not restricted to quantity alone but also relates to location and quality, and, generally speaking, the mis-match in all these areas is steadily increasing irrespective of material. The organizations which generate, handle and consume scrap also have great effect on recycling opportunities.

An examination of Fig. 5.5 reveals that the amount of obsolete scrap generated of a particular material, fails short of the amount
consumed of that same material. One would expect this because of the amount of new material going into stock. However, the amount of obsolete scrap generated far exceeds the amount which is actually recycled. The problem appears not to be one of supply but one of industrial demand. Plant capacity within a particular country might not be large enough to handle all the scrap available, especially when the country is a net importer of the material being considered for recycling. In Britain this happens with respect to paper, which is imported on a large scale and has a short in-use life. The capacity of Britain's paper plants is less than the amount of scrap generated, so 100% recycling within Britain is impossible and the situation is not likely to change quickly.

The effort to increase overall plant capacity on the other hand, by no means guarantees a corresponding increase in the recycling capacity. British Steel's current efforts are a case in point. The ability to accept scrap is decreasing because of a change in technology and scale. The switch in technology from open hearth furnaces capable of a scrap charge of 40%, to the basic oxygen furnace capable of a 30% scrap charge has the effect of reducing scrap demand. Economy of scale has encouraged the use of large amounts of foreign ores which can be extracted on equally large scales and discouraged the use of obsolete scrap, whose dispersed generation is detrimental to either the large scale operations or total organizational control.

This situation is closely associated with the locational mismatch which is increasing between scrap generation and industrial demand: demand being concentrated in fewer and fewer locations, around either port facilities or natural resources, while the generation of scrap seems to be increasingly dispersed. Ironically, by its very nature
generation of obsolete scrap and the ultimate product demand are in the same location; it is the intermediate material manufacturing stage of production which is becoming increasingly dislocated through economy of scale.

Looking into the future, this increase in scale and dislocation could paradoxically lead to increased recycling in countries such as Britain which have few high quality natural resources of their own. Historically, material manufacturing developed largely around the natural deposits of minerals or fuel, and often both; this was certainly true in Britain. Currently, the developed countries have retained the material manufacturing operations as well as subsequent fabrication and assembly operations, but have largely given up the extraction of minerals, usually because larger and richer grade ores have been found abroad.

It could well be that the countries which have natural resources will want to expand their operations vertically to include material manufacturing as well as fabrication. Indeed this is happening in Jamaica in relation to aluminium production, as well as in the OPEC countries in relation to petro-chemicals. It is quite conceivable that this trend will continue with mega plants not occurring in Europe but in such places as Brazil or the Mid-East, especially when one also considers the cost of labour and the environmental objections which are more likely to be encountered in developed countries. If material manufacturing does shift to the developing world in the future, any home production would have to be supplied from scrap.

Even without this shift, production entirely from scrap is feasible even today in developed countries. Already there are "mini-
steel works' in the U.S. and France, whose production is based entirely on scrap. Lafitte and Bouillette (1974, p. 519) describe, the first French 'mini-steel works' at Bonnières which is typical of those developed in the U.S. as well as those beginning to operate in the U.K.

There are semi-integrated establishments specializing in one or two types of relatively simple steel products, of uniform quality in quantities varying from 100,000 to 300,000 tons per annum... prepared from regional scrap iron, using the continuous casting and hot rolling processes for bars and wires intended for the recycling market... the technical process achieved in preparing and casting of the steel has made these current economic conditions, and at the same time has given the 'mini-works' the ability to adapt, which is characteristic of them in regard to the supply of raw materials, development, commercial aspects, the fixing of prices, services, the customers and the way in which they face local situations.

Significantly, these plants were developed quite independently from the major manufacturers of steel; in fact Lafitte and Bouillette point out that the mini-plants "manufacture and sell metallurgical products; the output of which the large steel works do not wish to develop". Not only does this type of mini-plant eliminate much of the locational disparity between scrap generation and material use, it again illustrates that environmental efficiency and production is by no means dependent on large scale operations of institutions, a subject discussed in relation to by-product utilization. An extreme example of the adaptability of a small scale recycling operation is described by John Lambert (1975) in relation to the Italian steel industry

And then there are the "Bresciani", the backyard producers around the Northern city of Brescia. After the war, they found themselves sitting on a huge dump of scrap German raw material which they used for years to make special steels when times were good, going back to tomato-growing when they were bad.

Collection and dressing of scrap has always been a small scale operation and in Britain there are around 15,000 large and small scrap
processors and merchants. The number is being reduced somewhat by the movement towards capital intensive mechanization of separating and handling systems. Even so, these firms are small in relation to the large multi-national metal producers. Another interesting feature of the scrap industry is the development of small scrap-dressing plants which operate on a rotational basis over a large area made up of a number of small scrap catchment areas which are not large enough in themselves to justify such mechanical plant on a full time basis.

Perhaps the largest problem in recycling obsolete scrap is scrap quality. The complaint common from all manufacturers producing recycled materials is that contamination is preventing them from recycling obsolete scrap. Bengston and Regan (1972, p. 190) typically describe the problem in relation to metals.

The metals industries are under continuous pressure from their customers for products that will meet increasingly rigid specifications. Their operating practices and the raw material from which the metals are produced are, therefore subject to increasing quality requirements... However, obsolete scrap, the products of metallic solid waste, can be significantly different (from the metals demanded). Occurring in many shapes and forms, from beverage cans to junked autos to salvaged electrical cable, it presents a number of quality problems. For example, the copper parts and wiring in automobiles and the aluminium tops of steel beverage cans make vehicles and cans difficult, if not undesirable, products for recycling, in the steel industry; by the same token, the iron and steel content of these products makes them undesirable for recycling in the copper or aluminium industries.

This quality problem is partly due to the conflict between recyclability and performance mentioned earlier in this section; does one design a

\[\text{\footnotesize 1}]

\text{\footnotesize Paradoxically, some material manufacturers indirectly advertise, as an advantage, the recycling difficulties encountered with composites and alloys. British Steel, for example, in their advert (\textit{A.J.}, 27 January 1975, p. 15) for stainless steel tubing emphasizes that "Stainless steel doesn't attract thieves", when compared to copper tubing.}
sophisticated product made up of unique alloys and composites which meet very high performance specifications but which are very difficult to recycle, or does one use a single and usually less sophisticated material with greater recyclability but with a corresponding loss of performance? It should be pointed out that recyclability does not necessarily jeopardize performance. The all aluminium beer can performs as well as the multi-metal one, for example, and various heat treatments can improve performance of metals without adversely affecting recyclability.

The contamination problem can be largely overcome by technology, and research is being carried out by many institutions to improve separation techniques. The techniques which could improve the quality of scrap and consequently its potential for recycling are themselves similar to those employed in the dressing of natural ores. Indeed, in the U.S. it is the Federal Bureau of Mines which is one of the leading organizations in the field of scrap separation. Unfortunately, this close similarity in separation techniques will mean that any breakthroughs in technology, such as the use of super conducting magnets, could be applied to both primary and secondary materials, thus maintaining their relative gap. The economic validity of applying new technology to separation methods could well be in favour of dressing natural ores which occur in a few large deposits, providing economy of scale.

**Recycling Materials Within and Between Product Systems**

The discussion of primary recycling has so far made little reference to the product systems in which the recyclable materials are used. Today, with the possible exception of glass and paper; the manufacture of recyclable materials is done by large specialized firms
which have no control over the final fabrication or product assembly, and consequently have little direct concern with the product systems using their material. For example, it would be difficult for a designer to specify a structural steel member produced entirely from recycled obsolete scrap from a firm like British Steel.

There are however, examples where primary material recycling has taken place within a particular product system; two excellent examples of this in the building industry are the traditional recycling of non-hydraulic lime and calcium sulphate cements, both simple cements discussed earlier in relation to primary by-product utilization. These cements are largely restricted to building and are today not even thought of as being recyclable; historically, however, this was not the case. Salzman (1967, p. 151) refers to the practice of removing mortor from old walls and reburning it, and goes on to point out (p. 157) that even plaster was burnt and recycled, citing as evidence a contract involving a York plasterer who in 1327 was paid "collecting and bringing together old plaster coming from the house thrown down in Skelvgate, and making kilns for burning new and old plaster." Derry and William (1960, p. 405) even go so far as to suggest that "a holocaust of ancient marble statuary" could be attributed to the fact that pure lime made from burning marble provided the best plaster.

The nearest thing to this happening today in the developed world is the use of worn and broken moulds from the ceramic industry being used as raw material in the manufacture of portland cement, as is done in Ohio, Pennsylvania and West Virginia. With respect to energy, not nearly as much energy would be saved from the pre-burning or recycling of gypsum to produce plaster or portland cement as would be gained by
burning non-hydraulic lime; this is partly due to the lower temperatures required to burn lime but more particularly to the fact that lime cements only carbonate near the surface actually exposed to air. Consequently lime mortars contain only a small portion of CO₂ which has to be disassociated when being burned as compared to natural calcium carbonates such as limestone or marble.

Lead is the other material which was often recycled solely in the building system, even though it was not nearly so restricted to it. Salzman (1967, p. 264) mentions the advantages of medieval lead roofs recyclability in that "the initial expense of lead may be offset by the fact that when a leaden roof got into disrepair it could be stripped and recast, and there are fairly frequent references to this being done." However, he goes on to point out that lead's recyclability made it rather tempting for workmen to steal lead off the building on which they were working. Indeed one of the ordinances of the London Plumbers drawn up in 1365 was that "None shall buy stripped lead from the assistants of tilers, bricklayers, masons or women, who could not find warrant for it." Theft remains with us today, so much so that the manufacture of "Zincon" an alloy flashing material advertises (A J, 13 February, 1974, p. 73) as an advantage the difficulty of recycling the product in relation to lead, stating "...although it's worth its weight in lead to you, thieves find it particularly inattractive."¹

¹The most commonly recycled building materials i.e. lead, copper, zinc, are often located in the most critical area of a building's fabric. This is unfortunate since these materials are first to be removed from a disused building, leading to the rapid deterioration and possible loss of the remaining materials in the building.
These examples of recycling within in the building system, were to a large degree dependent on small scale operations performed by craftsmen whose responsibility in providing materials involved much more personal participation than is found today in the construction industry. Stripping recyclable materials from buildings today involves a firm or individuals with no direct link to construction activities and the materials that are recycled are passed on to material manufacturers where it can be redirected or recycled into different product systems.

In closing this section on primary recycling it is worth speculating as to the future movements of recyclable materials which are likely to occur, into and out of building fabric product systems. There are two general ways in which recycled materials can be redirected into different product systems. The first involves material moving from a product system where its use is non-essential and where substitutes are available, to those systems or end uses where its use is essential and few competitive substitutes exist. This first situation is likely to occur with heavy non-ferrous metals (i.e. zinc, lead, copper) being recycled out of the building fabric system where substitutes are available (and are cheaper), into mainly utility systems (water, electrical distribution systems and electrical machinery) where substitutes are more limited.

In the second situation, materials move from product systems and uses, where high performance and tight exacting specifications are required, into end uses or systems requiring less stringent specifications and performance, because of the degrading which can occur through recycling. The building fabric system is an ideal outlet for recycled scrap because of its relatively low-performance specifications and there is a likelihood
that the remaining easily recyclable materials, if recycled, would shift from other product systems into the building fabric system.

The shift of some scrap into the building system is in fact, already happening; as mentioned earlier the major end product of the mini-steel plants is reinforcement bars\(^1\). The 'Recycled House' project co-ordinated by the Reynolds Aluminium Company in the U.S, would also suggest the interest in recycling aluminium into building fabrics; the project used joists, trusses, windows, doors, and rain goods and duct works, all produced from recycled aluminium\(^2\). Paper, which is not normally associated with building fabrics, is currently being recycled into it as wall paper, plaster board facing, building felts and roofing shingles\(^3\). Natural cloth fibre is also recycled into felts and shingles but the trend is diminishing because of the synthetics being combined with the natural fibres. Plastics and glass, primarily from the packaging system, are likely, if recycled, to be directed into the building system usually in a secondary fashion as bulk materials.

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\(^1\)It is worth noting that recycling high grade specialized steel from the aero-space industry for example into lower grades has one detrimental effect. The high grade steels can contain small amounts of alloying materials which are themselves quite rare whose natural sources could be exhausted within the century. By recycling these high grade steels into lower grade ones the alloys, which really need to be recycled, are effectively lost even though the parent material which is fairly abundant in the earth crust is recycled.

\(^2\)A far more logical use for recycled aluminium, in energy terms, would be in transport systems where weight is directly related to operating energy. Unless aluminium is used for its reflective or conductive properties (e.g. in solar devices) its use in buildings would save little if any operating energy, though it could be argued that it saves some maintenance when used in an exterior situation.

\(^3\)A large part of the paper collected by Edinburgh District Council goes into plasterboard facing.
i.e. bricks, blocks, sheets and boards (discussed in the next section, on "secondary recycling"). Paper can also be used in this fashion but both plastic and paper would have a fire resistance problem; they do have the advantage of saving production energy when they are recycled, unlike recycled glass.

One potential asset common to recycled plastic, paper and glass is the insulative values which can be achieved by these materials and which would save thermal operating energy. Paper and glass can be recycled in a loose fibrous form and glass and plastic can both be foamed; recycling these materials in these forms should be further investigated and encouraged in practice.
Section Six

Secondary Recycling

Historically there are few examples of secondary recycling outside the building system, for the secondary recycling outside the building system was largely dependent on the urban consumer society itself. Urban refuse, which would include domestic, municipal and commercial refuse (but excluding sewage) did not become a problem in the western world until the nineteenth century. Packaging was minimal or non-existent and food refuse would be eaten by domestic animals such as cats, dogs, pigs and chickens. Other organic waste could easily be burnt in solid fuel fires, commonly used in earlier periods. In fact the ash from the solid fuel fires was the most common item found in urban refuse. This was probably the first type of refuse to be recycled in a secondary fashion, in the form of clinker blocks around the turn of the century. This type of construction is now discouraged because of the impurities of the aggregate but methods have been developed or proposed for secondary recycling of all the major discarded materials which are common in today's refuse.

1Bridger and Sellick-Smith (1973), Bynum et al (1972), Grindstead (1972) and Neal (1971) are representatives of the literature describing various methods of the secondary recycling of obsolete scrap.
Paper, rubber and glass separated from refuse have all been used as aggregate with various binders (Portland cement and asphalt being the primary ones). Blocks and bricks have been developed out of paper, plastic, glass and even unseparated though highly compacted refuse. Blocks of baled metal scrap have also been proposed for building spot-welded together to form walls. Boards and panels have been produced from waste paper and plastic; loose and rigid insulation materials have also been manufactured from waste paper and plastic, as well as from glass cullet, melted down and made into foamed units or glass fibres.

It is interesting to note that the building system seems to be one of the most commonly suggested outlets for urban waste but obsolete buildings and the materials contained in them are seldom even mentioned as a source of refuse or waste, even though the tonnages involved are quite often large. There have been recent attempts at the secondary recycling of building materials or rubble within the building system. The FMC Corporation have developed a plant making small building units for use in urban renewal areas. Panel, bricks and blocks are made by a process called 'vibrocompaction' using the rubble from demolished buildings; such a plant, unfortunately, is capital-intensive and would probably have to produce enough building materials for one thousand houses of 120 m² before becoming economical (Vale, 1973, p. 16).

The secondary use of demolition rubble in the construction field is by no means new, though it has never been so sophisticated as to need 'vibrocompaction'. The foundations of Newgate Prison, for example, laid in 1770 were made of cart loads of broken bricks. Obviously, if the demolition site providing rubble for secondary recycling were near the site of the new construction, as in the case of FMC proposal, transport
energy savings could be realized by reducing or eliminating both the transport energy costs required to deliver alternative new materials as well as those required to remove the demolition rubble.

In principle, transport energy could also be saved by the secondary recycling of obsolete scrap from commercial and domestic refuse, because of their proximity to population centres, and consequently building demand. However, the Reynolds 'recycled house' project illustrated that this might not be the case in actuality; located in Richmond, Virginia, the house incorporated waste glass collected in California, old newspapers from New Jersey, processed garbage from New York City and rubber from tyres discarded in Mississippi.

With the possible exception of transport energy, there appears to be little if any energy advantage in mechanically processing obsolete scrap to provide bulk materials for building use; rather than from mechanically processing bulk materials from natural sources. The energy intensity of the products made from old scrap depends more on the energy intensiveness of the matrix material than on the aggregate or bulk materials themselves. There are situations where energy savings could occur; for example, a brick made out of newspaper could save energy if it were substituted for a brick processed from non-fuel bearing clay. In general, the energy savings applicable to secondary recycling would be similar to those already discussed in relation to secondary by-product utilization. The potential for the secondary use of recycled scrap however, is probably less than that for the secondary use of by-products due to the contamination and dispersed nature of obsolete scrap and
simply because far less obsolete scrap is generated\(^1\).

Even though significant energy savings are not likely from secondary recycling, and the total tonnage of obsolete scrap generated is less than the total requirement of bulk materials, this does not justify the small amount of secondary recycling currently taking place. Indeed the fact that the demand for bulk materials is greater than the old scrap produced should be an incentive for more recycling; architects should consciously try to specify much more recycled scrap to provide the bulk or aggregate in composite materials.

\(^1\) The product/by-product ratio discussed in Chapter One illustrated the fact that the by-products involved in producing a final product often outweigh the product itself. Since the materials in refuse were at one time final products themselves the by-products to produce them would be in most cases greater; consequently, in the U.S. for example, 256 M tons of urban waste, about half of which was domestic, was produced in 1967, while in the same year solid waste by-products amounted to 3351 M tons - 2115 M tons of which were agricultural in nature, 1126 M tons were minerals and the remaining 128 M tons were from conventional industrial activities (Blum, 1970, Table 2.)
### Section Seven

**Tertiary Recycling**

Obsolete materials that are recycled in a tertiary fashion are utilized for their chemical properties and after being recycled the original material is no longer recognizable. The three general methods of tertiary recycling can be illustrated by using scrap paper as an example. Pyrolysis of paper into various organic compounds which could be used as feed stock in the manufacture of synthetic organic materials would be an example of the first general method, whereby an obsolete material is processed into intermediate compounds which are subsequently processed into a final product. Using scrap paper as a fuel or food would be an example of the second type of tertiary recycling and using old paper as a soil conditioner in the production of food crops would be an example of the third method. In the latter example the material is recycled in order to support another productive system (but not as food or fuel) and does not emerge in the final product. In fact, the second and third methods of tertiary recycling described above could be considered as terminal recycling, in other words the change in the material is so fundamental there is virtually nothing left to recycle.

Because of the numerous materials and methods encountered in
tertiary recycling, and its very tenuous connection to the building system a discussion of energy savings is extremely difficult. However, it is important to recognize the significance of tertiary recycling in the context of sequential or hierarchical recycling, because of its terminal nature. In sequential recycling materials are initially used at their highest performance level and any subsequent recycling observes the principle that minimal degradation will enhance the potential for further recycling. (This gradual degradation applies to energy as well as materials as discussed in Chapter Four).

To illustrate sequential recycling, we shall take wood as an example. In an ideal energy economy, wood would initially be used as a structural material effectively utilizing its cellular composite nature (cellulose fibres in a matrix of lignin). It would next be cut and recycled in a secondary fashion as the main constituent in chip, particle, or block board. The material in this board could be in turn recycled again by pulping to produce paper or cardboard which itself could be subsequently primarily recycled into progressively lower grades of paper and paper board. Eventually the lower grade paper could be recycled in a secondary fashion providing bulk in the production of bricks or papier mâché. These products could be recycled in a tertiary fashion; by pyrolysis they could be de-composed into chemical compounds which could provide feed stock for the chemical industry, a portion of which could be used in the production of synthetic plastic materials. These plastics could be melted (if thermoplastic) and recycled in a primary fashion, chipped and used in a secondary fashion as aggregate and finally, if the matrix material permitted, recycled in a tertiary fashion as fuel.

This idealized sequence could hardly be achieved in practice,
though the scope for such sequencing would be far greater starting with natural organic materials, such as wood, than with inorganic materials. Unfortunately it is unlikely that obsolete materials today are recycled more than once in any fashion; if recycled at all. The possible exception to this would be in relation to the metals, but these materials are normally only recycled in a primary fashion. The lack of recycling is especially true for the common construction materials which are continually becoming available through demolition. It is not uncommon to see wood, for example, being burned at demolition sites ignoring all possible methods of recycling and even wasting its value as fuel. The record for recycling materials from the building system is today bad, and it is unlikely that the situation will improve in the future; in fact it is most probable that recycling will diminish if current trends in material technology continue.

Roofing materials illustrate the likely future towards complex composites and increased diversity in basic types. An example of new composite roofing material is the stone-coated steel tile, recently introduced by F.E.T. Building Products, which consists of galvanised steel, coated with mastic and stone granules, over which a pva binder is spread; another is the stainless steel roof cladding sold by Langley which consists of a glass-cloth reinforced bituminous cladding faced in stainless steel. Such composites would deter any recycling attempt. Even the simple concrete roofing tile which has performed quite adequately is becoming more complex in its material make up. Marley Ltd. advertises (A J, 17 October, 1973) that the demand for acrylic-coated concrete tiles "continues unabated as specifications rise in a steep upward curve".
A paradoxical situation is arising where by raising material specifications results in more energy-intensive materials (as the roofing case study has shown) making recycling more attractive in energy terms; while at the same time these higher specifications often result in proprietary composite materials similar to the ones just described, which are progressively harder to recycle. The recycling of building materials by all methods, but particularly tertiary, was far more widely practiced on a small scale during earlier periods. As late as the nineteenth century for example, thatch and turf, used for roofing on Scottish farms, were commonly used for fuel and manure when removed. Ironically, the materials involved had intrinsically low energy intensities, so little energy savings could be realized through recycling.
Section Eight

Primary Re-Use of Components

Composite materials are among the most promising of all developments. The increasingly severe demands imposed on materials by our building practice cannot be met by simple-component materials; they call for the combined behaviour of several materials acting in concert to provide properties not obtainable by the constituents acting alone...and many composites can be expected. (Dietz, 1972, p. 16).

Albert Dietz presents the consensus of a great majority of writers who have predicted future trends in building. If this scenario does materialize in the future, re-use of building components would be far more viable than recycling the materials in them; composite materials being difficult to recycle, as we have seen. In addition the building system is heavily dependent on inorganic materials (concrete and ceramic materials) which are almost impossible to recycle in a primary or tertiary fashion.

Comparing Potential Energy Savings Through Re-use and Recycling

Component re-use, in addition to being more feasible, in the construction context, would also save far more energy than recycling. In both recycling and re-use some energy needs to be expended in the deproduction process to prepare the material or component for re-entry
**Fig. 5.7** Energy savings by recycling materials.

**LEGEND**

- $E_p$: Production energy required for processing materials from primary sources, eliminated by recirculating materials or components from secondary sources.
- $E_{dn}$: Net deproduction energy required for processing materials or components from secondary sources.
- $E_s$: Net energy saved by recirculating materials or components from secondary sources.

**Fig. 5.8** Energy savings by re-using components.

**Fig. 5.9** Accumulative net energy savings gained by the recirculation of materials or components from secondary sources.
into the production sequence. The mechanical dis-assembly required to
remove a component would require far less energy than scrap dressing,
which usually involves mechanical crushing or shredding and can even
involve heat, freezing or chemical operations as well. The net
deproduction energy cost \( E_{dn} \) would be the deproduction energy cost
required for re-use or recycling minus the energy cost which would
otherwise be required for the disposal of the material or component.

Re-use would also require less energy than recycling because
of the reduced amount of production energy required; components can re-enter
the production sequence in the assembly stage of production, the last
stage in the sequence, while scrap would be entering a stage or two
earlier in the sequence, at either the material manufacturing or
fabrication stages of production. The net energy saved \( E_s \) by
recycling or re-use would equal the energy cost of the activities
eliminated by re-use or recycling that would otherwise be required
if a product were produced from deproduction energy cost \( E_{dn} \).

To illustrate graphically the difference between the energy
saving brought about through re-use and recycling Figs. 5.7 and 5.8
have been constructed. One can easily appreciate how much greater the
energy savings can be through re-use by comparing the net energy savings
\( E_s \) in Fig. 5.7 which represents the energy saved through recycling
with those shown in Fig. 5.8 representing re-use. Both figures are
based on hypothetical cumulative energy profiles for production and

\[ \text{Dis-assembly operations usually involve less energy than}
\text{scrap dressing, but they could well cost more, being far less}
\text{adaptable to large scale mechanized operations.} \]
deproduction; and the cumulative profile for net energy saving due to recirculation of obsolete scrap or components is sequential in Fig. 5.9.

Description, Examples and Possibilities of Primary Re-use

Primary re-use of components, whereby a component is re-used by merely transferring it to another assembly, without changing its function in any way, is the most natural method of re-use. Whether or not re-use actually occurs depends on the type of component. A 'dependent' component, such as a plumbing fixture or a concrete block which can only be moved with difficulty, could be considered re-used even if re-located within the same overall assembly or structure, whereas a 'semi-dependent' component, such as a moveable partition, which can be relocated with some ease, would not be considered re-used if moved within the same structure; it would have to be re-located in a totally different building to meet the definition of re-use employed here.

Historically, the components contained in the building’s fabric were commonly re-used in a primary fashion. Davey (1961, p. 70) points out that during the Roman period even "broken materials were re-used again and again until the end of the Empire". The Saxons re-used available bricks left over from the Roman period in their churches. The Normans continued this practice and the Norman Tower of St. Albans Cathedral, built of brick and tile from the adjacent Roman City of Verulamium, is an example of this still standing today. Bricks were not the only walling material re-used during the middle ages. Knoop and Jones (1933) mention in their book The Medieval Mason that:

As the scappling and cutting of stones were comparatively
expensive processes, those responsible for building operations were quite willing to obtain dressed stone second hand when it was feasible. Thus... at Eton College in 1444-45 some of the rag employed was the gift of the King, from the old walls of the Savoy Palace at London...

Timber was also frequently re-used; Innocent (1971, p. 102) states that throughout the middle ages and after "it was usual [emphasis mine] in building to use the same timber over and over again with the gradual decrease in the size of scantings, the use of old timber compensated somewhat for the declining supply of new wood". Early examples of the primary re-use of roofing units such as tiles or slates in Britain have already been given in the roofing case study but the common re-use of roofing units is not restricted to the middle ages or Britain. Edward Morse has a fascinating passage in his book Japanese Homes and Their Surroundings (1961, p. 87) about tile re-use in Japan in the late nineteenth century.

The older a tile is the better it is considered for roofing purposes. My attention was called to this fact by a friend stating to me with some pride that the tiles used in his house, just constructed, were over 40 years old. Second hand tiles therefore are always in greater demand. A new tile, being very porous and absorbent...

1 The best example of second hand stone becoming available in large quantities throughout Britain followed the Reformation in 1530; many of the redundant Abbeys and Priories became virtual quarries.

2 It is interesting to note that nails, the problem which plagues timber re-use today, presented difficulties to the medieval carpenter as well. Salzman (1967, p. 342) finds from the building record of Restormel Castle in 1343 a reference to the 6d spent on "an ardze for smoothing old timber, because the timber was so full of nails that the carpenters would not set their own tools to do it". No doubt with common usage of morticed joints far fewer nails would have been encountered than they are today.

3 Removal of these Japanese tiles at this time must have been especially easy, for Morse mentions (p. 84) that they were bedded only in mud "scraped up from some ditch, moat or canal, while in the city one often sees men getting much for this purpose from deep gutters which border the many streets". Mud bedding also allowed "the firemen to shovel tiles off the roof with ease and rapidity in case of conflagration, when it becomes necessary to tear down buildings in its path".
In the past some architectural components, which would now be considered permanent parts of a building, were thought of more as fixtures and their ownership was more akin to that of loose furniture. This naturally would have encouraged re-use. Roof timbers, for example, in rural Scotland, even in the early eighteen hundreds were by tradition the property of the tenant and could be removed for re-use, the rest of the structure belonging to the laird. Likewise, Salzman mentions (1967, p. 185) that "in the fifteenth century glass windows were regarded still as luxuries rather than essentials, and being set in hung casements, were usually treated as tenant's fixtures".

In the future architectural elements could once again become more independent from the basic structure if the basic support structure concept put forward by Habraken (1972) gains acceptance. Already, in Scandinavia, France and Germany, there exists flexible housing using walls and cupboards which are fairly movable and in Britain the GLC PSSHAK project (Hambi, Wilkinson & Evans, 1971, and 1974) includes semi-dependent stair elements. These semi-dependent elements could be owned by the occupier or tenant, or they could be leased or rented from a public authority or private rental firm; the latter was proposed by Michael Farr (1966) for a complete range of kitchen equipment.

The idea of renting architectural components is particularly relevant to those which are connected to utilities such as plumbing fixtures, since these tend to have a much shorter life than the fabric of the building because of fashion obsolescence. At present, the

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1For a review of a number of European flexible housing schemes one should refer to the Rabeneck, Sheppard and Town (1973/74) article on "Housing Flexibility/Adaptability".
telephone is the most obvious example of a hired piece of equipment and
cookers have been rented from the electricity and gas boards for years,
(though the practice is already diminishing). The rented television set
is now common place and more companies are renting suites of office
furniture, including free standing partitions for landscaped offices.
The latter is only a step away from being an architectural element itself.
The rental idea should lead to more sensible, efficient and durable
equipment. The rental agency would be responsible for maintenance,
which would be carried out on a regular basis and when the component
changed hands, which does not normally occur in more conventionally
owned equipment.

Another factor which should, in principle, favour re-use now
and in the future is the effort being made towards standardization and
modular co-ordination, the future of which is typically described by
George Leon (1971, p. 16)

The building industry is moving from a craft industry
towards a more intensively mechanized industry based on
the substitution of machinery, factory labour and semi-
skilled labour for craft trades. It is passing through
a transitional stage of 'system building' before
entering a final stage based on the site assembly of
factory produced standardized interchangeable components,
mass-produced in a vast series for a variety of building
types. The efficient re-organization of the industry
will necessitate increased standardization of component
production and construction techniques; modular
co-ordination on a national basis; improved communications
and management; integration of demand and production.

In conventional construction, "factory produced standardized
interchangeable components, mass-produced in vast series for a variety
of building types" have long been in use with respect to basic units

1Standardization of basic building units is nothing new in
Britain. The standard dimensions for plain roofing tiles, for example,
such as bricks, blocks, boards, slabs and sectional units. Walter Segal and his followers have also shown on a very small scale how these off the shelf units can be assembled so that component re-use is easily achieved. In fact Segal's whole philosophy on construction has resulted from a temporary house, which he designed for himself which used basic units off the shelf, unaltered, which were held together by dry mechanical joints (bolts) designed so that all the units in the house could be removed and sold after it had served its purpose. Walter Segal's approach to re-using standard open system components is by far the most outstanding demonstration by an architect in Britain, of what might be achieved in this field, and there are promising signs that his many disciples may extend his influence in future, for example, the housing by David Lea. David Lea, himself is well aware of the resource conservation aspects of the Segal type of construction. In discussing his designs (Lea, 1975) he states that one objective is "that elements were established in England by Edward IV in 1477; the Act was repealed in 1856 but the dimensions ordered are very nearly the standard dimensions on roofing clay tiles, made today, i.e. 10\(\frac{3}{4}\) inches by 6\(\frac{3}{4}\) inches, 3/8 inch thick. An act of 1722 fixed minimum dimensions of pantiles which are still in effect today. However the dimensional standards of bricks and tiles were brought about not for reasons of production or application, but as a means of standardizing the taxation applied to those products.

1 Metrication and the Common Market will help to standardize supplies on a larger scale, but Britain has the initial disadvantage of a tradition of imperial dimensions which will affect the re-use of older components in the future.


3 The buildings themselves could almost be described as a cross between the American stud frame construction and the traditional Japanese timber framed buildings. However, Segal's idea of demountability based on a timber frame can only be considered as a renaissance in Britain, for the traditional European (and Japanese) morticed and tenon timber framed buildings also permitted easy disassembly and component re-use and this (as pointed out later in this and the next chapter) was frequently done in the middle ages.
should be changed easily during the life of the building without wasting materials" (p. 1133). Closely associated with this aim is the following list of criteria he uses for "choosing materials rationally":

- choose materials which can be used as far as possible in their standard sizes, with the minimum of conversion of any kind;
- avoid waste;
- choose wall materials on the basis of their performance, price and dimensions, and build up different sandwiches to give different required performances;
- use the minimum amount of material for each purpose;
- allow dimensions of standard wall materials to determine the horizontal and vertical module of the building;
- limit the number of different sizes of each material as far as possible.

Problems Encountered in Primary Re-use

No doubt George Leon, and others predicting future building trends, are referring not only to the standardization of basic units such as bricks and blocks but also to the standardization of compound units such as door and window units, as well as elements and sub-elements such as plumbing "heart" units and entire wall or stair sections which in principle should befit re-use. This trend is already apparent to some degree in the multi-national automobile industry, with elements and sub-elements being fabricated throughout the world to fit a standard range of cars. But the interchangeability at the element level is restricted to a closed proprietary system, and not the open one implied by Leon, even though the simpler units such as tyres can be re-used on automobiles produced by other manufacturers.
The utopian open system for elements and sub-elements is unlikely to ever be achieved in the building system; despite its advocacy by many architects, including the well known Renzo Piano and Richard Rogers. In an article about their designs (Piano and Rogers, 1975, p. 276) state that a design objective in their work is the capability of "internal and external elements being demountable and re-usable". Yet, out of their thirty-seven schemes reviewed in the article, no two use the same interchangeable components; in spite of the fact that many of the spaces are similar in size and function.

If an architectural firm does not try to apply its own system to as many projects as possible, it is doubtful whether other architects would use it either. In fact there is a basic contradiction between individually designed, 'one-off' buildings and the use of universal 'plug-in' elements. There would be a redundancy if one were to use both. The situation really amounts to the designers expressing their interest in adaptable or flexible buildings, using universal elements, as long as the components are designed by their firm. There are hundreds of proposals for neatly detailed, interchangeable units and elements which,

1Another design objective stated by the firm is that "all forms of technology, from low energy intensive to high energy intensive, must aim at conserving natural resources or minimizing ecological, social and visual damage to the environment, by using as little material as possible as functionally as possible..." (Piano and Rogers, 1975, p. 276) Besides containing a contradictory statement (i.e. high energy intensive technology must aim at conserving natural resources), here is the common misconception of light weight structure somehow has a low environmental impact; if anything, the opposite could be argued, as pointed out in Chapter One. There is little need to worry about consuming the most common chemical compounds on earth, and heavy construction such as Adobi, often has minimal environmental impact.
if ever built become truly "one-offs", with virtually no chance of component re-use, and these units also completely miss the market resulting from the alteration and repairs of traditional structures, which make up the building stock. An extremely common characteristic of the ingenious "clip-together" systems of interchangeable components is the architect's naive approach to the question of integrating the supply/disposal of the new components within existing marketing systems: key factors are the unpredictable, necessarily random demand, production planning and stock control and distribution all of which involved with the issue of capitalization \(^1\)

Any future in interchangeable elements in the West will have little to do with architects, but will follow the automobile industry's example, with interchangeable elements being restricted to closed proprietary systems developed by large multi-national building firms like 'Marley', 'Butler', 'Atcost' and 'Charcon' who design and manufacture building systems and then find activities or customers to fit them. These companies often advertise particular building systems as suitable for a whole range of activities, including agricultural, recreational, municipal, commercial and industrial. This approach is quite the reverse of the architects, who find a customer with an activity, then design a system around them.

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\(^1\) These factors of course are relevant to the demolition industry and largely explains the inefficiency of their 'marketing' of 'old' and obsolete materials and components, but in this field the components have at least been 'paid for'. 'Redundant' supplies of new components, vital to 'prime' any new system of interchangeable components - would be using up capital, and the risk accepted in other manufactured spare-part industries would seem to be far less than it would be in the present organization of the building industry.
The trend towards all-in-one compound units, whether used in an 'open' or 'closed' system, does present a redundancy problem. This is well illustrated when considering the re-use potential of large composite external wall elements. Because of their nature these components they have 'frozen' into them at the time of manufacture a particular set of specifications based on local codes and environmental conditions, (criteria on wind loading, U-factors, and sound attenuation limits). These components are static and passive objects, while the standards to which they were built are quite capable of change. One could well find that in 50 or 60 years, when re-use is being considered for this type of element, that one or two of the original standards have risen, making the whole element sub-standard. Likewise, material redundancy could also occur even if the standards were lowered, or the elements were re-used to a different type of building in different geographical location requiring lower overall performance.

Despite the fact that there will probably be both vertical and horizontal consolidation among the producers of building materials, components and pre-fabricated buildings, the number of components becoming available (from the basic units such as tile to the most complex compound elements) will probably continue to increase. Obviously the proliferation of proprietary components severely limits the potential for future re-use. The reason for this increase in components is due to

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1. This composite redundancy problem could be largely overcome by construction techniques described by Lea, in which composites are built up in independent layers fixed together by dry mechanical joints. In this way simple basic units could be arranged in different combinations to meet various specifications. One disadvantage to this method of construction is that structurally it might be less efficient than say a stressed skin sandwich panel. It could also be argued that this layer type of construction would be more labour intensive even though the basic components used can be mass produced in large automated plants. Whether or not this method of construction is more labour intensive it still provides probably the cheapest method of building dwellings in Britain (especially if self-built which is easily done with the 'Segal ' system).
commercial pressures to diversify into 'new' models, ranges, types or styles to meet "customer requirements".

This expansion in the number and type of components can be illustrated with respect to simple concrete roofing tiles. 'Redland', a large manufacturer of concrete tiles, offers a range of 75 different tiles which are based on 10 basic shapes and 13 different colour and surface treatments. The problem is compounded by the fact that 'Redland' is only one of several firms producing tiles with similar ranges, indeed their main rival 'Marley' advertises a "community of roof tiles which collectively provide the most complete choice for domestic, commercial and industrial applications". (A J , 8 January 1975, p. 34) 1. One can well imagine the problem in fifty years of trying to find enough second-hand 'Marley Mendips Acrylic tiles' in 'Rich pewter yellow' to tile a moderately sized bungalow. Compatability for re-use after all, is not limited to dimensional and jointing considerations only; surface treatment also has to be compatible for acceptance by most.

In roofing, the re-use potential is further reduced when one considers that the above example was restricted to concrete tiles; the tile family alone includes those produced from other materials such as clay, asbestos cement and re-constituted slate as well as imitation tiles made of galvanised steel and plastic. And there are many other varieties included in other major roofing systems, such as the corrugated sheet

1Facing bricks provide another example of where choice has got out of hand. The Brick Development Association advertises that "already, 600 panels of different facing bricks are on permanent exhibition at the London Building Centre. And it is really a case of no two are alike".
group or the shingle group. A very good indication as to the real extent of product propagation in the British building field can be gained from the 1974 comprehensive 'Barbour Index' of building products which contains 150,000 pages of product information from 4,500 manufacturers, covering 1,500 product types and 1,400 trade names.

Supposing the type and variety of components could be reduced and their connections, dimensions and surface treatments coordinated in some way, would this ensure or even encourage component re-use? The Eastern Block countries exercise considerable control over the production of building components and have endeavoured to mass produce buildings made up of a limited range of standard components; perhaps this comes closest to the future of building envisaged by George Leon, as described above. Yet even with this degree of standardization re-use appears to be no more common in the Eastern Block countries than in the rest of the world; it could even be less.

**Historical Factors which encouraged Re-use**

There was far less dimensional standardization in the past and yet far more components were re-used. Stone and brick walls were prime examples which flourished on re-used materials, yet by today's standards each stone and brick was quite irregular in both shape and size. Earlier components were simple, small and homogeneous units, capable of being handled by a single man. They could be re-used even after repeated re-dressing had reduced their size (this principle tends to be overlooked by those advocating modular standardization). Davey (1961, p. 71) speaks of the increases in thickness of Roman mortar joints from about half the thickness of bricks in the first century B.C. to joints nearly equal...
to the thickness of bricks by 300 A.D. "largely due to the increasing re-use of the bricks".

History seems to indicate that component scale was a critical factor in re-use, large scale (material able to be handled by one or two men) being detrimental. Small basic units, such as bricks and blocks, can be used in a large range of designs including curved surfaces and they can be accumulated into larger elements, whereas it is often difficult to cut modern large components into small ones and it is more difficult to use them in alteration and repair work.

Unfortunately, as units become smaller the cost of handling, in site assembly per unit area, will be greater, which ultimately leads to the labour versus energy cost argument presented in Chapter Four. If labour costs rise faster than energy costs the trend would be away from small scale labour-intensive components, particularly used ones to large scale ones which would be more difficult to re-use in an open system.¹

The re-use of components in earlier periods, however, was not merely due to the physical nature of the component itself, it was far more fundamental. Standardization was not in the morphology of the component, but in the ways of building. The methods of construction were much more regional in nature and far more restricted; this was due

¹The production of large pre-fabricated elements would almost inevitably result in capital intensive large scale plants based on the principle of economy of scale. This consequently would lead to heavy and costly erection equipment capable of handling the units; which could only be justified if a large and concentrated demand could be guaranteed. It is not likely that any of the parties involved at this scale would be interested in finding compatible elements (even if they existed) which were produced years before and over which they have little control as to quality or quantity.
in large part to the energy restrictions which were faced by builders. These natural energy restrictions also curtailed the rate of change in building techniques. Before the industrial revolution, fueled by cheap coal, building customs tended to remain the same throughout the centuries so that in areas where stone was the main material of construction stone from walls hundreds of years old would go into new construction, and the craftsmen knew as their ancestors did, what the materials could do and the best ways of utilizing them. This situation no longer exists today in developed countries.

To really appreciate how close past relationships were between construction, demolition and component re-use one needs only to review the numerous contracts contained in the Appendices of Salzman's Building in England Down to 1540 (1967). So close was the relationship between the tradesman and old building materials that the latter was often used as a form of remuneration for work done. An example of this practice is contained in an agreement (Salzman, 1967, p. 490) with a carpenter in 1314 to provide a new roof for Halstead Church in Essex, which specified that "for his work he shall have all the old roof, 26s 8d and new cloth for a gown". The use of demolition material as remuneration is not a direct reference to component re-use, but surely it is a strong inference of it. Contracts for re-building, as one might expect, frequently referred to re-using components coming from the structure being replaced. Typical of this type of contract was that for

1 Interestingly, the contracts of the middle ages, similar to the contracts used by the clients of Walter Segal, in that they normally deal directly with a particular tradesman without going through a general contractor.
a new gatehouse at Dunstanburgh Castle in 1383, in which the mason was "to use the materials of the old gatehouse and provide what else was necessary" (Salzman, 1967, p. 463).

Another important factor affecting component re-use deals with the general separation between the trades involved with production and de-production. The contracts contained in Salzman's appendices reveal a very close connection between these activities. A contract for new work made with three carpenters in 1387 provides a case in point; it called for "two adjacent houses to be pulled down and the timber used for the construction of a new mill [emphasis mine]" (p. 467). Of course the situation also commonly occurred in the relocation of buildings, as in the case of an agreement made in 1374 "for the pulling down of a timber frame house at Brede and its re-erection at Wye" (p. 452), but building re-use, even though it requires disassembly, is a subject which will be discussed in the next chapter. The separation between those involved in production and deproduction has, without doubt, increased over the years; and the more separation between these activities, the less likely the chance for component re-use.

Historically, transport was far more difficult and expensive than it is today. This fact would also have encouraged a closer relationship between production and deproduction; for the local re-use of building components would have eliminated the need to deliver new components and avoided the need to cart away the old ones. Today's practice of hauling used building components out of town for disposal would surely have been considered in most of Britain as a waste of money, energy and materials well into the nineteenth century, despite the fact that the haulage distances involved were usually less than today.
Used building components were certainly handled by small firms, even individuals in the past. Even today 'used' building components are handled by relatively small demolition firms, and are usually utilized by small scale builders, or do-it-yourself individuals (in developing countries this includes most of the squatters). Because this type of small scale building has existed over a long period of time, and since each project does not require large numbers of uniform components, re-use is quite feasible; and the labour intensiveness associated with component re-use is offset by the fact that labour is not costed in the conventional sense. Component re-use would be better promoted by assisting small scale operators (whose ingenuity in using non-standard components is described by Suha Ozkan (1972) or Boericke and Shapiro (1973)) rather than by creating the equivalent of a natural resource husbanding corporation.

One has difficulty imagining a large construction firm or tradesmen today being the least bit interested in re-used components or materials. One suggestion to overcome this lack of interest and to better co-ordinate deproduction output with production inputs has been made by Jordon Baruch (1972) in his article "Demanufacturing - threat and opportunities for Manufacturers". He suggests that a disposal tax, coupled with a national 'Resource Husbanding Corporation', would encourage large and small manufacturers to be more aware of the disposal of their products and encourage them to redesign with re-use in mind; alternatively, it might encourage the idea of leasing (mentioned above) which is already common in the field of computers or photocopying and industrial machinery.

Would Baruch's suggestions really be applicable to large
building elements? A component could well outlast the organization which made it. Unfortunately, today in both the automobile and building systems, it is not the manufacturer of the components who is involved with their re-use. In reality, it is small firms or individuals who handle the second-hand or re-conditioned component trade. In the U.S., for example, there are at least 1,000 're-manufacturers' of automobile parts which re-condition old automobile components. These firms supply the vast majority of replacement starters, generators, clutches, carburettors and water pumps in the U.S.

Perhaps the most important reason for the decline in second-hand construction components over the years in the developed nations, is society's attitude towards re-use in general. In the middle ages re-used building components were incorporated into the most prestigious buildings including castles, universities and churches, paid for and used by nobility. Today's worker, on the other hand, would most likely be quite offended at the suggestion that his house, or the buildings in which he works, should include second hand components.

The change in attitude towards old building materials and components and their decline in value to society can be appreciated by comparing the reactions of the authorities in London after the two events which left the city in ruins, the London Fire in 1666 and the bombing during World War II, 275 years later. In his book The Rebuilding of London, Reddaway (1940) mentions that, the city's orders were "always careful to stipulate that the materials removed [from buildings severely damaged by the Great Fire] should be either preserved or sold to help
towards the cost of rebuilding\(^1\)" (p. 124). This did in fact happen for "the church warden's accounts show that materials of the old churches [destroyed in the fire] were carefully collected and preserved and that their value was after appreciable..." (p. 124). The rubble left after World War II in London, on the other hand was treated with no such official concern.

Have government attitudes towards the re-use and recycling of building components or materials changed since the war? The government's green paper War on Waste: A Policy of Reclamation (Secretary of State for the Environment and Secretary of State for Industry, 1974) dealt with the recycling of materials, industrial by-products from mining, power and agriculture and the disposal problem of conventional containers and packaging. However it totally neglected to mention the problem (or opportunities) encountered in the disposal of the largest "containers" produced - buildings.

In component re-use we have a situation similar to that mentioned in relation to recycling. Historically, society had a good

\(^1\)An interesting example of continuous re-use in London before and after the Great Fire concerns the components and materials which made up Aldgate. This London gate was substantially rebuilt in 1215 using in part "the materials obtained from the destroyed houses of unfortunate Jews" (Wheatley, 1911). It was taken down over 5 centuries later in 1760 (roughly 100 years after the Great Fire); and the materials in it were still capable of fetching £177 (Wheatley, 1911). Some of the stone in the gate could even have been Roman, for as Liversidge (1973, p. 111) remarks:

"Stone has to be brought from some distance (from London) and consequently Roman buildings were intensively robbed and their materials re-used. Much of the Roman sculpture recovered consists of fragments used in strengthening the wall and many of these are tombstones."
record of re-using low energy intensive products (in this case building components) today, when components have generally higher energy intensities, producing an opportunity to save even more energy through re-use, the record is poor. It is not likely to improve unless there are some substantial changes in attitudes regarding scale, the use of second-hand components, and the cost of labour in relation to that of energy.

1Salzman questions the actual use of ship timber in Medieval England, stating that "of the constantly alleged use of ship's timber in ancient buildings, the only documentary evidence I have found is at Dover in 1237, when 460 was paid "for an old ship bought for the planking of the turret"." (1967, p. 200)
Section Nine
Secondary and Tertiary Re-use of Components
and Tertiary Re-use of Independent Articles

Essentially this section deals with re-using items in ways which differ from their designed or initial use. Charles Jencks would generally classify this as 'ad hoc' use of an item. In the secondary re-use of a component, the component performs the same function but in a different context, either as a component of another assembly, or as an independent product or article. In either case the component usually changes from one general product system to another. A historical example of the first would have been the re-use of ships' decking as flooring in a building\(^1\). A more recent example would be the use of an automobile door being used as a door or window. The other type of secondary re-use of components occurs when a component is removed from its original assembly and is used for the same basic purpose but as an independent object or article. This type of re-use is uncommon and has little application to buildings; an example however outside the building field would be the

\(^1\) Salzman questions the actual use of ship timbers in Medieval England, stating that "of the constantly alleged use of ship's timbers in ancient buildings, the only documentary evidence I have found is at Dover in 1227, when 43s was paid 'for an old ship bought for the planking of the turret'." (1967, p. 200).
removal of an automobile seat and its re-use as a lounge chair.

Tertiary re-use of components involves a change in the component's function; like secondary re-use, the component may be re-used again as a component or as an independent article. The re-use of barrel-staves as wall lathing provides an historical example of tertiary re-use, where components from outside the building system were re-used as components within it. An example of the tertiary re-use of components within the building system occurs when roofing tiles are used for walling units, which was a common Roman practice. Another instance of Roman tertiary component re-use in Britain, with the building system, was uncovered in 1973 at the Roman outpost town of Vindolanda, where an oak gate had been re-used for flooring.

Examples of tertiary re-use where a component is removed from an assembly and used for another function as an independent article are numerous. Most building components can be removed from the building system and re-used in such a manner, the old brick being re-used as a table are examples. The converse of this type of tertiary component re-use (i.e. where a table is re-used as a door), is the tertiary re-use of an article or independent end product. There have been numerous proposals for the tertiary re-use of discarded containers in the building field, the usual

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1 Today, new flush doors are often used as tables; this however is not re-use, but merely an 'ad hoc' use of a door. An item has to be used in some capacity, before it can even be considered as being re-used.

2 An independent product or article is one which is movable and can easily function without reliance on any outside support system; they are usually small, simple articles like ashtrays, bottles or cans, but an automobile would be another example.
example being the re-use of cans or bottles as simple walling units much in the same way as a substitute for bricks or blocks. 'Garbage housing', currently advocated by Martin Pawley (1973 and 1975) largely incorporates this type of product re-use. Certainly a lot of containers could be absorbed by such re-use. The 'Recycled house' sponsored by Reynolds Aluminium in the U.S., absorbed, through primary recycling, 183,000 aluminium beverage cans and 124,000 soft drink bottles. It is quite likely that a house of the same size would absorb as many containers if they were re-used in a tertiary fashion. The vast numbers of containers does, however, present a practical collection problem not likely to be accepted by conventional construction enterprises; it is the individual or very small builder who is, or is likely, to re-use articles of this type in this tertiary fashion.

In principle, components and simple article should be re-used in a sequential fashion somewhat similar to that described for materials. Component re-use, however, does not have such a distinct hierarchical order as encountered in material recycling. Nevertheless in an ideal recirculation pattern the material recycling hierarchy would be characterized by sequential component re-use as well. An example of this compounding can be demonstrated through the recycling example given in the section on tertiary recycling. Instead of wood being directly recycled in a secondary fashion as chip board, the wood component would be re-used in various ways first. For example, if initially the wood were used for ship decking it could be re-used as decking again (primary re-use) then it could be re-used as flooring in a building (secondary re-use), and ultimately, be re-used in a modified form in a piece of furniture (tertiary re-use), before the wood was even considered for secondary recycling as chipboard (which itself could go through the same general re-use pattern).
In practice sequential re-use of this kind is very unlikely. The secondary and tertiary re-use of components, or the tertiary re-use of simple articles, is very restricted for the same reasons as those already discussed in relation to the primary re-use of components; institutional attitudes and structures would need to change considerably before any improvement could be expected. Indeed, the resistance to secondary and tertiary re-use would be far greater than that for primary re-use.

The energy saving of these types of re-use is based on the same principle as that illustrated in Fig. 5.7 and 5.8, but in building it would be reasonable to expect that the energy saved through secondary and tertiary re-use would be generally less than that from primary re-use; this is due to the likelihood that more alteration would be required to components or articles in order to make them suitable for re-use in building assembly for which they were not designed.
Section Ten

Restrictions on the amount of Energy Savings Through Component and Material Re-Circulation

As pointed out in discussing primary component re-use, greater energy savings could be expected from re-using components than from recycling the materials in them; in other words, it requires less energy, for example, to disassemble structural steel members and reassemble them in a new structure than it would to disassemble, melt down the steel, fabricate it back into a structural section and assemble it into a structure. Re-use would therefore be the natural choice for energy savings. Unfortunately, a fundamental trade-off exists between re-use and recycling. As a material moves along the production sequence, the end product of each production activity has a progressively narrower possible range of uses. For example, iron ore has the potential of being used in any number of product systems, the number of uses diminishes when it is turned into mild steel and further reduces when it is rolled into sheet steel of a certain thickness. End use is again limited when the sheet steel is galvanised and is very restricted by the time it is fabricated into a cistern, for example.

Cox and Goodman (1956, p. 56) found in their study of the
marketing of building materials that manufacturers were quite aware of this progressive reduction in end uses which each production activity entailed. And it was natural, that most manufacturers operated on the 'principle of postponement'. Postponing each progressive step of the production sequence until a firm requirement existed for the next activity. This reduced the likelihood of mistaken production commitments which are difficult and sometimes impossible to reverse. This postponement principle also offered transport and storage advantages. The less a material or component is processed, the less expensive it usually is to store and transport it. Iron ore, for example, can be stored indefinitely outside with little security and can be transported in bulk by mechanised means without incurring any damage to the product. A steel tank, on the other hand, would probably require secured storage under cover and would involve a large amount of space because of the large volume of air being stored inside it. It would also require some packaging and could not be transported in bulk.

In deproduction the principle of postponement still applies, obsolete products being held as received and stripped only when required. The auto scrap provides an excellent example of this type of reverse principle of postponement. This does present a distinct disadvantage to deproduction operations because of the extra storage and transport requirements as compared to those involved in conventional production. The extra storage and transport requirements usually involved with components removed from buildings would increase conventional costs much more than it would increase energy costs.

In a conventional production sequence the largest use potential is at the beginning of the sequence and the least potential at the end of
Fig 5.10 Accumulative net energy savings through recirculation compared to demand for materials or components.

Fig 5.11 Obsolete products generated as a percentage of production requirements for various growth rates and product lives (Betts, 1973, Fig 2)
the sequence with deproduction this is reversed and because of this reversal a trade-off develops between energy costs and re-circulation potential. The earlier a component or material is reintroduced into the production system, the greater the potential demand for the product, but pushing an item back into the system requires additional energy for both deproduction and reproduction. This compromise between increasing the potential for recirculation at the expense of reducing the amount of potential energy savings through recirculation is illustrated in Fig. 5.10.

The most fundamental restriction as to the amount of energy saved through recirculation of either components or materials involves two basic parameters: 1) the rates at which the total demand for the material or component is growing and 2) the length of the in-use lifetime of a material or component. Where total demand is growing through time, the materials and components becoming available through obsolescence can never be more than a fraction of the currently required supply of these same materials or components, even with 100% recirculation. For a given rate of growth, the proportion of obsolete products available is smaller, the longer the period the product has been in use. A general representation of this relationship is shown in Fig. 5.11. The choices in a growth situation are, a short life product with a high potential for re-use and recycling, with their inherent energy savings or a long-life product that is made with a higher portion of materials coming from either primary sources or by-products.

\[1\] One advantage that 'new' secondary sources of materials has over 'old' sources is the fact that by-products are closely linked to current demand.
In building, the latter is the better choice for the following reasons:

1) buildings are naturally long life products,

2) the recirculation of obsolete components or materials does require some energy expenditure which accumulates in direct proportion to the number of cycles,

3) when buildings are taken down only a very small proportion of the components or the materials contained in them are in fact recirculated irrespective of the potential energy savings.

A neat little prescription that is often given is: 'cycle and re-cycle'...re-cycling - fails to go to the root of the matter. Why tolerate a high rate of waste and then try to cope with the problem of recycling? We might do well to distinguish between permanent and ephemeral goods. A life style which puts primary emphasis on the consumption of ephemeral goods and services...creates innumerable problems of pollution, tends to ruin the environment and inevitably runs up against severe resource bottlenecks.

(Schumacher, 1974)

Despite Schumacher's valid remark there is no excuse for the appallingly small amount of material or components actually recirculated from demolished buildings, even though there are difficulties and theoretical limitations involved with such re-circulation.
CHAPTER SIX
REDUCING PRODUCTION ENERGY DEMAND

Chapters Four and Five dealt with energy savings which are directly related to the production sequence. Chapter Four was concerned principally with the possible application of technological innovations to a production system, considering raw materials from primary sources; Chapter Five dealt with the possible energy savings during production, considering secondary sources, including the utilization of by-products, the recycling of obsolete scrap and the re-use of components. This Chapter is divided into three sections and is not directly concerned with the production system; rather it deals with what could be considered passive methods of energy savings.

The first section deals with extending an end product's life, involving product re-use and the efficient use of end products, both of which have the effect of reducing the overall demand for the product concerned, thus avoiding production and deproduction activities completely. The second section deals with factors which affect the life of a building, and consequently determine whether or not energy savings can be realized through an extended life. And the third section is concerned with design considerations, if new construction is required; this section is again mainly concerned with the idea of avoidance - using the minimum amounts of material and using intrinsically less energy intensive materials.
Section One

Reducing Demand by Utilizing Buildings Effectively and Extending Their Lives

We may interpret the human allocation of resources in the built environment as a problem of optimising the utilization of energy and so adapt policies for the provision of shelter which reduce the demand for new buildings by extending the useful life of existing buildings to the maximum length. (Jones, 1973, p. 4)

The strongest arguments for both intensifying the use of buildings and extending their lives through rehabilitation, maintenance or building re-use, have to do with the savings of resources.\(^1\)

For the Meadows and Randers (1972, p. 20) expression, Pw/L (for the flow of materials in the steady state discussed in Chapter Four), we can see both the amount of primary resources needed for new construction, and the amount of waste involved in their production could be reduced by either minimizing the amount of products required (P) or as Jones suggests above by extending the life (L) of the products in use, both of which are complementary. This would apply to both materials and energy, but (as mentioned in Chapter One) the materials usually used for construction are very abundant and, as long as we use capital energy instead of income energy, saving in energy is far more critical. As Berry (1972, p. 9) points out: "so long as matter is consumed within a region we inhabit, there is no real shortage of any substance; there can only be a shortage of thermodynamic potential to do the work required to recover the substance". (The energy and resource saving implications of reduced product demand will be discussed at the end of this section.)

\(^1\)Another very strong argument is summarized by J.E. Gordon when he states that, "a 20% increase in the effective working life of a product is more or less equivalent to a 20% increase in productivity".
Effective Use of Existing Buildings

Before considering ways of extending a building's life, one needs to question how effectively buildings are currently being used. There is considerable evidence that scope exists for using our building stock more effectively for their designed function, without reverting to building re-use through either function or locational change. In Britain, there are examples of empty buildings of every major type. One could well understand churches being empty where supply has outstripped demand but one has difficulty understanding the vacancy of buildings which are of the types that are in short supply.

The most notable example occurs in the field of housing; Bowen (1972) estimates that in 1972, 10,000 council houses alone, were vacant "because they have been built where people do not want to live or are the wrong size." Laidlaw (1975) indicates that under-utilization occurs with government backed 'advance factories' as well. In these cases, it appears that local authorities have some problems in matching supply with demand. It could be argued in the case of public housing that bureaucratic inertia inhibits the development of more flexible allocation policies, for example in letting family houses to single people; and in the case of factories, the authorities' attempt to carry out a social/industrial regional policy may not be sensitive to the real market. The departmentalization of government can also lead to complete building redundancy. This is particularly well illustrated in the medical field where clinics have been provided with no staff to run them. Government, however, is by no means the owner of all empty buildings; there are numerous examples of privately owned buildings being vacant as well. The almost empty shopping complex at Gateshead and Centrepoint bear witness to private
commercial buildings lying empty, and much privately rented accommodation is unoccupied due to the 1974 Rent Act.

Effective use of our building stock is not limited simply to occupying empty buildings; it also applies to intensifying the use of already occupied buildings, using them more effectively. The Department of Education and Science Report, *Space Utilization in Universities and Polytechnics* (1975) shows that often more students could make use of existing facilities. It would not be unreasonable to expect similar judgements of other types of buildings, such as offices, but under-utilization of buildings is found more often in those with uneven or fluctuating demand, such as assembly halls. The once-a-week use of a church, or the vacancy of education buildings over the summer months are classic examples of fluctuating uses.

Intensifying building usage can save both running energy and costs; it also raises the real issue of whether or not we need to invest production energy in constructing or modifying buildings, to provide buildings which could very well already exist, but are unoccupied or under-utilized. This is largely a question of building management, but it is also a question which planners and architects need to ask themselves before starting work.

**Extending a Building's Life and Product Re-Use**

Cultural factors have been traditionally the most common arguments for extending a building's life. In fact, these considerations, for all practical purposes, are exclusively 'pro' preservation and are summarized by the Civic Trust's (1967, p. 129) criteria for preserving buildings:
First, the building is commonly agreed to be a work of art in itself...

Second, the building is a notable example of a particular architectural style or period...

Third, the building holds a historic place in the community...

Fourth, the building has particular historic association with great men or great events.

Fifth, the building's presence lends to the surrounding a sense of sequence of time...a town without old buildings being a town without an apparent past, resembling a man suffering from loss of memory.

An equally important though often neglected argument for extending the life of a building is the saving of resources, an argument which is becoming increasingly more relevant. It is, today, unusual for old building materials or components, once removed from their original structure, to be re-utilized in any fashion, even though recirculation would save both materials and the energy invested in them. At present the most likely and logical way of avoiding this wastage is simply by not destroying existing buildings in the first place - using the materials and components which are contained in them in the original structure. There are indications that in Britain, and other countries, retaining older buildings is gaining acceptance among the public and building professions.

One of the principle ways of retaining buildings by extending their life is through the principle of product re-use. Through re-use one can avoid some of the constraints that normally affect the life of a building, constraints which will be discussed in the next section. Product re-use is of a fundamentally different nature than the component re-use discussed in the last chapter. Component re-use is dependent on
production and de-production activities while product re-use is achieved through functional or locational changes without absolute dependence on physical change or production activities. Of course, eliminating or minimizing these activities would result in greater energy savings. In discussing product re-use, we shall consider primary, secondary, and tertiary methods in turn, as was done with component re-use in Chapter Five (see Table 5.1). A brief description will be given of each of these methods along with examples and past and present trends in their use.

The Primary Re-Use of Buildings

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<th>PRIMARY RE-USE</th>
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In primary product re-use the general function of a particular article remains the same while the specific function changes. In a building context this would involve a building being re-used with the general function of providing shelter remaining the same, while the building's specific use might change from, say, a commercial to a residential use. In the past few years there has been much publicity given to the idea of this particular type of building re-use. The popularity of it is indicated by Sherban Cantacuzino in his book *New Uses for Old Buildings* (1974) which is also one of the best summaries of the current state of
primary building re-use. The idea is, however, by no means new; in fact this type of building re-use was probably as common if not more so in earlier historic periods.

The most notable period for this type of re-use in Britain occurred during the Reformation when a great many religious buildings were made redundant in a very short period of time. Besides using these buildings as a source of material and building components, they were often functionally re-used. In Gloucestershire, for example, the Grey Friars' college was transformed into a brewery; while in Malmesbury, the Abbey buildings were used as weaving sheds. In London the Monastery of St. Thomas was used for housing poor, sick and helpless; and today's Christ Hospital was founded in what was Grey Friars' Abbey. In very many cases, religious buildings were modified and served as manor houses or country mansions, as in the case of the old abbey at Lacock.

It is not surprising that this type of re-use was, and should still be, common, when one considers that most buildings were and still are designed to shelter man from the elements. He is the common denominator and his comfort falls within a very limited range which remains the same regardless of building types; furthermore, room sizes also fall into a relatively small range as Peter Cowan (1963, p. 69) describes in his article on growth, change and ageing of buildings.

The largest single group of rooms almost always occurs in a very narrow size range, between 100 and 150 square feet. Hospitals contain a fairly typical cross section of social functions, and since most rooms in houses are also about this size, it may well be that the majority of human activities occur in spaces of under 200 square feet. In addition, it is quite reasonable to suppose that rooms of 150 square feet will serve a very large proportion of human needs.
Even the basic room sizes of ancient buildings are amazingly similar to today's, even though they probably would have contained more activities and people. Indeed, archaeologists identify rooms not so much by their size or shape but by the fixtures and objects left in them.

Today access and services have as much, if not more, influence on the number of potential uses of a space as either shape or size. The general lack of services in the past, and the fact that commerce, industry and agriculture were carried out at much smaller scales (often within the home) makes primary re-use far more likely as one looks further back in history. Innocent (1971, p. 2) suggests another factor which was probably more prevalent in the past - descent of buildings themselves down the social scale. He cites the example of a coal miner's house in South Yorkshire which was said to have been the manor house of the village; and the old palace at Hatfield eventually became the stables of an early Renaissance Mansion. Today in Britain, buildings seem, if anything, to go up the social scale with humble cottages and stables providing shelter for the affluent!

The descent of buildings should really not be based on a social scale, but on a building's capacity for change, with the general higher performance buildings (i.e. high structural capacity, large spaces, exacting environmental control requirements) gradually descending into less physically demanding uses, such as storage, sales, even housing. Hopefully people will begin to remove the labels applied to buildings based on original use (i.e. schools, churches, barns) and think of buildings as spaces adaptable to many different types of activities much in the same way as the military viewed the Nissen huts in the last war, or the
manufacturers of fabricated buildings view the use of their standardized units. Designers are beginning to think about the primary re-use of buildings by designing "adaptable" or "flexible" buildings, a subject discussed in more detail in the next section in relation to functional obsolescence. However, it is encouraging to note here that the RIBA, under the leadership of Alex Gordon, recently stimulated considerable interest in the study of "long-life loose-fit" building design.

The Secondary Re-use of Non-architectural Structures

The secondary re-use of end products involves not only a functional change in the specific use of an article from its designed function, but also a change in its general function.

Using an empty beer can as a rolling pin would be an example of the secondary re-use of a simple product. The can is not used for either its specific purpose, i.e. as a container for beer, or its more general function as a container. The unlikelihood of using buildings for anything but buildings excludes their secondary re-use. However, the secondary re-use of non-architectural structures outside the building system as buildings is quite feasible; obsolete vehicles being re-used
as static shelters is the most notable example. There are numerous cases where old railway rolling stock, lorries, buses, boats, even plane fuselages have been used in an ad hoc fashion as buildings.

Normally, the scope of such re-use is limited by public opinion and is only carried out in developed countries by 'drop-outs' or farmers. Perhaps the most notable exception, as well as the most sophisticated example of this type of secondary re-use, is the proposed American space laboratory which will be housed in the 50 foot third stage of an expended Saturn V rocket. Unlike most examples of re-use and re-cycling, this type has very little historical precedence until the mid-eighteenth century when transport vehicles started to be produced which were large enough to provide shelter. The only exception before that date would have been the use of overturned boats for basic shelters.

The Tertiary Re-Use of Buildings

The tertiary re-use of a simple independent product is achieved by using it as a dependent component in an assembly. This type of re-use was discussed in the last chapter with reference being made to the use of
bottles and cans as simple walling units. A building is a product fixed
to a particular site and infrastructure; and the tertiary re-use of such
permanent structures is dependent on a locational change and not a
functional change, as in the case of primary and secondary building
re-use. Locational changes can be accomplished by removing the entire
building as a whole or by disassembling it into elements or smaller
components which are themselves moved and re-assembled.

In the past, moving an entire building as a whole, would be very
unusual because of inadequate vehicles and roadways; though Salzman (1967,
p. 198) in his studies did find a few references to houses being moved
bodily over short distances by using a combination of pulleys and
rollers. Today, moving buildings on wheels by road is quite feasible
in many cases, and is an alternative to new construction which is
probable under exploited. The use of air cushions, a recent development
for moving heavy and bulky items, might make it even more feasible in
the future to move buildings overland.

Water transport is another mode suitable for large loads and the
problems of overland cables and bridges encountered when moving buildings
by land could be eliminated by its use. A good example of moving
buildings by water occurred in California in 1964 when a group of timber
framed two-storey apartments, built during the last war, for Naval
dependents, were removed from their original site in Long Beach and

1 Another slightly more futuristic proposal for carrying bulky and
massive objects which would also avoid power lines and bridges would be
the use of airships; an early illustration by Buckminster Fuller showed
one of his light weight high rise buildings being delivered to its final
site dangling from an airship.
barged down the coast to provide housing in Northern Mexico¹.

The increasing trend towards sectionalized or mobile buildings which are designed for movement by road or rail will naturally increase the potential for tertiary building re-use. In the U.S., mobile homes are taking over the lower end of the housing market². This is also happening to some degree in Britain, though there is a strong stigma against using them. The architectural profession's attitude in Britain towards such mobile buildings is best summarized by the RIBA's paper on housing policy presented to Anthony Crosland in 1975. The report was highly critical of mobile homes because they were considered a 'perishable' and depreciating asset, constituting 'a very poor investment compared with permanent housing'³. (The Architects' Journal, 15 January, 1975, p. 145).

The more common form in Britain of re-use through re-location requires the disassembly of the building into elements or smaller

¹A more unique form of moving buildings by water occurs among the many inlets and islands along the coast of Maine, where traditional wood frame structures are eased into the sea and towed to a new location.

²In 1972 mobile homes accounted for 97% of the single-family housing market under $15,000 in the U.S. (excluding housing constructed by owner-builders and housing built for rent), 80% under $20,000 and 67% under $25,000; or 45% of all new single-family housing. (Engineering News Record, ENR, 10 January, 1974).

³The strength of such an argument is questionable; permanent housing is also perishable, and one important cause for the appreciation of permanent housing is not due to the construction but due to the appreciation of the land to which it is permanently attached.
components to facilitate the moving operation\textsuperscript{1}. Some forms of construction lend themselves to this type of relocation. Salzman (1967, p. 199) mentions that in Medieval Britain "...it was a comparatively simple matter to take a timber building to pieces, remove it, and re-erect it elsewhere and this was frequently done". He devotes two pages to examples of such building re-location. Typical of these examples was the "chamber 40 feet long by 18 feet wide taken from the manor at Thundersely in 1363 and set up as a hall in Rayleigh Park, in Essex, at a total cost of 73s. 4d." The appendices also contain references to a number of contracts for the relocation of buildings; representative of these was an agreement for pulling down a timber framed house in Brede and its re-erection at Rye in 1374.

The disappearance of timber framed structures in Britain severely limited the tertiary re-use of buildings, until the re-emergence of pre-fabricated structures, first in iron in the nineteenth century, and later in wood, steel and eventually pre-cast concrete. The advent of the pre-fabricated building made of the latter group of materials was largely brought about by the two world wars. A review of any Exchange & Mart

\textsuperscript{1} One might ask what the difference is between the primary re-use of building components and the tertiary re-use of buildings involving assembly and disassembly. In the latter case the components removed are considered as belonging to a particular building which basically remains the same before and after re-location. In component re-use the disassembly produces components with no particular identity with structure from which they were removed; when re-used they constitute only a part of an entirely new building. If one were trying to re-use all the components in order to maximize the re-use of components contained in a particular building, the tertiary re-use of the building would most likely result in a higher proportion of the components being actually re-used, than if the building were dismantled and the components incorporated into a number of different structures.
clearly demonstrates that "pre-fabs" from the last war (e.g. Seco and Arcon houses and nissen huts) along with pre-fabricated agricultural buildings, are being re-used in a tertiary fashion today on a very informal scale.

Currently pre-fabricated buildings dominate the agricultural industrial building market and sectionalized houses, schools and office buildings are gaining acceptance. Most of these buildings are mechanically jointed and quite capable of tertiary re-use. Some manufacturers of these 'system buildings' have developed systems specifically around the issue of demountability, for example the 'demountable car-park' developed by Dow-Mac concrete Limited (AD, September 1971, p. 210). Tertiary building re-use is one method of re-use with growing potential. This type of re-use not only makes environmental and energy sense, but it also can be economical in the conventional sense, as shown by Trevor and Rabeneck (1974) in their article concerning student self-build housing consisting of re-erected 'Uni-Seco' pre-fab houses.

It would be appropriate to close the general discussion on the various methods of re-use on the architectural profession's reaction to it. Primary re-use has generally been accepted by the designers; indeed one of the most prolific examples of primary building re-use involves the homes or offices of architects, who have converted small agricultural, industrial, educational, religious, or commercial buildings to meet their needs. Secondary re-use of buses and tram coaches etc. into buildings has been largely ignored in the architectural field, while tertiary building re-use receives mixed reaction. The profession; as mentioned earlier, shuns the 'mobile' building and in practice most 'demountable' buildings are designed by the firms actually producing them and not
architects. Nevertheless, there are well known architects, such as Cedric Price, Yona Friedman, Konrad Wachsmann, Buckminster Fuller, and the firm of Piano and Rogers who strongly advocate 'demountable' buildings. But one wonders about the enthusiasm for demountability if such well known architects were to be asked not to design the original prototype demountable building, but were instead asked to specify site adapt, and supervise the re-erection of a demountable building designed
by someone else. The reaction would probably be similar to that of Walter Gropius when he was faced with this situation, described by Paul (1974):

The machine hall of Gropius's Werkbund modern factory which is so often held by historians to show Gropius at his early best...was not designed by Gropius at all but was a re-use of a hall designed by the firm of Breest and used the previous year (1913) at the Leipzig Building Exhibition. Its use was forced on Gropius by his patron K.E. Osthaus, against the Architect's wishes. In fact, Gropius wrote to Osthaus asking him how the hall could be integrated into the overall design!

Potential Energy Savings Possible Through Extended Product Life and Effective Produce Use

Both using a product to its full potential and extending its life result in reducing the demand for the product, which effectively reduces the requirement for both materials and energy otherwise required to meet the demand. Needless to say, reducing amount of energy and materials would reduce the environmental impact as well. One may reduce demand by using long life products more efficiently in all product systems. The substantial energy savings possible have already been established in the beverage containers and automobile product systems.

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1 Many of the 'demountable' buildings projects by these architects are contained in:  
Architecture: action and plan (Cook, 1967)  
Architecture 2000 (Jencks, 1971)  
New Directions in British Architecture (Landau, 1968)
Hannon (1972) in analysing container systems found that the 'returnable' beverage container was thermodynamically the most efficient method of packaging, assuming adequate trippage. He calculated that 16 oz. refillable bottles use about 1.4 kWh less than one-trip short-life throw-away glass bottles and 0.7 kWh over disposable steel cans. Berry (1972, p. 14) in analysing the energy cost of automobiles comes to similar conclusions for the automobile systems.

Extending the life [of an automobile from the present 10 year life to 20 or 30 years] could achieve an energy saving of about 50-100%, whereas re-cycling the materials in the car apparently achieves savings of about 10% now and probable less than that in 1980. Of course extending a product's life, and recycling the maximum amount of materials contained in it, are quite compatible objectives; even though, as pointed out earlier, in a growth situation extending a product's life does reduce the amount available for recycling. In the building situation, extending life is more appropriate than recycling because of the difficulty in recycling most common building materials, unlike either the automobile or beverage container whose life is relatively short, and which are generally made of thermoplastics easily recycled.

The same scope exists for saving energy through extended life in the building system. The SAVE Report (1975, p. 1289) mentions "that the equivalent of ten tons of coal is needed to build a new house, but only one ton is needed to renovate an old one." By applying these figures to British housing statistics one begins to appreciate the

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1 Bousted (1973) in comparing non-returnable two pint plastic milk bottles with returnable one pint glass bottles found that four trips were required before any energy savings occurred with the returnable bottle and seven if the plastic containers were used as fuel. However, Hannon, in his study assumed eight trips, this on the Illinois bottling industry's average rate in Chicago of eight, even though in rural areas the averages were up to thirteen.
potential energy savings possible. In 1971 there were about 19 million dwellings in the U.K. During that year roughly 100,000 disappeared for various reasons (representing about 0.5% of the stock), while about 372,000 (representing about 1.9% of the stock) were built, which produced a net gain in stock amounting to 272,000 units (1.4% of existing stock). Applying the SAVE energy figures to these housing statistics would have meant an expenditure of the equivalent of 3.72 million tons of coal, (372,000 units @ 10 ton of coal per unit). If on the other hand the 100,000 units that disappeared were to have had their lives extended through rehabilitation the energy costs would have amounted to 272 million tons of coal (Mtce) for new construction (272,000 units @ 10 tons of coal/unit) plus 0.1 Mtce for rehabilitation (100,000 @ 1 tce/unit) or a total of 2.82 Mtce. If one were to add the energy costs of demolition and disposal of the 100,000 units which actually disappeared the energy savings through extended life would have amounted to roughly 1 million tons of coal in 1971.

Of course some of the houses that were demolished in 1971 had to be (nothing lasts forever!) and that at least some made way for roads, schools, etc. The arithmetic was intended only to indicate the scale involved. Even though a hypothetical exercise, the calculations clearly do show the wastefulness of a short life throw-away philosophy and brings into question the factors which affect a building's life, a subject dealt with in the next section.
Section Two

Factors Affecting a Building's Life

It is clear from the last section that retaining buildings, could be justified on both cultural and environmental grounds, particularly in the conservation of energy. In this section we shall examine, mainly in relation to housing, the factors which prevent an extended life, their validity and possible ways of avoiding them - these factors are the usual cause for the destruction and loss of a building and the materials and energy which were invested in it - the factors which prevent an extended life and the reduction in product demand which it can bring. These factors fall into two broad categories: external and internal. External factors do no relate to the building itself, but the physical condition of the areas surrounding it and to the existing economic, technological and social climate. Internal factors relate directly to the adequacy of the building itself. Each of these categories will be discussed, but generally speaking internal and external factors are far more easily expressed in financial terms than the resource or historical considerations which provide such a strong argument for building retention and long life mentioned in the last section.

External Factors

External factors usually fall into one or a combination of the following four categories:

1) the original need for rebuilding disappears, (stables becoming redundant with the advent of the automobile, mining buildings located where the mineral deposits have become uneconomic, or churches becoming redundant with the dwindling or disappearance of the congregation).
2) the infrastructure supporting the buildings is inadequate (e.g., roads, parking, or public utilities.)
3) a change in land use (e.g., land being re-zoned for new roads.)
4) an increase in land value.

The first category, in which the original need for the building disappears, can be overcome by the primary re-use of the building; of course, land use and the adaptability of the building would be critical in assessing the potential for this type of re-use. The second group of adverse factors can only be dealt with by either the acceptance of the existing infrastructure, which is often inadequate only with respect to regulations and not actual performance, or by eliminating the deficiencies.

The third and fourth categories concerning land use and land values are closely related. It is the increase in the value of sites rather than anything else which brings an end to the economic life of buildings. There is some scope for government intervention, in regulating the supply of available sites in order to reduce commercial pressure on existing built up areas, which would allow for a better match between the economic and physical life of buildings.

Another approach to reducing the possibility of demolition due to all four of the external factors mentioned is by moving the building itself, i.e., tertiary re-use, since these external factors are usually based on location. Even though this would appear to be a rather radical

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1 An interesting proposal for reducing commercial pressure on selected sites without inhibiting growth is the concept of 'development of rights transfer' proposed in Chicago whereby the owner of a building whose floor area falls short of that allowed on the site can sell his unused expansion rights (under zoning laws) to another developer or building owner: the buyer of the right then could use these for expansion on other sites. (Hall, 1975).
approach, Switzer (1963, p. 76) in his prize winning article "The Life of Buildings in an Expanding Economy" suggests that current trends in construction "lead inevitably to the building made from factory-produced components which can be dismantled and re-erected elsewhere,...so that the economic life of the building is as long as the life of the components". Providing for possible tertiary re-use is particularly applicable in situations like those arising out of the development of North Sea oil, where the demand for housing and industrial buildings could well fall off after the initial development phase. The general attitude, however, towards portable buildings in Britain is discouraging this trend. This attitude seems to be based on the false assumption that an increase in portability leads automatically to a decrease in durability. However the physical durability is strictly related to the material used and moveable buildings could in some cases be designed in very durable materials if so desired.

Internal Factors

Internal factors affecting a building's life are concerned primarily with the question of obsolescence; this can be divided into three general types:

1) physical, i.e. what exists has decayed or been worn out.

2) functional, i.e. a mis-match between what exists and what is required.

3) symbolic, i.e. what exists is 'out of fashion'.

Of the three the first type of obsolescence is most easily evaluated objectively, and the last, least easily. None of these types of obsolescence affect a building in a uniform manner, but affect different areas of a building to differing degrees. Even though there are numerous
areas affected they can generally be classified into four main building divisions: (1) the main fabric, (2) finishes, (3) user equipment and services to it, (4) environmental control equipment and related services. Each type of obsolescence will be discussed along with the building divisions which they most affect.

**Physical Obsolescence**

Physical obsolescence is involved with the decay or deterioration of a component caused by occupational or mechanical wear or physio-chemical deterioration, or damage due to environmental conditions, fire or pests. This type of obsolescence has the most marked effect on finishes and equipment of various sorts, which have moving parts. The last item normally to be affected is the main building fabric, a designer should distinguish components with different rates of obsolescence to allow easier access for maintenance and replacement of those items with shorter lives. Designing in such a way reduces the chances of a few obsolescent items rendering the entire building obsolete. Physical deterioration is perhaps the most rational reason for demolishing a building. Unfortunately as Switzer (1963, p. 71) points out:

> The life of something as durable as a 'permanent' building is very elastic and in practice it is usually brought to an end not because the structure is literally worn out, but because of changes in the demand for it. In other words, it is normally the decision to replace the building which precipitates its discard and demolition, rather than the reverse.

**Functional Obsolescence**

Of the three types of internal obsolescence, functional obsolescence has the most significant impact on a building's life. Unlike the other three types of obsolescence it is not generally concerned with
the deficiencies in the quality of what already exists, but is largely concerned with the deficiencies in the quantity or the arrangement of what exists. The two building divisions most affected by functional obsolescence concern 1) user equipment and its related services, and 2) the morphology of the building's main fabric; and it is largely these two areas which define the activities which can take place in a particular space. This accounts for the importance of functional obsolescence. The spaces and equipment themselves are passive while the requirements of the owner or occupant using the space and equipment change with time. The requirement put on space and equipment, of course, can also vary with changes in the user even though the overall building retains its general function, (i.e. remains an office or a house). As long as a mis-match occurs between what exists and what is required the parts of the building could be considered functionally obsolescent.

The technical solution to reducing the mis-match between either the morphology of the building or the equipment servicing it and the user or owner of the building is to design and use 'flexible' or 'adaptable' buildings. As mentioned earlier this type of design would also increase the potential for the primary re-use of the entire building.

1The terms flexible and adaptable are often used interchangeably, however there is a difference. Flexible buildings require a constructional technique by which components or equipment can be easily moved. In other words the building is capable of being moved or flexed into different configurations. Adaptability on the other hand, emphasises planning and layout rather than constructional technique, and service distribution. It is based on carefully considered variation in room sizes, the relation between rooms, slightly generous usable floor areas or provisions for adding more floor area, generous room openings, and little overt expression of function - in other words a space which is adaptable to many activities without physical modification.
building. Designers who are interested in the 'flexible' or 'adaptable' building tend to look at the obsolescence problem as a strictly technical one, and devote much effort in designing ingenious "kits of parts". Even though designing with functional obsolescence in mind, can minimize its effects it by no means eliminates the possibility of a building being demolished because of functional obsolescence. Indeed the very fact the numerous buildings which were not specifically designed around the criteria of flexibility or adaptability have in fact been converted to new uses; suggests that special designs are not vital in preventing functional obsolescence.

The problem could be to some degree psychological; Hillier and Leaman (n.d., p. 8) point out that "research has shown that the common state of space is to be empty and that the obstacle to more intensive use may be the tendency to identify spaces by named functions, rather than by the basic physical attributes of the space". (This problem of labelling applies not only to the spaces within a building but to the entire building itself which would affect primary building re-use).

Ownership and control have a great deal to do with functional obsolescence as well. Rabeneck, Sheppard and Town (1974, p. 76) found

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1 One of the strongest arguments in favour of adaptable/flexible designs are the potential reductions in rehabilitation costs. The GLC Department of Modernization and Rehabilitation found that rehabilitating a conventional council house could cost up to £1800 more than PSSHAK, an adaptable/flexible housing scheme (Hambi and Wilkinson, 1974, p. 487). Interestingly, schemes like Hambi and Wilkinson's PSSHAK, are promoted mainly on the ground of user participation. To sell such projects in Britain it would be better not to emphasize this point. Hambi and Wilkinson themselves (1974, p. 486) remark that both authority architects and housing managers feel threatened by such projects. In fact they found that participation was discouraged by a "conscious attempt to prescribe, in the form of standard plans as well as attached rules and regulations, a standard performance pattern to which the user must conform". Since, in reality, the authority establishes the need for the user and often pays for any modernization to meet those needs, the argument for adaptable buildings for public housing should emphasize savings in rehabilitation costs to the authority and not user participation.
that adaptability in housing was not of vital importance to owner occupiers "...his central concern is gaining security and rights of being an owner...but to the renter a flexible layout can be important as an extension of the very limited franchise which he holds on his rented property".

The owner is more likely to meet his changing requirements by moving house. Even with the renter the actual moving of walls and fixtures in a flexible scheme is not always essential for satisfaction. Again Rabeneck, Sheppard and Town found that in 'flexible' houses it was "the mere knowledge that the layout of the dwelling could be altered, if so desired that had a positive effect on the resident's satisfaction". (1974, p. 76). The group goes on to mention (1974, p. 78) that successful flexible/adaptable housing depends a great deal on an authority's "good management, their preparedness to undertake an effort to help the occupants". (qualities that would go a long way in satisfying the user of even a traditional 'non-flexible' house). Authorities are, however, likely to be far more concerned with "the critical problem of administration as to whether occupants should be allowed [emphasis mine] to arrange buildings in a way that could countervene building regulations, safety and health codes etc." (Rabeneck, Sheppard and Town, 1974, p. 78).

This issue of administration and authority brings us back to the question of who actually determines functional obsolescence?. The changing requirements which cause functional obsolescence are themselves quite often abstract being based on subjective judgements. Is a change in requirements really essential or is it more an expectation or aspiration? More importantly, whose requirements are they? Are they user requirements or non-user requirements? The mis-match which is occurring more and more often is not so much between user and building, but between the requirements of the user and non-user. The actual user of a space often is very
flexible himself, he bends to the building or space and his requirements are not set down in definitive terms; they have a certain amount of latitude. It is the non-user requirements, i.e. regulations, codes and standards, which establish the inflexible requirements, they must be rigid to be administered. Thousands of buildings have been lost because of the mis-match between non-user requirements and the buildings they were applied to. One might think that user requirements would come first since the user is directly affected by a particular space or building, but so often throughout the developed world the reverse is true. The over-riding of user requirements by non-user requirements has undoubtedly created problems of deficiency, which are not perceived by the occupier.

All forms of obsolescence, but especially functional obsolescence based on non-user requirements, can be particularly destructive because of the tendency to condemn an entire building even though only a specific and often very small division of the building is affected by obsolescence, or is considered substandard. For example, a house lacking hot water could well be deemed substandard, when in actual fact it is the provision for heating water which is substandard and not the rest of the house. One way of reducing unnecessary demolition would be to analyse building types not so much in terms of overall buildings but in terms of specific deficiencies. In other words, in a housing area deficiencies would not be in terms of substandard houses but in terms of deficiencies in hot water or in insulation. Some authorities do survey specific deficiencies, unfortunately, according to officially recommended procedures, they are

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1 John F.C. Turner is one of the most outspoken critics of the "contradiction between what the central body considers desirable and what the users consider desirable." (1972, p. 153.)
"scored" in order to establish an overall ranking in assessing priorities for rehabilitation, and thus become abstract qualities which apply to the entire building.

Closely related to this question of non-user building requirements is another tendency for some government bodies to relate building standards to social performance, particularly with regard to housing. A vast number of houses have been lost because of this notion, usually in slum clearance programmes. The argument crudely stated is that bad housing means bad people and the housing is bad because it usually does not meet non-user standards. Removal of the offending houses with the possible creation of new houses which meet the standards, results in a transformation of the people for the good. The fact of the matter is that the conclusions of architectural research to date "...point to the lack of any simple relationship between people and buildings." (Hillier and Leaman, n.d., p. 8).

Despite this tenuous connection between house and resident, demolition continues. The most notable recent example occurred in St. Louis in 1972 where the public housing authority dynamited 20 eleven story housing blocks of the Pruitt-Igoe estate built in 1951 largely to "stop vandalism". The items being vandalised were eliminated, but the vandals continued to roam. Currently in Britain demolition of public housing is being considered for similar reasons, the Wirral housing estate outside Liverpool, built in the early 1960's, and the Quarryhill estate in Leeds, being the most notable cases. Interestingly both the Pruitt-Igoe and the Quarryhill projects were acclaimed as original pieces of architecture when built.
Symbolic Obsolescence

Pruitt—Igoe and all that was associated with it could, in a sense, be considered symbolically obsolescent and the act of blowing it up was a symbolic gesture of action against what it stood for. Symbolic obsolescence is normally far more mundane and its effect much more restricted to the removal of 'out of style' building components and not the entire building itself. As with physical obsolescence, finishes and user equipment are most affected by fashion and trends. This overlap is somewhat unfortunate, for equipment easily removed on the more valid grounds of functional or physical obsolescence, is also far more susceptible to being removed on fashion grounds alone; because obsolescence based on style tends to precede that of other forms of obsolescence, equipment can often be removed before it ends its useful life. This can be seen in the case of electric cookers whose turn-over is far more rapid than one would expect from a built in range, even if it were electric. In Britain it is unfortunate that so much of the resources spent on house improvement schemes is devoted to replacing fixtures or equipment often on the grounds of fashion alone. Old bathtubs and sinks, for example, quite often perform just as well as the 'new models' that replace them. Resources for improvements could be better spent on other improvements; insulation would be the best from the energy point of view.

The Economics of Extending a Building's Life

We have already mentioned exterior economic pressures to demolish, most of which are directly or indirectly tied to land values and use. These pressures are often coupled with pressures to demolish existing buildings on the grounds of obsolescence. This is usually the case when
high income buildings such as offices are being proposed in place of housing. However external factors have much less significance when the land use does not change.

Housing provides perhaps the best example on which to comment on the economics of extended life. Local authorities have traditionally justified demolition on the grounds of obsolescence alone, the properties being considered substandard or 'unfit for human habitation'. But there have been efforts to establish economic criteria as to whether one should extend the life of existing stock through improvement or demolish and build new. The economic model developed by Needleman (1965 and 1969) to determine whether housing should be rebuilt or renovated is perhaps the best known. Needleman, in developing his model, argues that generally it is considerably cheaper to modernise than re-build, which by implication means more dwellings could be provided for a given expenditure if modernisation were emphasized rather than re-building. Needleman's arguments are questioned by Sigsworth and Wilkinson (1967) who modify his model

—in Needleman's model, expressed algebraically below, renovation is economic if:

\[
b > m + b(1 + i)^{-L} + \frac{r}{i} \left[ 1 - (1 + i)^{-L} \right]
\]

where

- \( b \) = the cost of demolition and re-building
- \( m \) = the cost of adequate modernisation
- \( i \) = the rate of interest
- \( L \) = the useful life of the modernised property in years
- \( r \) = the difference in annual running costs of renovated property against running cost of new property

The problem with this model is not so much the algebraic relationship between the above factors, but the near impossibility of quantifying all of the essential factors contained in the model (which also form the basic of the Sigsworth and Wilkinson model) — rates of interest (i) and the difference in running costs (r) are subject to abrupt arbitrary changes over a period of time; the cost of demolition and re-building (b) and 'adequate' modernisation (m) can vary violently between estimates and in relation to final costs, and there is virtually no way of accurately predicting a building's life (L) whether new or modernised because of the numerous unknowns which can affect the life of a building.
slightly and arrive at the opposite conclusion - re-building is generally cheaper than renovation which indicates the controversy of the subject.

Needleman's conclusion which favours rehabilitation over re-building on the grounds of cost savings however, is supported by others, perhaps the most notable being the building economist P.A. Stone (1970 and 1971).

The quality of the urban environment depends far more on the standard of existing buildings than on the standards of the comparatively small increments of new buildings. For various reasons the standards of many new buildings, particularly buildings in the public sector, are set far too high in relation to the standards of existing stock. Far too little is spent on the maintenance and improvement of existing buildings. (Stone, 1971, p. 842)

More recently the Royal Institute of Chartered Surveyors, who have never been in the vanguard of conservation, in their study The Economics of Conservation (1974) show in an unbiased way that "it can often make better sense to restore and to modernize old buildings than to tear them down"; examining a number of refurbished buildings, the authors found that comparable new accommodation would not have been significantly more economic.

There are other economic factors which could be used to argue for improvement instead of rebuilding but which are usually ignored because of the difficulty in quantifying them. The problem of quantification should not however detract from their validity. The social disruption and moving expenses caused by demolition and

\[1\] Needleman (1965) also argues in favour of rehabilitation on the ground that it could be done more quickly and without 'social disturbance' and argues against re-building because of its inflationary effect, the physical and organizational limitations of the building industry, and administrative problems imposed on the local authorities. Sigsworth and Wilkinson (1967) question all of these arguments.
re-building are notable examples of costs normally overlooked.
Another diseconomy neglected is the pollution caused by both the
demolition and disposal process as well as the processing of new
materials to provide the replacement. Demolition itself is getting
more expensive and dangerous (Campbell, 1973) with more sophisticated
forms of construction, particularly those associated with high rise
building in urban areas.

An economic argument could also be made for the retention of
buildings because of their value to tourism which affects the national
balance of payments. Closely associated with this idea would be the
economic considerations associated with the uniqueness of old buildings.
Frequently old buildings contain building materials and workmanship which
simply cannot be replaced at today's prices, this largely being due to the
rapid increase in the cost of labour rather than the cost of energy.
cussing the proposal to demolish Coutts Bank, "a fine example of
Edwardian opulence" and the surrounding Nash terraces in London, to make
way for a Miesian office block, asks:

what is posterity likely to appreciate mosϊ - these facades
(which might cost, shall we say £250 per m² at today's
prices - if we could get the quality of workmanship) or the
same area of bronze and glass at £70 per m²? Does it really
make sense to pull down the first - personal, unique,
irreplaceable - to make way for the second - impersonal,
requiring slight skill and which can be bought off-the-peg
for putting anywhere?

Government Policy affecting Building Improvement and New Construction
Despite the economic arguments for improving stock in lieu of
re-building the post-war government policy has not traditionally been
very sympathetic to it; for example, slum clearance provisions of the 1957 Housing Act required a local authority to prove, in order to get a new housing subsidy from central government that it had demolished one old unit of housing for each new one.

More recent legislation is much more sympathetic to rehabilitation. For example, the '64 and '69 Housing Acts made home improvement grants sufficiently attractive to be taken up on a large scale for the first time since the improvement grants were introduced between the wars; and more recently was the government's gradual renewal policy set out in the 1974 Housing Act (described in Renewal Strategies, DOE circular 13/75). However, this support is brought into question, by its recent budget cuts which affected rehabilitation for more than new construction in the housing field. The government announced in January 1976 that the cash spent on existing housing stock '76-'77 would be some £61 million less than for the previous financial year. The severest cuts were on local authority mortgages with smaller reductions in rehabilitation of local authority property and the municipalization schemes. The reduction in rehabilitation combined with the effects of inflation will mean the number of units converted and improved will be substantially reduced from previous years; yet ministers hope that municipalization - the purchase of generally substandard houses by local authority - will be stepped up. This will most likely lead to authorities buying properties which they

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Cutting local authority mortgages indirectly affects improvements because they often cover property which building societies consider a risk, generally because they are substandard. Such houses can be improved by government discretionary improvement grants, but they are subject to ownership which is in itself dependent on meeting the standards. In other words a dwelling cannot be bought until the improvements are completed but the improvements cannot be started until the dwelling is bought. This 'Catch 22' situation has been personally experienced by the author.
cannot afford to improve. Because there is no formal limit on funds for new building, authorities will be tempted to demolish and rebuild rather than leave the property to decay. Until new building and rehabilitation can be seen together there is little hope for the gradual renewal policy.

A society's attitude towards rehabilitation, essential in extending a building's life, is, perhaps best reflected by their government's economic policies; and the SAVE Report (1975) summarizes the current official attitude towards rehabilitation in general:

When Britain followed the continental example and adopted Value Added Tax it was decided for good reason, not to increase the cost of new building and construction was zero rated (so was demolition, less understandably). Official kindness went no further, repairs and maintenance attract VAT at the standard rate. The government has therefore, if unwittingly, given the bulldozer an appreciable edge over the restorer. (p. 1306).

Central government encourages repairs to historical buildings through the giving of grants...in all, not more than about £43m a year has been given. It is a pitiful sum when measured against the strength of public enthusiasm for conservation and against the size of the National Income. If just one mile of urban motorway were foregone, the money saved would double the expenditure on architectural heritage. The cost of military bands in 1974-75 is estimated at £15.2m. Do 250,000 listed buildings and 3,800 conservation areas deserve less than a third of the amount we devote to uniformed performers and makers of minuets?

In this section we have discussed briefly the factors preventing a reduction in the demand for buildings mainly through a long life policy. It was pointed out that external factors could be controlled if so desired or minimised through tertiary building re-use. Internal

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1 This amount represents less than 0.1% of the total expenditure on Concorde or Britain's annual expenditure on roads.
factors concerned with physical, functional and symbolic obsolescence could also be controlled to a large degree and minimised by building re-use which itself could be facilitated by flexible/adaptable building. However, as Goodacre, a strong advocate of adaptable buildings, admits (1972, p. 295) for an adaptable system to develop fully:

it would be necessary for several changes to occur in present attitudes. The main obstacles to the initiation of this form of development, do not seem to be technical or financial problems; they seem more likely to arise out of the rigidity in limitations of the present system of administration and management.

It was also suggested that functional and symbolic obsolescence which are often the bases of the decision to terminate a product's life could be quite arbitrarily defined even by those not directly involved with the building or product concerned. Buildings are being needlessly demolished even though many are substantially sound, and despite strong economic arguments in favour of retention; there is, consequently, an unnecessary increase in demand on natural resources. Regardless of the advantages of retaining buildings, society's attitude, reflected in government spending, appears to be unsympathetic to the idea of "long life" buildings.
Before going into design considerations which affect energy consumption it is useful to review the overall strategy for saving non-operational energy in the building system. The techniques of saving energy in the building field follow a certain hierarchy which is roughly in the reverse order from which they were presented in this study.

The first line of approach in reducing energy consumption was presented in the first section of this chapter - reducing the demand for products. The question that must be asked is, is the building or space really needed? Re-organisation, more intensive use of existing space and just cleaning house could eliminate the need for additional space. Sometimes the requirement for a building is not based on a lack of space, it is based on the present facilities being 'inadequate'. But is it really necessary to demolish prematurely the facilities we have? One should try to retain and extend the life of existing buildings through maintenance and rehabilitation. Secondly, if additional space is required we should ask whether another existing building can be re-used in a primary or tertiary way, there is even the slight chance of a non-architectural container providing the space.

If these options are exhausted and new construction is required the building should be designed to be as adaptable as possible and detailed to allow for disassembly. 'Old' secondary sources of materials and components should be considered for the new work (as well as for rehabilitation work). Re-use of components should be considered first followed by the use of recycled materials. In construction, secondary recycling would be easier to specify, primary recycling being in the control of major
material manufacturers.

If the possibility of re-utilizing old sources of materials and components has been exhausted one is faced with a situation where, unfortunately, the majority of today's designers begin, that is the use of materials from 'new' sources. New secondary sources or by-products should first be considered followed by materials from primary sources.

Berry (1972, p. 14) feels, that in relation to the automobile:

The largest potential saving, in terms of energy and thermodynamic potential, can be achieved with improvements in the basic methods of material recovery and fabrication. The savings that could, in principle, be so achieved would reduce the thermodynamic cost of an automobile by a factor of 5, 10 or more.

Because Berry feels that the greatest potential energy savings lies not in the design considerations but in the basic production process (perhaps because he himself is a Professor of Chemistry), he suggests that most effort be concentrated on "the development of new technology for extractive and manufacturing industries, technologies that would operate with efficiencies closer to the ideal limits" (p. 11). So important is this "technological fix" that he even suggests the principles of recycling and extended life be used essentially "during the interval when new technology is being developed". Is Berry's statement correct - are not the principles of extended life and recycling still applicable even after the new technology is developed (if it is developed)? Even if processes are evolved which are substantially more efficient, implementing them on a commercial scale is often slow and plagued with difficulties (as discussed in Chapter Four). This is evident in the present difficulties experienced by British Steel in trying to adopt modern technology which is more efficient. Indeed British steel would be euphoric if the problems of new plants were limited to technical ones.
One of the reasons the "technological fix" solution appears to save so much energy is that it is based on a comparison between present day practices and theoretical minimums which in practice will never be met. It also looks attractive in the case of the automobile because it is made up of wholly processed material where technology will have an effect. But does this apply equally to construction materials such as wood, ceramics and cement? These basic materials used in the building field do not offer such technological savings. So what is the best strategy for saving energy in relation to the built environment when designing new buildings using materials from primary sources?

Obviously in a growth situation even with 100% recycling and re-use, there would be a requirement for new construction using materials from primary sources. It was not the intention of this study to analyse this situation, but because of the importance of the subject it will be briefly discussed in closing. Berry, in the study of the automobile, left out three other approaches to reducing energy demand which will form the basis of this section. The first deals with reducing the total amount of materials used in a product, through more efficient design, the second deals with reducing operating energy costs and the relationship between production and operating energy costs and the third concerns the possibility of substituting less energy intensive materials in products which are closely tied to material selection based on maximum performance per unit of production energy.

**Reducing the Amount of Material Used - Doing More with Less of the Same Material**

Reducing the amount of material used in a product is not to be taken
as reducing weight through the substitution of lighter materials for heavier ones, but is taken to mean the reduction in the amount of a given material through improved design or format. Less material in this sense would normally result in less processing energy. In the case of the automobile, unit construction has accomplished a reduction of weight using the same materials. Automobiles can also be designed to allow more usable space. The form of a building can likewise be optimised to reduce external area and share walls. Spherical buildings provide the minimal surface area for the enclosed volume but the volume is not always usable and the shape in general has not been accepted. Cubical shapes with flat facades have smaller surface areas than elongated and elaborately configured shapes and are far more acceptable. Within limits, small individual buildings use more material than the same space combined into a single block. These configurations not only minimise material and consequently production energy but also save running energy.

More sophisticated structural engineering is continually reducing the amount of materials required to perform a given structural task. Stein (1972, p. 18) suggests, there is still much room for improvement. In the U.S. he estimates the design loads are three times greater than those actually incurred in actual use; in addition, the design computations use values much lower than the actual strength of materials. In structural reinforced concrete work for example, the design strength for the concrete is only about one third of its actual strength, the steel is rated at only about half its actual strength, and additional safety margins are provided by the selection of dimensions above those computed. All of these factors together can result in a safety factor of over nine. He calculates that using reasonable margins of safety would permit concrete to be designed with less than half the material now used.
Material redundancy is also a problem with sectional structural members, whose configuration is uniform for reasons of fabrication, even though the stresses vary along their length. It is worth noting that the primary problem preventing a tighter fit between the structure and the stresses revolves around the issue of the cost of labour versus that of material, itself tied to the cost of energy (a subject already discussed in chapter Four).

There is considerable room for improving the structural performance of materials themselves. The introduction of cold rolled, high tensile steel for example has lead to substantial reductions in the amount of steel required to perform a given structural task\(^1\), and the scope for further improvements in the structural performance of materials is quite staggering. The mild steel used in automobiles, for example, has a tensile strength of 0.5 GN/m\(^2\) while the theoretical strength of iron is about 17.5 GN/m\(^2\). An even higher discrepancy exists in the carbon-carbon bond materials whose maximum Young's modulus (\(E\)) is about 1,172 GN/m\(^2\) (achieved naturally in diamonds). Synthetic carbon-carbon chains such as polyethylene could theoretically produce an \(E\) of 248 GN/m\(^2\) higher than the \(E\) for steel which is 207 GN/m\(^2\) even in a whisker form. In experimental fact the Young's modulus (\(E\)) of polyethylene is around 2.07 GN/m\(^2\). Gordon (1971, p. 247) in his book on The New Science of Strong Materials foresees "at least a possibility of making an unreinforced plastic with a Young's modulus about the same as that of steel but with one eighth of the density. It would also be reasonable to expect the strength and

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\(^1\)GKN advertises (AJ, 8 May, 1974, p. 84) that 3000 tonnes of their cold rolled high tensile, steel reinforcing bars could effectively replace 5000 tonnes of mild steel reinforcing bar, a 40% savings in weight.
toughness also to be high." Though he goes on to mention (p.249) that "there is no question of traditional materials such as steel and wood being superseded for bulk commercial uses for a long time to come."

Of course, such materials would be far more appropriate in the transport field, where weight is critical, than in the building system. It should be pointed out that even though the potential of improving one aspect of a material's performance is vast, to do so often involves reducing the material's performance in other areas, and to produce such high performance materials can itself involve more production energy.

Materials are by no means limited to structural use. In construction they more often act as environmental barriers keeping, in or out, sound, heat, precipitation as well as providing fire resistance. Improving a material's performance in relation to these functions also saves energy. A mundane but very relevant example in Britain, concerns the use of perforated bricks. Putting holes in bricks is simplicity itself. Searle (1956, p. 642) cites the advantages gained by perforated bricks which are also supported by the BRE: (1) perforations allow easy handling especially in laying the bricks, (2) less relative weight reduces the cost of carriage in both energy and money terms, (3) they can be dried and burned more easily and more rapidly using less fuel especially if made by carbonaceous clay as the perforations provide improved circulation of kiln gases, and (4) they have higher thermal insulating properties (1.3 - 2.5 times that of solid bricks). The last three advantages all reduce energy consumption, but the last one is the only one which affects in-place performance; all these advantages are gained at no significant sacrifice in strength.\(^1\)

\(^1\) Searle (1956, p. 642) complains that British manufacturers use too few perforations, using only 14-24. German and Swiss bricks can contain up to 512. He goes on to state that in spite of the advantages, the number of perforated bricks made each year in this country does not exceed 3% of all the wire-cut bricks...they are used extensively in Germany, Switzerland and the U.S. and there appears to be no sound reason why many more should not be used in this country.
Using a material to perform a combination of functions is another way of effectively reducing the amount overall of material used, even though the amount of specific material concerned would remain the same. Thatch, for example, combined the functions of providing a waterproof barrier as well as thermal insulation. A more modern roofing example of this principle can be found in relation to asbestos cement, which can be used in tile form to provide weather protection only, or can be corrugated to provide weather protection and structural properties: employing no less cement but eliminating the wood sarking and purlins which would otherwise be required to support the tiles.

The principle can be pursued even further by curving the corrugated sheets to form a semi-circular roof which eliminates the support structure all together. Even better is the idea of a 'purlin tile' being developed by the BRE, a hollow roofing component which eliminates both timber sarking and joists as well as tile and spans up to 3.66 m, enough to cover the conventional family house in two spans. Being hollow the 'purlin' tiles also have some insulation value. This particular unit is being designed in glass reinforced cement, and not asbestos cement, though the principle could be applied to asbestos cement; indeed it has already been done. In the early 1940's a similar principle was used in the 'Hendon purlin tile'; though not marketed today, it was capable

1 Most sheet materials can be profiled to be at least partially self-supporting, but in energy terms one of the most interesting corrugated roofing materials is the corrugated asphalt sheet described by Rao (1974) and used in India. They are made of waste materials such as scrap paper, bagasse and jute wastes impregnated with a standard grade of paving asphalt and surfaced with mineral granules. Since it is made from either by-products or obsolete waste material, the energy intensity should be quite low compared with other profiled sheet materials, though the purlin spacing is rather narrower at 600 mm.
of spanning 1.8 m. Today, hollow asbestos roof decking is comparable in behaviour.


In the design of automobiles, reducing the amount of steel in the body saves production energy, while simultaneously reducing running energy since the weight is less. In building, this simple relationship does not exist; the major operating energy requirements are those involved in environmental control, keeping heat in or out. In this case, investing production energy in additional insulation material could well be justified by the subsequent savings in running energy. This additional production energy is very quickly amortized; for instance, to insulate the whole envelope of a typical semi-detached house in the West Midlands with 50 mm of polyurethane foam would take 0.1 tonnes of foam, which would require 0.15 tonnes of oil to make. That same insulation, however, would save the equivalent of 0.45 tonnes of fuel a year (Bloom, 1975, p. 93). Jones (1976) finds similar results from adding 50 mm of fibre glass loft insulation, double glazing and rock wool cavity insulation to a hypothetical 100 m\(^2\) semi detached house; he calculates the following recovery time:

<table>
<thead>
<tr>
<th>Insulation Type</th>
<th>Recovery Time (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loft insulation</td>
<td>3</td>
</tr>
<tr>
<td>Double Glazing</td>
<td>7</td>
</tr>
<tr>
<td>Cavity wall insulation</td>
<td>15.6</td>
</tr>
</tbody>
</table>

Jones estimates that adding a second layer of 50 mm fibre glass loft insulation would require 14.4 months to amortize its worth in energy terms, while requiring 84 months in cash terms, indicating diminishing
Barnes and Rankin (1975, p. 40) describe a design trade-off between construction energy costs and operational energy costs. They found in general, that high rise housing required more energy to build but less to operate, while the reverse was true of low rise detached housing. Their figures, if correct, are quite surprising; the authors calculate that the energy consumed in building a conventional bungalow (77 m\(^2\) gross) is 123 GJ while their assumed 12 storey high rise (76m\(^2\) gross) cost 176 GJ (51 GJ's more). The energy required annually for heating (in Glasgow) was 50 GJ for the bungalow and 25 for the high rise; the difference in running energy in two years would equal the difference in construction costs! The higher running energy costs for the bungalow units was attributed to the greater amount of external surface area as might be expected.

The Barnes and Rankin figures would also indicate that the production energy costs are equal only to 2.45 years of operating energy for the bungalow and 6.9 for the high rise. This implies that if a group of bungalows were demolished and replaced by high rise flats, the construction energy costs would be recovered by reduced running costs in seven years. In Britain this fact could be used to argue for retaining existing high density urban stock instead of demolishing it, and replacing

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1The most effective insulation with undoubtedly the quickest recovery time lies outside the building system. Clothing is the most effective form of insulation and the quantity required is miniscule when compared to the amount required to insulate a building; after all a person standing wearing short underwear, light cotton trousers and short sleeved open shirt would require a room temperature about 10\(^\circ\) higher to be comfortable than one wearing long underwear and a heavy tweed suit and waistcoat (Burberry, 1975, p. 246).
it with semi-detached houses on the outskirts of towns. The transport energy requirement would also be higher with this dispersed approach. (In the U.S., where suburbs and individual houses are the rule, the situation is somewhat reversed.) However demolition of an uninsulated building on the grounds of high running energy costs would, in reality, be a questionable practice. In the case of the bungalow, the energy costs of the glass fibre insulation that was provided represented only 0.15% of the total energy costs of producing the building. Doubling or even tripling the amount of insulation still would represent a small percentage when compared to total production energy costs. It should also be pointed out that the Barnes and Rankin study favoured the high rise by not considering fenestration or orientation which would most likely have a more detrimental effect on the high rise building, especially in relation to wind. The study assumed a minimal insulation as well (46m² of 25 mm of glass fibre for a house with a gross floor area of 77m²!); additional insulation of course favouring the detached house because of the greater external area.

So far we have been comparing the material energy costs with running costs, with the thermal behaviour of the building being thought of in a passive sense, conserving energy by keeping heat in or out of the building; we should also consider material energy costs in an active sense, in creating useful energy. The energy cost of materials to produce devices such as wind generators and more importantly solar collection devices

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1 In comparison, Brown and Stellon (1974) estimate the production energy cost of a typical 100m² semi-detached house at 397 GJ and the annual running energy costs at 82 GJ. The running costs exceed production costs in about five years.
can be compared with the cost of the energy which they produce\footnote{Some would argue that calculations of this sort do not allow for the quality of the energy produced. The energy used in production being generally high grade while that produced for the devices being low grade, i.e. relatively low temperature heat (with electricity being produced from a wind generator being the exception). It should be pointed out, however, that in normal conditions the heat which would otherwise be provided by the ambient sources, would have to be provided from high grade fuel and energy, as, for example, the heating of water with electricity.}

Solar devices can be divided into two parts - the collector, and storage. Storage requires mass and sometimes can be incorporated into the building's fabric, thus combining functions; it can even be an integrated part of the collection system (e.g. the Wallasey School and the Trombe and Michel Solar wall system). In this type of system there is some difficulty in allocating energy costs between the structural and thermal storage functions; there is also a conflict with the fact that massive materials required for storage are inherently poor insulation as well.

This same energy allocation problem occurs with solar collectors which double as roofs. However, these small energy accounting technicalities should not detract from a building which can amortize its energy costs very quickly. Harper (1976, p. 38) calculates that a solar roof used in Wales consisting of aluminium corrugated sheets with a grp covering amortized its energy costs within 2-3 years and the collector considered was by no means the most efficient, nor was its location in Wales ideal. He neglected, however, in his calculations the manufacturing energy costs of the insulation, which in this case doubled as roof insulation and the storage tanks which would have lengthened amortization time to a small
degree.  

Whether materials are used in a passive or active sense in creating or retaining useful energy, the energy invested in the materials is usually recovered in a short time. Unfortunately, this does not necessarily hold true in a conventional economic sense. The high initial cost in relation to the price of energy is continually discouraging the more widespread use of better insulation and ambient energy. This is another classic example of the conflict between money and energy investments.

There are two other areas where material energy costs can be compared with life-cycle energy costs - maintenance and lighting. Obviously durable materials which age well require less maintenance than those which require constant cleaning and painting, but maintenance energy costs are quite small when considered against the thermal performance of a material and should be a secondary consideration. The maintenance figures used by Barnes and Rankin (1975, Table 4) indicate that annual

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1 Some solar systems are reversible and are capable of cooling during the summer as well as heating in the winter, and thus would reduce air conditioning loads as well as heating loads. Solar shading devices and rational building orientation and form are much simpler devices which also can effectively reduce heating loads.

2 Chapman (1975, chaps. 11 and 12) discusses the effect of solar collectors, double glazing and insulation in relation to two possible future energy scenarios. He estimates two to three year energy pay-back periods for such devices which agrees with the other authors cited. Chapman also examines the ramifications, to the material industries, of providing such devices on a large scale in Britain. Among other things he estimates that the sheet glass industry would have to almost double its output to double glaze all new houses. One would think that in Britain, where government support of industry is so common, the glass industry would be a logical choice. It would also be a way of employing people which would eventually lead to import savings, and it is based on silica one of the most abundant materials in the earth's crust.
running costs for heating and lighting are from 13 to 65 times greater than the annual maintenance costs. Investing energy in transparent or translucent materials to provide natural lighting in lieu of artificial, would in Britain be unlikely to result in a saving of energy, because of the climate and short days. Even double glazing has three times the rate of heat loss of the average external wall. However, uninsulated and often unheated industrial and storage buildings, incorporating roof lights would provide nett energy savings.

It is interesting to note that the energy investment in a material can be used to advantage or disadvantage in saving running energy costs. Take glass for example, which can be produced in solid sheet, foam blocks or fibres; the energy content per unit of mass of each form is roughly the same though significantly different on a volume basis. The same amount of glass could conserve energy by 1) providing insulation, 2) helping create usable energy in a solar collector or 3) conserving materials by reinforcing weaker ones; and yet many designers do not use this material as an asset in energy terms, but as a liability, for example by using sheets of sold glass as an external envelope through which heat is lost or gained to such a degree that cooling and/or heating devices are required.

Reducing Energy Demand Through Material Substitution

Contrary to general belief, materials are not chosen to suit a product but rather the product designed to suit the material... (Gordon, 1971, p. 232).

Berry (1972), in his energy analysis of the automobile did not consider the possibility of building a car out of different materials to
reduce production energy costs\(^1\). The possibility does exist however; in the United States for example it is increasingly common for body parts to be replaced by glass reinforced plastics (grp). Substituting the one piece grp bonnet for one made of steel on an intermediate sized American car is calculated to save 216 kWh in production energy costs, even though the energy intensity per unit of mass of grp is 1.4 times greater than that of steel (SAE, 1975 tables 1 and 2). The savings are due to the fact that the weight of a steel bonnet is 2.5 times greater than that of grp. Being lighter, the grp bonnet also saves running energy costs; these savings over the life of a car are calculated at 1376 kWh's. Thus replacing a mild steel bonnet with one of grp produces a nett total energy savings of 1592 kWh's (SAE, 1975, Tables 1 and 2)\(^2\). In this case the substitution reduces maintenance costs as well, by eliminating the possibility of rust and improving the chances of extending the life of the vehicle or component; however, grp is a material with

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\(^1\)The three methods analysed by Berry (1972) for reducing energy in relation to the automobile involved 1) maximising material recycling, 2) extending the useful life of the car and 3) developing more (thermo-dynamically) efficient processes. He calculated that 10% energy savings could be made through recycling efforts, 50-100% by extending a car's life and 500% by improving on basic methods of metal recovery and fabrication, the principle reason this last choice appears so attractive is that it compares theoretical figures with those of commercial production. It is curious that Berry neglected to analyse the potential increases in the strength of the materials in the same way; for as mentioned earlier the potential for possible improvements between a material's theoretical and actual structural performance are of the same magnitude.

\(^2\)It was calculated that making the bonnet in aluminium would require 550 kWh's more energy than steel but would recover that in running energy costs (estimated at 1280 kWh's), producing a net overall savings from substituting aluminium for steel of 736 kWh's. The substitution would be even more attractive if the aluminium and steel used were recycled; for the aluminium bonnet would require less energy to produce in the first place.
limited recycling potential. This example illustrates two important points:

1) reducing the amount of material can be compatible with saving life cycle energy costs, and

2) there is danger in comparing material energy intensities without regard to end use.

When the function of a product or component is simple and well defined, one can fairly easily estimate the consequences of substituting one material for another in terms of production energy and, when applicable, in-use energy costs. Energy analysis such as those discussed—the automobile bonnet or the use of various beverage container systems, (Berry and Makino, 1974, and Hannon, 1972) are useful when one is comparing like with like. In the construction field, similar comparisons can be made. A comparison of the production energy costs of equal lengths of comparable piping, for example, would be meaningful, as well as a comparison of rigid, non-structural insulation having equivalent 'U' values (not equivalent thicknesses). However, it is more difficult, when comparing building materials in general, to make such categorical statements; despite this, material manufacturers and trade associations are increasingly using the slogan "low energy" in their advertisements. The

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1 Automobiles made from grp might not suffer from physical obsolescence but the widespread use of grp would increase symbolic obsolescence since another main advantage of the material is the moderate tooling costs which permit more frequent changes of style. Aluminium body parts would also eliminate the rust problem and suffer as much from the potential symbolic obsolescence.

2 ICI have calculated the energy costs of producing 100 mm drainage pipe and 25 mm service piping out of various materials. They found that PVC drainage pipe consumed the lowest amount of energy, followed by asbestos cement, pitch fibre clay and cast iron, which use 1.1, 1.2, 1.4 and 5.5 times more energy respectively. Polyethylene-service pipe required 1.15 and 4 times less energy to produce than copper and galvanized iron pipe respectively (Bloom, 1975, Table 2.)
American Wood Council (Time, 1 April, 1974, p. 37) claims that "processed wood requires only about 430 kilowatt hours per ton - compared to 2700 for steel and 17,000 for aluminium," and the Timber Research and Development Association announce that wood-frame houses require less energy to build and to heat than traditional brick ones (Herman, 1974); they neglect to mention maintenance and sound transmission, which are not nearly as good with timber construction, and the thermal savings of such construction is more dependent on the 50 mm of mineral wool than on the wood frame. Likewise the Brick Development Association advertises (The Scotsman, 23 April, 1974, p. 8) that "...enquiries carried out by the British Ceramic Research Association indicate that brick is a low energy material", they go on to point out that:

...a load bearing brick structure with small amenity windows is a viable alternate to a glass-clad concrete frame structure, the superior resistance to climate penetration of the brick work leading to savings of fuel throughout the life of the building far in excess of the immediate savings inherent in its low energy requirements in manufacture and construction.

The Cement and Concrete Association (1974) defend their interests in the report Energy and the Construction Industry, which concludes that, in energy terms, light-weight concrete is superior to brick, and reinforced concrete better than steel.

Energy analyses have to be far less biased. Materials are used to perform specific functions and how they perform these functions depends on their inherent properties. These properties fall into four general

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1 Energy calculations in this study are very biased in favour of wood construction; the bricks assumed were on the heavier than average side and the specific energy for both plywood and mineral wool were very low. Adjusting the specific energy of the mineral wool to that of glass and assuming a brick weight of 2.2 kg per brick instead of 3.2 kg assumed, would influence the energy cost to such a degree that traditional brick construction would actually involve less energy to produce than that of timber; though the heat loss through the wood system would be much less than that of brick.
<table>
<thead>
<tr>
<th>Material</th>
<th>Specific gravity</th>
<th>Energy cost per unit of mass</th>
<th>Energy cost per unit of volume</th>
<th>Young's Modulus (stiffness) unit of stiffness</th>
<th>Tensile strength</th>
<th>Energy cost per unit of strength</th>
<th>Thermal resistivity (U)</th>
<th>Energy cost per unit of thermal resistance</th>
<th>Energy cost per unit of mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALUMINIUM^5 alloy (85/15)</td>
<td>2.65</td>
<td>73</td>
<td>195.5</td>
<td>69.35</td>
<td>2.77</td>
<td>0.624</td>
<td>0.007</td>
<td>41170</td>
<td></td>
</tr>
<tr>
<td>STAINLESS^5</td>
<td>7.95</td>
<td>13.2</td>
<td>103.6</td>
<td>207</td>
<td>0.5</td>
<td>0.207</td>
<td>0.0176</td>
<td>5186</td>
<td></td>
</tr>
<tr>
<td>GLASS^5,6</td>
<td>2.52</td>
<td>7.2</td>
<td>18.15</td>
<td>63.9</td>
<td>0.26</td>
<td>0.18</td>
<td>0.016</td>
<td>18.35</td>
<td></td>
</tr>
<tr>
<td>Fibre mat</td>
<td>0.014</td>
<td>7.2</td>
<td>1.06</td>
<td>1.21</td>
<td>0.04</td>
<td>0.25</td>
<td>0.0059</td>
<td>28.6</td>
<td></td>
</tr>
<tr>
<td>Fibre (type 8)</td>
<td>2.55</td>
<td>7.2</td>
<td>18.81</td>
<td>72.4</td>
<td>0.25</td>
<td>0.0053</td>
<td>18.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GLASS^5,6</td>
<td>2.7</td>
<td>7.8</td>
<td>17.7</td>
<td>4.14</td>
<td>0.41</td>
<td>0.63</td>
<td>1.19</td>
<td>1.62</td>
<td></td>
</tr>
<tr>
<td>Brick</td>
<td>1.9</td>
<td>0.18</td>
<td>0.36</td>
<td>5.5</td>
<td>0.062</td>
<td>0.405</td>
<td>0.19</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>CONCRETE^7</td>
<td>2.66</td>
<td>0.305</td>
<td>0.69</td>
<td>26.6</td>
<td>0.024</td>
<td>0.175</td>
<td>1</td>
<td>0.69</td>
<td></td>
</tr>
<tr>
<td>POLYSTYRENE^8,9</td>
<td>1.05</td>
<td>19</td>
<td>20</td>
<td>5.1</td>
<td>6.5</td>
<td>4</td>
<td>12.5</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>POLYSTYRENE^8,9</td>
<td>0.024</td>
<td>19</td>
<td>0.46</td>
<td>0.69</td>
<td>0.0013</td>
<td>0.0015</td>
<td>0.118</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WOOD^7,10</td>
<td>0.51</td>
<td>0.6</td>
<td>0.3</td>
<td>15.8</td>
<td>0.02</td>
<td>103</td>
<td>0.003</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>SAWDUST^11</td>
<td>0.2</td>
<td>0.2</td>
<td>0.06</td>
<td>0.26</td>
<td>0.005</td>
<td>0.004</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CORK^11</td>
<td>0.24</td>
<td>0.056</td>
<td>1.5</td>
<td>0.6</td>
<td>0.003</td>
<td>0.0015</td>
<td>0.118</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FLAX^11</td>
<td>2.3</td>
<td>0.3</td>
<td>0.73</td>
<td>0.062</td>
<td>0.003</td>
<td>0.004</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASBESTOS^11</td>
<td>2.2</td>
<td>0.3</td>
<td>0.73</td>
<td>0.062</td>
<td>0.003</td>
<td>0.004</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Materials summarised in descending order of energy-performance 'cheaper'.
categories:

1) **Mechanical** - strength, stiffness, elasticity, ductility, hardness, and resistance to creep, impact and fatigue;

2) **Physical** - thermal, acoustic, optical, electrical, surface colour and texture, permeability and deformation;

3) **Chemical** - resistance to sunlight, biological attack, fire and corrosion;

4) **Technical** - production characteristics.

A rational approach to analysing the effectiveness of the energy invested in a material is to compare it to the material's properties which have a quantifiable performance. An index of energy cost per unit of performance could be produced which would be very useful to a designer, who specifies materials. This type of comparison is represented in Table 6.1; this is by no means comprehensive, covering only a limited number of materials and restricted to only three (though very important) properties - strength, stiffness and thermo-resistivity. It does, however, illustrate the concept\(^1\). What is clear from the table is the vast difference between energy costs and performance; the least striking differences occur in relation to stiffness\(^2\) (0.02-6.5), with much larger variations in tensile strength (0.00015-2.26) and a vast difference occurring in relation to thermal performance (0.002-41,170).

\(^1\)This approach has been applied (Alexander, 1967, p. 261) to conventional costs (pence per unit of strength) and may be applied for environmental impact, (by-products produced per unit of performance.)

\(^2\)Gordon (1971, p. 235) mentions the fact that the specific Young's Module, i.e. the 'E' value in absolute terms divided by the materials specific gravity of a large group of common materials are remarkably, almost the same, about 26 GN/m\(^2\).
Table 6.1 reveals that the form of the material is critical in its structural performance, even though the specific energy of the material is the same. This is illustrated by glass in Table 6.1 which has been included in four basic forms - window, foamed, fibre mat and fibrous. The most important reason for comparing performance with production energy is to illustrate that high performance can be achieved by relatively low energy materials; 'primitive', or 'traditional' unprocessed materials are especially good in this respect, with wood providing the best all-around performance. Interestingly enough, the materials most commonly associated with construction also are good value per unit of energy, particularly with regards to strength; perhaps this fact is largely responsible for their popularity.

It is also important to comment on thermal performance which is so important in energy accounting. Table 6.1 confirms the conclusions drawn by Barnes and Rankin (1975, p. 41) that "there is no correlation between energy costs of manufacture and subsequent value as insulation; improvements in insulation properties could be made without greatly increasing the capital energy costs of the material." This fact needs to be stressed, for so often, those concerned with energy accounting dismiss production energy because running energy (especially in a temperate climate) represents a larger absolute amount. However the two are compatible and not mutually exclusive; you can have the best of both worlds.

Since long-life buildings should be encouraged a comment should also be made on durability and material energy costs. Here again, good durability and low energy costs can be compatible. The Danish National Institute of Building Research found "that asbestos cement roofs (when
compared to clay tiles) are cheaper from the point of view of amortization as well as maintenance," (U.N., 1963, p. 75), and yet asbestos cement roofing is less energy-intensive than clay tiles, particularly if one uses it in a corrugated form, making the units structural as well. Slate is another example of a low energy roofing material which is extremely durable.

Comparing energy costs with performance as in table 6.1, is certainly useful, but caution is needed; other factors may be involved. Materials like corrugated asbestos cement, often perform more than one function and "trade-offs" are inevitably encountered. Is it better, for example, to have a wall made of clearly identifiable parts, each part using the most energy-effective material, or is it better to have fewer materials with perhaps a higher energy cost but combining several functions? To find out one must compare the total wall section. It is

1 Corrugated asbestos, is an example of a material which performs well and even costs less that other roofing systems, but whose use is almost non-existent in some building types, not because of the general performance or cost but because of the strong association with farm and industrial buildings which give it a certain stigma. It is a material which society subjectively rejects.

2 The construction technique developed by Walter Segal in which layers of material are held together by frictional dry joints, built up to provide the desired wall section, represents a good example of this first approach. An interesting low energy approach could be developed around the second as well. It would involve the use of one material only which would perform all the combined functions of a wall. This method, which could be described by the paradoxical description as light-weight heavy construction, might, for example, involve the use of thick and preferably interlocking (for re-use), density graded (a smooth high density surface and low density core) concrete block. It could be made entirely from by-product aggregates such as expanded slag or PFA, and use a super sulphated cement binder to ensure low energy intensity. This material is not particularly strong and its insulation value is low compared with the ultra-light insulation materials. However, its thickness (200–300mm) would be adequate to provide the necessary load bearing capacity, thermal and sound insulation for a conventional house. The thickness would also exclude water even though the material is permeable; this would help eliminate any condensation problems. It would not even require surface treatment and would be easy to erect and maintain. This method of construction could also provide a nice compromise on the question of thermal capacity so often debated today.
here that material promoters are frequently in error; they are not comparing like with like. Timber in a stud wall is used for its structural performance alone, while a conventional block wall can also provide thermal capacity and weather resistance. It is not enough simply to claim that wood has a lower specific energy content than concrete block.

Before the substitution of materials to save energy becomes a serious study, there has to be a better understanding of how to establish material energy costs; in other words, ground rules need to be established, particularly with regards to by-products and co-products which are so suitable for use in construction. It is in these very materials that most hope exists for reducing production energy costs; unless there is a drastic change in society's attitude towards the use of second-hand materials or 'primitive' ultra-low energy, but highly labour-intensive materials such as thatch and cob. But it is also precisely these sorts of materials that are least researched. There is a desperate need for the study of energy intensiveness of such mundane materials as fibre board, light weight slag concrete and wood wool before any substitution strategy can be fully worked out. No doubt, as the current sources of energy dwindle, the cost and importance of energy in the manufacture of materials, maintenance and running will become more significant in relation to the cost of building.

Substitution of materials should of course be considered as a means of saving energy, but it should also be considered with respect to other criteria as well. For example, selecting materials with low environmental impact (though the two are quite often complimentary) or selecting materials without unique properties. Copper for instance is unique for
its electrical conductance and is a relatively scarce material. It has often been said that the limit of electrical generation will eventually be set not by the amount of nuclear power available, but by the amount of copper necessary for the manufacture of generators. The same could be said of lead in relation to battery operated transport. Lead has already become a luxury material for plumbing but copper may soon be as well.

One should select building materials which are abundant and, if possible, without any unique properties (as in the case of plastic pipe being used instead of either lead or copper pipe). Where a choice exists, the specifier must consider how unique is each material; roofing, for example, can be made with numerous materials, whereas electrical wiring is limited to only a few choices. To choose copper for roofing when asbestos cement would do is irrational. The specifier of building materials has to become far more conscious of many factors, the energy consumed in the production of a material, its effect on operational energy requirements, the environmental impact of the material, the consequences of its choice on the balance of payments, its uniqueness even the labour content at least should be considered. The specifier should select materials to achieve an objective beyond just providing an end product; especially a specifier of building materials, whose scope for substitution is so vast, when compared to the choice of materials suitable in other product systems, such as transport. However this is an issue of such complexity that it could easily justify a dissertation in itself.
Summary and Conclusions

In closing it would be appropriate to reflect on the general development of this study. In the introductory chapter we defined the PUD sequence on which this study was based, as well as material and end-product systems - such as the building system; the construction system's demand for materials and energy was discussed and attention was directed to the generation of unused by-products in satisfying this demand.

The energy 'costs' of producing specific common building materials and components were also related to demand. Emphasis was placed on the need to conserve energy rather than materials, primarily because of the abundance of raw materials suitable for construction and because of the fact that matter can not be created or destroyed. The latter applies to energy as well, but the second Law of Thermodynamics ensures that the "availability" of energy is lost. The first chapter closed with a discussion of the relative importance of production energy and operational energy in buildings, suggesting that a more comprehensive analysis might result in a more economical use of energy.

The second and third chapters and the supporting appendices were devoted to an energy analysis of British roofing materials. A historical review of the introduction of new roofing materials, and a quantitative analysis of the use of different materials over time, when associated with estimated production energy demands, allowed some appreciation of the consequences of changing fashion. The conclusion drawn was that in earlier periods the common unprocessed materials had extremely low energy intensities but that, the total demand for processing energy could have been quite high since the processed roofing materials even though used in very small quantities, were extremely energy intensive. In time, the
materials with extremely high or low energy intensity disappeared, leaving a group of moderately energy intensive processed materials, having intensities of the same order of magnitude. Transport energy was also studied and was found to have increased far more than processing energy and far more rapidly especially in the period between 1840-1925. However, even after the rapid increase, the overall consumption of energy in transporting materials is quite small in comparison to processing energy.

Despite the historical consolidation of material energy intensities described in the case study, Chapters Four and Five indicated that there was still much that could be done to reduce production energy demand. Chapter Four discussed the likelihood of increases or decreases in the production of materials from primary sources and concluded that the extractive and assembly operations were likely to increase in energy consumption while material manufacture and fabrication operations would decrease due to improved technology particularly with respect to the utilization of low grade 'waste' heat. This has the unfortunate effect of reducing the price of the energy intensive processed materials relative to low energy unprocessed materials. However, it was also pointed out that the technical means of reducing energy so applicable to processed materials are becoming progressively more difficult to realize; in other words we are reaching a point of diminishing returns. New rationalized plants have taken most of the slack out of the production system and, when prices adjust to these productivity and efficiency gains, further cost reductions will be progressively harder to come by; this could very well lead to more energy intensive methods of production in an increasing effort to reduce labour costs. In fact the labour productivity issue was found to present a major obstacle to the theory that the pricing mechanism will
inevitably to less energy intensive building systems. It was pointed
out that system definition could well bring conventional labour productivity
statistics into question, with direct production labour (the criterion of
conventional productivity estimates) being reduced, but reappearing
indirectly in the construction system in a non-productive capacity,
particularly in the fields of finance, sales and administration.

Chapter Five studied possibilities of producing products from
secondary sources either by using by-products or by recirculating into
the production sequence old materials or components. In the use of by-
products it was felt that the greatest promise of energy savings seems
to lie primarily in the utilization of by-products which eliminated or
shared thermal processes. The most interesting (and unexploited) by-
products were slags, for use in super sulphated cements, slags and PFA as
light weight aggregates and by-product anhydrite used as a plaster. The
primary recycling of thermoplastic scrap also was discussed as an
excellent way of reducing energy; even greater energy savings could be
realized through component re-use. Despite the savings possible through
the use of secondary sources, its potential remains undeveloped due to
barriers which primarily institutional or economic in nature and not
technical. This also applied to the methods of reducing energy discussed
in chapter four, but not to the same degree.

A basic conflict appears to be developing between the energy saving
methods described in chapter four with those in chapter five. The trends
towards larger scale, highly specialized, and often remote 'rationalized'
plant, which seems to result from pursuing the energy saving methods
outlined in chapter four, are becoming progressively more incompatible
with efforts to save production energy through the use of material and
from secondary sources which are usually highly dispersed and of increasing variety. The co-ordination and co-operation which are vital, especially with respect to re-use and recycling and which historically were so evident in the building system have disappeared mainly due to the complex grouping of industries operating today, each having a very narrowly defined objective and representing only a small portion of a linear (versus cyclic) process.

In this Chapter the possibility of saving production energy by passive techniques were examined; these seemed to offer the most realistic approaches to reducing energy demand. The first method considered, essentially questioned the need for new construction. Reducing the overall demand for new buildings through building re-use, either through more efficient utilization of the buildings we have, or by extending their life through better maintenance or rehabilitation is obviously technically possible; the problem lies in attitudes.

The second method of avoidance dealt with reducing the amount of materials used in buildings and with the idea of eliminating energy intensive materials through material substitution. It was found that energy could be saved through substitution of low energy materials; particularly wood which proved to have a very high performance per unit of energy along with other natural materials. It was also found that potential energy savings do exist by doing more with the same or less material, by using the material to perform multi-functions and or through more efficient structural design, though improvement in structural design is somewhat restricted, by regulations and by labour costs. The most important conclusion was the compatibility of conserving both production and in-use energy.
The main concern of this study has been to concentrate attention on the relationships between alternative strategies in building design, use and re-use, in the context of energy consumption. Such relationships are seldom clear cut, and with little precedent for the approach adopted, it has been necessary to review the subject historically over a wide field in order to develop a frame of reference for the future. The field remains open for more rigorous and detailed treatment once such a framework is agreed and understood, but at this point in the energy crisis it was felt that the need is for a conceptual understanding rather than further statistical analysis - for a better appreciation of strategies which might itself direct attention to necessary and practical detailed research. Both approaches are needed in the end but the former must precede the latter. This study provides a primer and like all primers, it needs additional and more rigorous development. A few tools have been presented which are necessary for an understanding of the problems of energy conservation. Hopefully the study was presented in such a way, particularly through the use of graphics, as to be easily understood.

Postscript

One of the main conclusions drawn during this study was that extending a building's life is one of the most effective ways of reducing production energy demand. Paradoxically the University building in which this conclusion was drawn (itself a re-used town house) is to be demolished despite the fact that it is one of the original buildings (1760) on the oldest Georgian Square in Edinburgh, and is structurally sound. The main justification for demolition seems to be that the design work on the replacement bio-chemistry building, started twenty four years ago is too far advanced.
APPENDIX A

Calculation of Material Quantity Factors, Relative Energies and Relative Energies Consumed in Processing Roofing Materials.

Appendix A is presented in tabular\(^1\) form (Table A-1). The figures from this table provide the basis for Figs. 3.1 to 3.6 contained in Chapter Three concerning processing energy.

The following paragraphs explain, by column, the table itself, the calculations, and terms involved.

**Energy Intensity, Column (1)**

The processing energy intensity per unit area (kWh/m\(^2\)) are established for individual roofing materials in Appendix B (Appendix E for transport energy intensities). The unit of area (m\(^2\)) applies to horizontal area covered, and not the surface area of the roof itself. Pitches for each roofing material have been assumed and the additional area and weight incorporated in Appendixes B and E. Energy correction factors are established for improvements in processing and transport in appendixes C and F respectively. The energy intensity for material processing is contained in Appendix B and for material transport in Appendix F (Table F-2).

**Material Percentage Mix, Column (2)**

The data contained in this column comes directly from the roofing

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\(^1\)The layout and basic method of calculations involved in Table A-1 are the same as those involved with transport energy calculated in Appendix C, Table C-1.
Relative Energy, Column (3)
The figures in this column are merely the product of the material mix (2) and the energy intensity (1). For example, the relative energy of clay in 1950 would be $-42 \text{ (kWh/m}^2\text{)} \times 0.24 \text{ (mix of 24\%)} = 10 \text{ (relative energy)}$.

Relative energy figures have no unit, it is solely used for comparative purposes, enabling one to see which materials would have used the most energy if the overall demand had remained constant. This is quite important, for a material with a very small mix percentage but a high energy intensity, can use far more energy than a high mix percentage material with a low energy intensity. The comparison between thatch and clay or metal is a case in point and can be quickly seen in Fig. 3.4.

Quantity Factor, Column (4)
"Relative Energy" expressed in Column (3) does not reflect the overall increases in roofing materials used, which would have an obvious effect on the overall energy consumed. A quantity factor based on population is used in order to establish relative energy consumption (4). The quantity factor for each material is produced by dividing the appropriate population figure (indicated in brackets at the top of Column 4 and expressed in millions) into aggregates which are proportional to each material's percentage mix (2). For example clay tiles in 1950 represented 24\% of the total roofing mix and the population was 50 million. The quantity factor for clay tiles in 1950 would therefore be 24 percent of 50 or 12.
Relative Energy Consumed, Column (5)

Figures contained in Column (5) indicate the relative overall increase in energy consumption. Like relative energy there are no units attached to these figures, and provide only a relative guide. The "relative energy" consumed for each material can be arrived at by two methods. The first involves multiplying energy intensity (1) of a material by its quantity factor (4). Using the 1950 clay example again; this would mean 42 (MWh/m²) x 12 (quantity factor) equals 500 (relative energy consumed). The second method involves multiplying the relative energy (3) by the total population. In the clay example this would be 10 (relative energy) x 50 (total population) equals 500. The rounding off of quantities produces very small discrepancies between these two methods. The first method was used in Table A-1.
<table>
<thead>
<tr>
<th>Year</th>
<th>Clay</th>
<th>Stone/Glaze</th>
<th>Total Population</th>
<th>Processing Energy Intensity</th>
<th>Relative Energy as Percentage of Mix</th>
<th>Quantity Factor</th>
<th>Relative Energy Consumed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1600</td>
<td>70</td>
<td>3.14</td>
<td>2.8</td>
<td>0.70</td>
<td>20%</td>
<td>0.72</td>
<td>2.8</td>
</tr>
<tr>
<td>1700</td>
<td>55</td>
<td>0.55</td>
<td>3.5</td>
<td>0.3</td>
<td>1.5%</td>
<td>0.5</td>
<td>3.5</td>
</tr>
<tr>
<td>1800</td>
<td>44</td>
<td>3.35</td>
<td>1.5</td>
<td>0.3</td>
<td>0.3%</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>1900</td>
<td>6</td>
<td>0.06</td>
<td>1.5</td>
<td>0.1</td>
<td>0.1%</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>1920</td>
<td>62</td>
<td>2.29</td>
<td>1.5</td>
<td>0.3</td>
<td>0.3%</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>1950</td>
<td>6</td>
<td>0.06</td>
<td>1.5</td>
<td>0.1</td>
<td>0.1%</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>1958</td>
<td>62</td>
<td>2.29</td>
<td>1.5</td>
<td>0.3</td>
<td>0.3%</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>1960</td>
<td>24</td>
<td>1.1</td>
<td>1.5</td>
<td>0.3</td>
<td>0.3%</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>1966</td>
<td>21</td>
<td>0.1</td>
<td>1.5</td>
<td>0.3</td>
<td>0.3%</td>
<td>0.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>
APPENDIX B

The Estimation of Roofing Material Processing Energy Intensities Along with Roofing Weight and Pitch Data.

Appendix B is largely concerned with estimating the unit area energy intensities of roofing materials; but the appendix also contains data, assumptions, and calculations, particularly those concerned with roofing weights and angles which are referred to in the text and other appendixes. In order to approach these estimations in a systematic way the appendix has been subdivided into sections each of which concerns one roofing material. Each of these sections will be further divided into nine subsections, listed below:

1. Range of roof angles (degrees)\(^1\).
2. Assumed average roof angle and cos of angle.
3. Roof area required to cover one horizontal m\(^2\) (1/cos of roof angle x 1).
4. Weight range (kg/m\(^2\))\(^1\).
5. Assumed average weight (kg/m\(^2\)).
6. Weight per m\(^2\) covered (3) x (5) = (6) kg/m\(^2\).
7. Processing energy per unit weight (kWh/kg).
8. Processing energy per unit of covered area (6) x (7) = (8) kWh/m\(^2\).
9. Assumed changes in processing energy in relation to time. This is applicable to processed materials only and is established in appendix C.

\(^1\)Except where otherwise noted the range of roof angles and weights are taken from AJ - Handbook of Building Enclosure (King & Parkes, 1974, Tables 2, 3 and 4).
Thatch

1. Range of roof angles
   - Exposed: 50° to 55°
   - Sheltered: 50° minimum
   reed: 45° minimum

2. Assumed angles
   - 50° \( (\cos = 0.6248) \)

3. Roof area per m\(^2\) covered \( (1/\cos x 1) \): 1.55 m\(^2\).

4. Weight range
   - Neufert (1970 p. 41): 10 kg/m\(^2\)
   - Bartlett (1911): 32

5. Assumed weight: 32 kg/m\(^2\)

6. Weight per m\(^2\) covered \((3) \times (5)\): 49.6 kg/m\(^2\)

7. Processing energy per unit of mass.
   Processing energy for thatch is not being calculated on a unit of mass area but on area basis (see below).

8. Processing Energy per m\(^2\) covered.

For thatch the processing energy only amounts to the energy consumed by man in harvesting, preparing, and applying the thatch. With processed materials this human element is so insignificant in comparison to the machine and chemical processing energy involved, that it is not included in their energy intensity calculation.

Application should not be considered in processing energy, but the distinction between processing and application in the case of thatch is so fine that this exception has been made.

Man consumes an average of three thousand kilo calories per day (Cottrell, 1955, p.18) in food. If it is assumed that seventy five percent of this energy is devoted to useful work, the resultant input energy per man day would be 2300 kcal or 2.66 kWh, it would be reasonable to also assume that one third of a man day would be required to cut, prepare, and apply 1.55 m\(^2\) of thatch. Therefore the energy required to cover one horizontal square metre would equal 2.66 kWh,
divided by 3 or .89 kWh/m² which will be rounded up to 1 kWh/m² for the purposes of this study. Transport of thatching material is covered separately in the appendices concerning transportation.

**Stone and Slate**

1. **Roof angle range**

<table>
<thead>
<tr>
<th>Stone slate</th>
<th>Slate</th>
</tr>
</thead>
<tbody>
<tr>
<td>exposed</td>
<td>sheltered</td>
</tr>
<tr>
<td>Yorkshire</td>
<td>35° min.</td>
</tr>
<tr>
<td>Cotswold</td>
<td>55° min.</td>
</tr>
<tr>
<td>exposed</td>
<td>sheltered</td>
</tr>
<tr>
<td>large</td>
<td>26.5 min.</td>
</tr>
<tr>
<td>average</td>
<td>30</td>
</tr>
<tr>
<td>small</td>
<td>35</td>
</tr>
</tbody>
</table>

2. **Assumed angle.**

   As it can be seen from the above there is a large variation in the angles for stone based roofs. Because stone slates and slates have been grouped together for the purpose of energy analysis, the angle assumed has to reflect both materials. In order to do this the angle assumed decreases with time. This decrease compensates for the general shift discussed in Chapter 10 from stone slates, with their corresponding steeper pitches, to slate which could be laid using lower pitches which were more economical and often dictated by contemporary architectural styles. Assumed angles:

   - 1600 and before - 40° (cos = .7660)
   - 1700 - 36° (cos = .8090)
   - 1800 and after - 30° (cos = .8660)

3. **Roof area per m² covered (1/cos x 1)**

   - 1600 and before - 1.31m²
   - 1700 - 1.24m²
   - 1800 and after - 1.15m²

4. **Weight range kg/m²**

   **Sandstone and Limestone**
   - 87 - 200

   **Slate**
   - Westmorland 44 - 75
   - Cornish 30 - 44
   - Welsh 24 - 40
5. Assumed Weight

<table>
<thead>
<tr>
<th>Period</th>
<th>Weight (kg/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1600 and before</td>
<td>70</td>
</tr>
<tr>
<td>1700</td>
<td>65</td>
</tr>
<tr>
<td>1800</td>
<td>50</td>
</tr>
<tr>
<td>1850 and after</td>
<td>40</td>
</tr>
</tbody>
</table>

Like angles encountered in stone based roofing there is great variation in material's weight. Similar to the angle assumptions for stone based roofing, the weight assumed also decreases in time for the same reasons, a shift from limestone and sandstone slates to true slate.

6. Weight per m² covered (3) x (5)

<table>
<thead>
<tr>
<th>Period</th>
<th>Weight (kg/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1600 and before</td>
<td>92.5</td>
</tr>
<tr>
<td>1700</td>
<td>80.7</td>
</tr>
<tr>
<td>1800</td>
<td>57.5</td>
</tr>
<tr>
<td>1850 and after</td>
<td>46.2</td>
</tr>
</tbody>
</table>

Like thatch the processing energy for stone is not being based on weight, but the above figures do play an important part in the calculations throughout energy covered in Appendixes D and E.

7. Processing energy per unit of mass.

The applicable energy is being established per unit of area. See below.

8. Processing energy per m² covered.

This is calculated in the same way as thatch by man/days (2.67 kWh/day) per unit of area. In this case 1.5 man days have been allowed to excavate and shape enough stone to cover 1.31 m² of roof (1600), the energy assumed to process stone based roofing materials would therefore be:

\[ 1.5 \times 2.67 = 4 \text{ kWh/m}^2 \]

It was felt that in the case of stone roofing materials the additional energy required due to the mechanisation of the quarrying and shaping processes of good quality slate would be offset by the additional energy required in handling and cutting the much heavier slates and sedimentary stone commonly used in pre-industrial days.
### Metals

1. **Range of roof angles:**

<table>
<thead>
<tr>
<th>Steel (profiled)</th>
<th>Aluminium (profiled)</th>
<th>Copper (shut)</th>
<th>Lead (shut)</th>
<th>Zinc (shut)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20° min</td>
<td>15° min</td>
<td>flat 0°</td>
<td>flat 0°</td>
<td>flat 0°</td>
</tr>
</tbody>
</table>

2. **Assumed angle**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>flat 0°</th>
<th>flat 0°</th>
<th>flat 0°</th>
</tr>
</thead>
<tbody>
<tr>
<td>20° (cos.939)</td>
<td>20° (cos.939)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. **Roof area per m² covered** ($\frac{1}{\cos x}$)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>1</th>
<th>1</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.065</td>
<td>1.065</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. **Weight range kg/m²**

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5.7 to 22</td>
<td>2.4 to 4.9</td>
<td>2.8 to 4.9</td>
<td>24.4 to 34.2</td>
<td>4.3 to 7.2</td>
</tr>
</tbody>
</table>

5. **Assumed weight kg/m²**

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>3</td>
<td>5</td>
<td>30</td>
<td>5.76</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(24 guage)</td>
<td>(12 guage)</td>
<td>(21 guage)</td>
</tr>
</tbody>
</table>

6. **Weight per m² covered** ($\frac{(3) \times (5)}{\cos x}$) $= \text{kg/m}²$

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>10.65</td>
<td>3.19</td>
<td>5</td>
<td>30</td>
<td>5.76</td>
</tr>
</tbody>
</table>

7. **Processing energy per unit of mass kWh/kg**

<table>
<thead>
<tr>
<th>Meier (1956, Table 9)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>12.8</td>
<td>116.3</td>
<td>40.6</td>
<td>11.6</td>
<td>23.2</td>
</tr>
<tr>
<td>Bravard, Flora &amp; Portal (1972)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.3</td>
<td>70.4</td>
<td>16.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chapman (1973 b)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.2</td>
<td>90</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NATO (1973, p. 56)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.9 - 13.9</td>
<td>16.7 - 75</td>
<td>6.9 - 8.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Makhijani &amp; Lichtenberg (1972, Table 1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.9</td>
<td>73</td>
<td>22</td>
<td>13.2</td>
<td>15.2</td>
</tr>
<tr>
<td>Assumed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.9</td>
<td>73</td>
<td>22</td>
<td>13.2</td>
<td>15.2</td>
</tr>
</tbody>
</table>

8. **Processing energy per m² covered** ($\frac{(6) \times (7)}{\cos x}$) $= \text{KWh/m}²$

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>137.5</td>
<td>232</td>
<td>110</td>
<td>395</td>
<td>87.6</td>
</tr>
</tbody>
</table>
The results of the above energy calculations are summarized in the matrix below which reveals a considerable variation in energy intensities (EI) required per unit area. It is interesting to compare the ordering (heaviest being first and lightest being fifth in both energy and weight) of a material's energy and weight intensity. The two metals with the extreme weight or energy requirements also have the two highest energy intensities per unit of covered area.

<table>
<thead>
<tr>
<th>Material</th>
<th>Ordering</th>
<th>kg/m²</th>
<th>kWh/kg</th>
<th>kWh/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead</td>
<td>1st</td>
<td>1st</td>
<td>1st</td>
<td>395</td>
</tr>
<tr>
<td>Aluminium</td>
<td>5th</td>
<td>4th</td>
<td>2nd</td>
<td>232</td>
</tr>
<tr>
<td>Steel</td>
<td>2nd</td>
<td>5th</td>
<td>3rd</td>
<td>137</td>
</tr>
<tr>
<td>Copper</td>
<td>4th</td>
<td>2nd</td>
<td>4th</td>
<td>110</td>
</tr>
<tr>
<td>Zinc</td>
<td>3rd</td>
<td>3rd</td>
<td>5th</td>
<td>87</td>
</tr>
</tbody>
</table>

Lead, the heaviest in weight, but with the second lowest energy demand comes first, followed by aluminium the lightest material in weight but the lowest in energy terms; the remainder falling into place in a very discernable order which decreases proportionately with the extremity of the two constituents (kg/m² and kWh/kg). Zinc in the middle of the spectrum in respect to both kg/m² and kWh/kg consumes the least energy among the metals on an area basis. These results are slightly deceiving, for steel and aluminium in a corrugated form provide not only weather protection but are structural as well, to be compared in a more equitable fashion some allowance would have to be made for this fact. This is a topic which will be further discussed in Chapter 4. It is the fact that corrugated metal does support its own weight, eliminating a sub-roofing system, that makes it so popular among the metal roofing; and it is this popularity that has largely determined the assumed value of 140 kWh/m²² for the combined category of 'metal roofing'. It is a value which would also fall into
the middle of the ordering.

9. Assumed changes in energy consumption in relation to time

(energy factor see appendix C.)

<table>
<thead>
<tr>
<th></th>
<th>kWh/m²^2</th>
<th>Eff. Factor</th>
<th>kWh/m²^2 (rounded off)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1900 and before</td>
<td>140</td>
<td>x</td>
<td>2.1</td>
</tr>
<tr>
<td>1925</td>
<td>140</td>
<td>x</td>
<td>2</td>
</tr>
<tr>
<td>1938 &amp; 1950</td>
<td>140</td>
<td>x</td>
<td>1.4</td>
</tr>
<tr>
<td>1966</td>
<td>140</td>
<td>x</td>
<td>1</td>
</tr>
</tbody>
</table>

Cement Based Roofing Materials

1. Range of Roof angles

<table>
<thead>
<tr>
<th>Concrete Tiles</th>
<th>Asbestos Cement (AC) Sheets</th>
</tr>
</thead>
<tbody>
<tr>
<td>exposed</td>
<td>sheltered</td>
</tr>
<tr>
<td>30° min</td>
<td>22° min</td>
</tr>
</tbody>
</table>

2. Assumed angle

25° (\cos 0.9063) = 10° (\cos 0.9848)

3. Roof area per m² covered (1/cos x 1)

- Concrete Tiles: 1.1 m²
- Asbestos Cement (AC) Sheets: 1.016 m²

4. Weight range kg/m²

- Concrete Tiles: 43 - 52
- Asbestos Cement (AC) Sheets: 15 - 17

5. Assumed weight kg/m²

- Concrete Tiles: 45
- Asbestos Cement (AC) Sheets: 16

6. Roofing weight per m² covered kg/m²

- Concrete Tiles: 49.5
- Asbestos Cement (AC) Sheets: 16.3

7. Processing energy per unit of mass kWh/kg

- Processing energy of Portland cement:
  2.3 kWh/kg (Chapman, 1973b)

- Processing energy for aggregate:
  0.03 kWh/kg (Bravard, 1972)

- Processing energy of Portland cement:
  2.3 kWh/kg (Chapman 1973b)

- Processing energy for asbestos cement, assume
  0.03 kWh/kg

- AC is 70 to 80 percent Portland Cement (PC) by weight (Everett, 1970, p.215)
  assume 70%
1kg concrete would contain
.166 kg PC
.833 kg aggregate

1kg AC would contain
.7 kg PC
.3 kg asbestos

Processing energy of concrete

tiles
.166x2.3+.833x0.3=.407

.41 kWh/kg for concrete tiles

Processing energy for

AC sheets
.7x2.3+.3x0.3=1.62

1.62 kWh/kg for AC

8. Processing energy per m² covered (6) x (7) = kWh/m²

Concrete Tiles
Asbestos Cement Sheets

49.5kg/m² x .41kWh/kg = 20.1kWh/m²
16.3kg/m² x 1.6kWh/kg = 26.4kWh/m²

9. Assumed changes in processing energy in relation to time

(ef ficiency factor, see appendix C)

<table>
<thead>
<tr>
<th>kWh/m²</th>
<th>eff. factor</th>
<th>kWh/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>(8)</td>
<td>(rounded off)</td>
<td>(rounded off)</td>
</tr>
<tr>
<td>1938 to 1966</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20.1</td>
<td>1</td>
<td>20.1</td>
</tr>
<tr>
<td>1925 to 1966</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>1</td>
<td>26</td>
</tr>
</tbody>
</table>

Processed organic

1. Range of roof angles
flat 0°

2. Roof angles assumed
flat 0°

3. Roof area per m² covered
1m²

4. Weight range kg/m²
Ramsey & Sleeper (1967, p.215) 2.2 to 32

5. Assumed weight kg/m²
15

6. Roofing weight per m² covered kg/m²
15
7. Processing energy per unit of mass kWh/kg

<table>
<thead>
<tr>
<th>Materials</th>
<th>kWh/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barnes &amp; Rankin (1975)</td>
<td>0.058</td>
</tr>
<tr>
<td>Asphalt</td>
<td></td>
</tr>
<tr>
<td>Berry &amp; Makino (1974)</td>
<td>11-13</td>
</tr>
<tr>
<td>Roof board, package paper</td>
<td></td>
</tr>
<tr>
<td>Crude petroleum</td>
<td>0.114</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>19.45</td>
</tr>
<tr>
<td>PVC</td>
<td>19.27</td>
</tr>
<tr>
<td>Makhijani &amp; Lichtenberg (1922)</td>
<td>6.4</td>
</tr>
<tr>
<td>Paper</td>
<td></td>
</tr>
<tr>
<td>NATO (1973)</td>
<td>6.95</td>
</tr>
<tr>
<td>Paper</td>
<td></td>
</tr>
<tr>
<td>Rose (1974)</td>
<td>13</td>
</tr>
<tr>
<td>Paper</td>
<td></td>
</tr>
<tr>
<td>Smith (1968)</td>
<td>19.27</td>
</tr>
<tr>
<td>Petroleum</td>
<td></td>
</tr>
<tr>
<td>Wright (1973)</td>
<td>9.9</td>
</tr>
<tr>
<td>Paper</td>
<td></td>
</tr>
</tbody>
</table>

Assume for processed organic roofing material

2.7 kWh/kg

The assumed energy requirements for 2.7 kWh/kg may appear low in comparison to the estimates listed, but it must be remembered that felts and paper used in roofing are of very low quality with a high content of 'recycled' material (Hornbostel, 1961, tables p. 20 & p. 21).

Asphalt processing energy costs would probably be very low about the same as "crude petroleum" and being a by-product considerably below the more refined and processed synthetic materials like PVC, however the trend currently would be going in this direction, especially with proprietary roofing 'systems'.

8. Processing energy per m² covered

2.7 kWh/kg x 15 kg/m² = 40 kWh/m²

9. Assumed changes in processing energy in relation to time

(eficiency factor see appendix C.)

<table>
<thead>
<tr>
<th>Year</th>
<th>kWh/m²²</th>
<th>Eff. Factor</th>
<th>kWh/m²² (rounded off)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1900 and before</td>
<td>40</td>
<td>x 2.4</td>
<td>= 96</td>
</tr>
<tr>
<td>1925</td>
<td>40</td>
<td>x 1.8</td>
<td>= 72</td>
</tr>
<tr>
<td>1938 &amp; 1950</td>
<td>40</td>
<td>x 1.3</td>
<td>= 54</td>
</tr>
<tr>
<td>1966</td>
<td>40</td>
<td>x 1</td>
<td>= 40</td>
</tr>
</tbody>
</table>
Clay Tiles

1. Range of roof angles

<table>
<thead>
<tr>
<th></th>
<th>Plain Tiles</th>
<th>Pan and Single Lap Tiles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>exposed</td>
<td>sheltered</td>
</tr>
<tr>
<td></td>
<td>40° min.</td>
<td>25° min.</td>
</tr>
<tr>
<td></td>
<td>35° min.</td>
<td>25° min.</td>
</tr>
</tbody>
</table>

2. Assumed angle

\[
\begin{align*}
1600 \text{ and before} & : 40° \quad (\cos 0.7660) \\
1700 \text{ and after}  & : 35° \quad (\cos 0.8192)
\end{align*}
\]

3. Roof area per m² covered \((1/\cos x 1)\)

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1600 and before</td>
<td>1700 and after</td>
</tr>
<tr>
<td></td>
<td>1.31 m²</td>
<td>1.22 m²</td>
</tr>
</tbody>
</table>

4. Weight range kg/m²

<table>
<thead>
<tr>
<th></th>
<th>Plain Tiles</th>
<th>Pan &amp; Single Lap Tiles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>73</td>
<td>34 - 49</td>
</tr>
<tr>
<td>King &amp; Parkes (1974 Table 4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bartlett (1911)</td>
<td>88</td>
<td>54</td>
</tr>
<tr>
<td>Ramsey &amp; Sleeper (1967, p. 217)</td>
<td>73 - 85</td>
<td>39 - 44</td>
</tr>
</tbody>
</table>

5. Assumed weight kg/m²

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1600 and before</td>
</tr>
<tr>
<td></td>
<td>70</td>
</tr>
</tbody>
</table>

6. Weight per m² covered \((3) \times (5)\) kg/m²

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1600 and before</td>
</tr>
<tr>
<td></td>
<td>91.5</td>
</tr>
</tbody>
</table>

The drop from 91.5 to 79.3 kg/m² reflects the decrease in weight due to the slight shift in the tile mix from plain tiles to the lighter single lap tiles. The angle of the roof was also lower to compensate for the same shift.

7. Processing Energy per unit of mass

No figures could be found specifically for tiles, the brick industry provided the basis for the energy intensity estimates, since the firing temperatures for both tiles and facing tiles are the same 1000 – 1290°C. (Diamont, 1970, p. 49). The assumed tile energy intensity would be slightly lower than that of brick, to allow for the quicker firing of tile due to their thinness. The following is a list of energy intensity estimates for bricks. Unfortunately all except one are
expressed per brick and not per unit weight. To give an idea of what this would be an additional column has been added which calculates kWh/kg using an assumed brick weight of 2.2 kg.

MacKillop (1972 Table 1)  
0.2 kWh/brick  
Chapman (1973a)  
1.74 kWh/brick  
Brown & Stellon (1974 Table A)  
2.79 kWh/brick  
Banel (1974, p.iv)  
6 to 25 therms/ton  

assumed (1.2 kWh/brick)  
0.54 kWh/kg

8. Processing energy per unit of covered area

1600 and before  
91.5 kg/m² x 0.54 kWh/kg = 49.4 kWh/m²
1700 and after  
79.3 kg/m² x 0.54 kWh/kg = 42.5 kWh/m²

9. Assumed changes in processing energy in relation to time and efficiency factors (see appendix C and Chapter 2)

<table>
<thead>
<tr>
<th>Time</th>
<th>kWh/m² (app.C)</th>
<th>kWh/m² (rounded off)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1600 and before</td>
<td>49.4 x 3</td>
<td>= 150</td>
</tr>
<tr>
<td>1700 to 1850</td>
<td>42.5 x 3</td>
<td>= 120</td>
</tr>
<tr>
<td>1900</td>
<td>42.5 x 2</td>
<td>= 80</td>
</tr>
<tr>
<td>1925 and after</td>
<td>42.5 x 1</td>
<td>= 42</td>
</tr>
</tbody>
</table>

Assumed changes in processing energy in relation to time and efficiency factors.

Generally speaking, mechanical operations are the least energy intensive processes. However, mechanical treatment of a product involves more energy intensive operations, if done right. More energy is required because the work is done more quickly, and less energy required to do a job varies not only with the time over which the work is done. The amount of energy in not directly
APPENDIX C

Changes in Material Processing Energy Efficiencies

The first part of this appendix discusses the way in which processing energy economies or diseconomies were made since the industrial revolution. The last part estimates the effect of the economies on roofing materials energy intensities. The values established are used in Appendix B (item 9).

The processing energy involved in increasing the 'form' utility of a product, is constantly changing due to advances in technology and industrialization. To see how these changes affect energy demand the processes involved have to be divided into the three general types of treatment; mechanical, thermal, and chemical. 'Processed' materials (metals, cement, etc.) normally encounter all three types of treatment, while 'unprocessed' materials (alate and thatch) are only affected by mechanical methods, in fact this is the distinction between the two. Generally speaking, mechanical operations are the least energy intensive processes. However, mechanical treatment of a product unlike thermal or chemical operations has generally become more energy intensive with time, or with the 'mechanization' of a process, i.e. substitution of machines for men. This is primarily due to two reasons:

1. More energy is required because the work is done more quickly, and the energy required to do a job varies not only with mass and distance but with the time over which the work is done. The amount of energy is not directly

\[ \text{amount of energy} = \text{energy density} \times \text{work done} \]

For more detail on the affects of mechanization on energy demands see the section on assembly in Chapter Four.
proportional to the increase in speed; rather it varies with the square of the velocity. Thus, a decrease in time (or an increase in productivity per man) are purchased with ever increasing energy cost.

2. The tools which permit great increases in power must themselves be ever larger, heavier, and more complex, than the hand tools which they replace. This means more energy for the manufacture, maintenance and repair of the tools involved. Once committed to mechanization, there are some benefits in scale, one large machine replacing two small machines, but this usually involves centralization which results in more transport energy which can offset the gains made through economy of scale.

Compensating for this general increase in mechanical processing energy will not be considered in respect to the processing of roofing materials. It was felt that in the case of stone the additional energy required due to increased mechanization would be offset by the reduction in the amount of roofing material used due to lower pitches and the case of slate. Increasing the mechanical processing energy cast over time would not apply in the case of thatch either, for it was always, (and still is) a non mechanized process; and considering it for the highly processed materials was not really necessary because they are relatively minor when compared to the thermal and chemical processing energy costs.

Heat and chemical treatments of materials, frequently occurring together, consume the major portion of the energy expenditure for processed
materials; though this is changing with the lowering of ore grade and in the case of very hard materials which require a lot of machining. It is however in the area of thermal/chemical material processing that technology has made a difference over the years. The energy cost in these areas has been reduced considerably. These savings were brought about by the following seven methods which are arranged roughly in the order in which they appeared:

1. Economy of scale.

2. The use of continuous processes.

3. Improvements in heat recovery.

4. Improvements in insulation.

5. Improvements in the quality of feed materials.

6. New heating techniques and improvements in temperature control, combustion and fuels.

7. Changes in basic processes.

The first four methods deal with the general suppression of heat losses. These are all well established methods of energy conservation. The remainder are more recent techniques and they hold the most potential for future developments in fuel economy, but do not have nearly as much relevance to relatively crude building materials and in our case roofing materials.

---

1Chemical processing by either electrolytic action or leaching methods will not be covered in much detail, their use in roofing materials is primarily restricted to nonferrous metals, which are used in very limited amounts. However many of the techniques which apply to thermal/chemical processes also apply to the methods mentioned above.
1. Economy of Scale

Energy economies gained by increasing the size of a processing facility deals principally with the relationship between capacity and the surface area of a vessel; the volume or capacity being largely a cubic function while area being a square function.

A 1m cube has for example a volume of 1m$^3$ and surface area of 6m$^2$ (1:6), while a 2m cube has a volume of 8m$^3$ and surface area of 24m$^2$ (1:3). The increase in facility size has closely followed that of demand and population. Dr. Finniston, Chairman of British Steel mentions the continuance of this technique today, in his article "Fewer Joules for Steel Making" (1974 p.66).

This type of energy economy was experienced by all the processed roofing materials.

2. Continuous Processes

The next general step in energy reduction was the introduction of continuous processes instead of batch processes, eliminating the need to repeatedly heat up the processing apparatus from room temperature (20°-40°C.) to working temperatures (300°-1900°C.) for each batch operation. Of the roofing materials, clay tiles benefitted the most from this type of energy saving, with the switch from batch to continuous kilns early this century and already described in Chapter Two. Metal smelting, cement manufacturing and the refining of petroleum products would have all benefitted as well, however the continuous techniques would have been incorporated into their respective processing operations, before the materials themselves were applied for roofing purposes (lead being an exception), therefore contributing nothing to the increase in thermal
efficiencies assumed in step 9 for these materials.

The continuous process can be examined in another way, the integration of different processes associated with the production of a material into a continuous process, rather than a series of individual operations. This integration procedure usually complements the 'economy-in-scale' technique previously mentioned but was generally employed after the two methods already described. Energy savings from integrated or continuous operations would apply to most of the processed roofing materials.

T.P. Colclough (1960, p. 203) discusses this type of integration in relation to the steel industry but the principles are common to other materials especially those employing a large number of operations.

"Traditionally, coke making, iron smelting, steel making, rolling and forging were frequently more or less completely separate operations, each delivering its product in solid cold form to the succeeding operation. Today, the standard pattern is to group together as many of these operations as possible...thereby reducing radiations and similar losses; to transfer the product of each operation to the next at the highest practical temperature to conserve the sensible heat of the metal, and to carry the heat of steel manufacturing into the rolling operations, minimizing re-heating requirements. Grouping different operations has also made it practical to make full and efficient use of valuable gasses made in the coke ovens and blast furnaces."

3. Heat Recovery

Heat recovery techniques can be applied in three ways. It can be applied to single operations, between two primary operations or between a primary and secondary operation. An example of the first would be
the employment of heat exchanges to impart the incoming air and gas with the heat contained in the outgoing waste furnace gasses which is the accepted practice in an open hearth furnace. An example of the second can be found in the ceramic industry, whereby the flue gases from the kilns are exhausted over the incoming 'green' ceramic materials, thus performing a drying function. The third type would be the use of waste heat for general heating or conversion to auxiliary mechanical or electrical power, normally achieved through steam generation.

4. Insulation
Improved insulation is self explanatory and applies to any operation when temperature differentials have to be maintained.

5. Increasing the Quality of Input of Materials
One of the more recent developments in energy economy is in the area of higher grade feed materials for processing. These higher grades can be achieved by the use of naturally high grade ore or through ore "dressing" which concentrates or upgrades the ore by physical means. In iron production, for example, the British have chosen to import natural higher grades of ore (with its corresponding balance of payments problem), while the US tends to utilize benification techniques to upgrade domestic ores. In either case the use of a higher grade feed material eliminates the unnecessary heating of a large amount of gauge and makes chemical reactions much easier to achieve. Even though dressed material increases the energy efficiency of an operation like smelting, the benification (Fine, 1968, pp 30-5) of ores is itself becoming quite energy intensive, particularly if heat hardening, drying, calcination or roasting are required; or as
Chapman (1973, fig 2) points out in his analysis of copper production, the grade of ore is very low. Other ways of enhancing the quality of feed in energy terms are demonstrated in the manufacture of bricks. One method involves the use of 'stiff plastic' clay pressing system mentioned in Chapter Two which brought into use relatively dry clays previously difficult to use. The use of dryer clays reduced the amount of moisture which would otherwise have had to have been driven off by heat in the kiln, thereby replacing a large amount of heat energy with a small amount of mechanical energy. Another example of better feed material in the brick industry was the introduction of highly carbonaceous clay containing up to 95% of the fuel needed to fire it in the case of fletton bricks, a technique incidently not applicable to clay roofing materials.

The ultimate in input quality of material feed is the use of recycled materials, not so much in the saving of energy of the melting or refining processes but in the elimination of most of the energy used in preparatory processes. The large potential in energy savings brought about by the use of a higher percentage of recycled materials is discussed in more length in Chapter Four. Manufacturers unfortunately, shy away from the use of scrap because of its 'impurity'¹ and the general lack of flexibility within the processes.

¹This applies especially to 'obsolete scrap' or material which has been used by society and not 'new scrap' generated from industry. Obsolete scrap which can contain traces of other materials which can amount to only a fraction of a percent are often considered by industry to be more contaminated than a low grade ore which can contain only a fraction of a percent of the material being sought.
to accept a larger proportion of recycled material. It is
doubtful whether recycling to date has played a very significant
role in reducing the overall energy cost of materials, especially
those commonly used for roofing.

6. New Heating Techniques and Improvements in Temperature Control,
Combustion and Fuels.

New heating techniques have had limited applications and their
potential really lies in the future, but some of the techniques include
the use of lasers for welding, hot isostatic pressing, radio frequency
and microwave heating devices, and induction heating and melting
methods.

Improvements in temperature control, combustion and fuels are closely
related and have been improving energy efficiencies steadily over
time. Combustion and fuel technologies have usually resulted in
higher working temperatures without the use of additional fuel.
Accurate temperature control has also ensured a steady output of
quality products, which would affect products like tile and bricks,
whose early manufacture involved a high ratio of rejects due primarily
to the lack of temperature control.

7. Changes in Basic Processes

For roofing materials changes in basic processes appear either very
early in the industrial revolution before the material was ever used
for roofing, or are proposals for the future. In fact the early
basic changes in a process could be so drastic that it made the material
practical for roofing applications, the introduction of electrolytic
method of aluminium production in 1886 and the Bessemer method of
Table C-1  Processing efficiency factors assumed by year, expressed as a multiple of a material’s base energy intensity (1966).

<table>
<thead>
<tr>
<th>Year</th>
<th>Clay</th>
<th>Metal</th>
<th>Processed organic</th>
<th>Asbestos cement</th>
<th>Concrete tile</th>
</tr>
</thead>
<tbody>
<tr>
<td>1600</td>
<td>3</td>
<td>2.1</td>
<td>2.4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1700</td>
<td>3</td>
<td>2</td>
<td>1.8</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1800</td>
<td>3</td>
<td>1.4</td>
<td>1.3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1850</td>
<td>2</td>
<td>1.4</td>
<td>1.3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1900</td>
<td>2</td>
<td>1.4</td>
<td>1.3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1925</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1938</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1950</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1966</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Fig C-1  Efficiency of three major types of energy conversions. (Starr, 1971, p.40)
producing steel are two classic examples. A change in the basic process does not guarantee a reduction in energy, sometimes they are developed merely to exploit a new type of feed material. The change from the open hearth furnace to basic oxygen steel making (BOS) is one of the current shifts in processes which does result in an energy saving.

Direct reduction of iron ore is typical of a basic process change, that is likely to occur in the future. And most of these basic changes are from thermo/chemical processes to either 'wet' chemical (leaching) methods or by electrolysis. The latter could actually increase energy demands depending on the electrical generating efficiencies which currently run about thirty percent.

Energy Saving Techniques and their Application to Roofing Materials

Energy conservation can be affected by any or all of the seven methods discussed; but what was the magnitude of these savings over the last two hundred years? Figure C-1 is reproduced from Channcey Starr's article on "Energy and Power" (1971, p.40) and indicates his composite idea of energy efficiency increases from 1800. Processing heat efficiency is shown to have increased about 5 times (7% - 35%). The energy estimates in Appendix B were based on current technology. In order to reflect the increases in energy efficiencies particularly with respect to processes involving heat additional energy costs

1 A negative aspect to this change in energy terms is the fact that the BOS method is only lower in energy consumption when using virgin ores, and it is capable of accepting only a very small portion of recycled iron whereas the electric arc and open hearth method can take large quantities of scrap which would result in high energy savings.
would have to be estimated which would increase with the recession of time. The energy intensities of a material are inversely proportional to the energy efficiency, for example a doubling of efficiency would half the energy intensity. Therefore the processed roofing materials should reflect decreases in intensity roughly proportional to Starr's increase in efficiency. The following paragraphs cover each roofing material separately and mention the applicable methods of economy used to achieve the reductions, and the reasons the decreases (to current level) have not been as great as those for industrial processes indicated as a whole by Starr.

Assumed efficiency factors by year for each processed material are shown in Table C-1. A material's current energy intensity is multiplied by those factors to produce the assumed energy intensity for a particular date. For example an efficiency factor of two was assumed for metal roofing in 1925 which would mean that metal was 2x more energy intensive than it was in 1966.

Clay Tiles
Clay tile manufacturing would have benefitted from all the techniques except the basic change in the process. The total assumed energy savings amounting to three fold between 1850 and 1925 does not match those suggested by Starr (1971, p.40). This is due to the simplicity of the operation which involved only two thermal processes, drying and baking. Improvements in drying through the use of exhaust gases from the kiln could not really be considered because traditionally tiles were dried in open air which required no energy. Furthermore once the first six economies discussed had been applied to the kiln operation, there was little more that could be done to save energy.
and savings could not be gained from preparatory processes involved in tile making, for they are mechanical in nature and if anything have become more energy intensive over the years.

Metal Roofing

The manufacture of metals has benefitted from all of the innovations discussed, in fact it was largely the metal industry which pioneered most of them. However it can be seen that the 2:1 fold assumed decreases in metal production energy intensities between 1900 and 1966 are again far short of Starr's estimate. This is primarily due to two conditions: the first having nothing to do with processing efficiency but dealing with the shift in the mix of metal roofing materials. In earlier periods the use of copper and zinc with their corresponding lower energy intensities per unit area constituted a higher proportion of the metal roofing materials. The use of aluminium which has the highest energy intensity did not even exist. The shift over the years was from lower intensity materials to higher intensity substitutes particularly aluminium and steel. The second reason has to do with the late application of metals to roofing which would have meant that many of the energy economies discussed would have already been in use before the material's widespread use in roofing.

Processed Organic

Processing energy for paper, felts and asphalt was assumed to have decreased by 2.4 times from 1900 to 1966; again below Starr's energy efficiency guide. In the case of felt/paper processes this could be explained by their relatively late entry for roofing purposes. The basic paper making operations used today were developed early in the
nineteenth century (Hall, 1974, p.58); so most of the economies would have already been made. It should be also noted that paper making involves a number of stages many of which are mechanical in nature, the remaining thermal/chemical processes are carried out at relatively low temperatures which would reduce the effect of most of the saving techniques discussed. Finally, unlike most of the other processed roofing materials, there is widespread use of recycled waster paper and the use of other industrial by-products for roofing felts and papers (Hornbostel, 1961, pp 363-369). This would reduce the potential area for energy savings when compared with Starr's efficiency estimates which were based more on the processing of materials from virgin sources.

Asphalt roofing products would not benefit from high energy efficiencies, because early supplies were from natural sources such as Pitch Lake, Trinidad. No doubt some pitch compounds were by products of the coal gas and coke industry which benefitted from many of the energy saving techniques discussed. With the development of motor transport asphalt products would have switched to being a product of the petroleum industry, whose chemical engineers were well aware of the science of thermo-dynamics. More recently the average drop in energy intensity would be slowed down due to the introduction of new and more energy intensive highly processed synthetic rubber and plastic based roofing products.

Cement Based Roofing Products

No allowance has been made in Table C-1 for increases in processing efficiencies for cement based roofing materials for two reasons: first, cement roofing consists mainly of unprocessed aggregates which are treated by mechanical means, which probably have increased in energy intensity; and second, like clay
tile production, cement manufacturing consists of only one major thermal process, a kiln in which clay and limestone are burned into a clinker. Portland cement was invented in 1824 and was made in a batch process until 1885 when in England the continuous horizontal rotating kiln was introduced; the same kiln which is used today. Cement roofing materials were not utilized until the 1920's, approximately thirty years after the major economies had been effected and the last date in the case study (1966) takes place before the considerable consolidation in the cement industry in Britain in the late 60's which resulted in very large integrated plants producing less energy intensive cement.
APPENDIX D

Calculations of weight/distance factors, energy intensities, material/mode mixes, relative energies and relative energies consumed in the transport time of roofing materials.

Appendix D is presented in tabular form (Table D-1) and the figures from this table provide the basis for the graphics concerning transport energy in Chapter Three even though some of the data is developed in supplementary Appendixes E through H. The calculations involved in transport energy intensities are far more involved than those of processing. Consequently Table D-1 is larger than Table A-1. It should be noted that columns are indicated by both capital letters and Arabic numerals. The numbers (1-5) columns are the same as those in table A-1 and the relation between them is identical and explained in Appendix A. Columns indicated by capital letters (A through E) apply to transport only and the relationship between them and cross references concerning them are summarized at the top of Table D-1 and are discussed in the main text.
### Table D-1

Calculations of weight-distance factors, energy intensities, material-mode mixes, relative energies and relative energies consumed in the transport of roofing materials by year, material and mode

<table>
<thead>
<tr>
<th>Cross references</th>
<th>App. B steps 1-6</th>
<th>App. M</th>
<th>App. E App. F</th>
<th>Chap. 2</th>
<th>App. G</th>
<th>(1)X(2)</th>
<th>(2)X(^2)</th>
<th>(3)X(4)</th>
<th>(1)X(4)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gallons</strong></td>
<td>(A)</td>
<td>(B)</td>
<td>(C)</td>
<td>(D)</td>
<td>(E)</td>
<td>(F)</td>
<td>(G)</td>
<td>(H)</td>
<td>(I)</td>
</tr>
<tr>
<td><strong>MATERIAL</strong></td>
<td><strong>Roofing weight per hour, unit of area</strong></td>
<td><strong>Distance travelled by mode</strong></td>
<td><strong>Weight distance factor</strong></td>
<td><strong>Mode energy intensity</strong></td>
<td><strong>Material transport percentage mix</strong></td>
<td><strong>Mode percentage mix</strong></td>
<td><strong>Relative energy and percentage mix</strong></td>
<td><strong>Quantity factor</strong></td>
<td><strong>Relative energy consumed</strong></td>
</tr>
<tr>
<td><strong>kg/m²</strong></td>
<td><strong>km</strong></td>
<td><strong>tonne km per m²</strong></td>
<td><strong>km per tonne km</strong></td>
<td><strong>kWh/m²</strong></td>
<td><strong>%</strong></td>
<td><strong>%</strong></td>
<td><strong>Relative energy factor</strong></td>
<td><strong>(Million)</strong></td>
<td></td>
</tr>
</tbody>
</table>

#### 1950

| **TREAT** | **cort** | **10** | **0.496** | **1.5** | **2.8** | **0.41** | **63.4%** | **3** | **2.25** |
| **CLAY**   | **cort** | **10** | **0.793** | **1.5** | **1.85** | **0.39** | **63.4%** | **3** | **2.25** |
| **STONE/SLATE** | **cort** | **10** | **0.652** | **1.5** | **1.65** | **1.85** | **2.8** | **4.4** | **1.9** |

#### 1955

| **TREAT** | **cort** | **10** | **0.496** | **1.5** | **2.8** | **0.41** | **63.4%** | **3** | **2.25** |
| **CLAY**   | **cort** | **10** | **0.793** | **1.5** | **1.85** | **0.39** | **63.4%** | **3** | **2.25** |
| **STONE/SLATE** | **cort** | **10** | **0.652** | **1.5** | **1.65** | **1.85** | **2.8** | **4.4** | **1.9** |

#### 1960

| **TREAT** | **cort** | **10** | **0.496** | **1.5** | **2.8** | **0.41** | **63.4%** | **3** | **2.25** |
| **CLAY**   | **cort** | **10** | **0.793** | **1.5** | **1.85** | **0.39** | **63.4%** | **3** | **2.25** |
| **STONE/SLATE** | **cort** | **10** | **0.652** | **1.5** | **1.65** | **1.85** | **2.8** | **4.4** | **1.9** |

#### 1970

| **TREAT** | **cort** | **10** | **0.496** | **1.5** | **2.8** | **0.41** | **63.4%** | **3** | **2.25** |
| **CLAY**   | **cort** | **10** | **0.793** | **1.5** | **1.85** | **0.39** | **63.4%** | **3** | **2.25** |
| **STONE/SLATE** | **cort** | **10** | **0.652** | **1.5** | **1.65** | **1.85** | **2.8** | **4.4** | **1.9** |

#### 1980

| **TREAT** | **cort** | **10** | **0.496** | **1.5** | **2.8** | **0.41** | **63.4%** | **3** | **2.25** |
| **CLAY**   | **cort** | **10** | **0.793** | **1.5** | **1.85** | **0.39** | **63.4%** | **3** | **2.25** |
| **STONE/SLATE** | **cort** | **10** | **0.652** | **1.5** | **1.65** | **1.85** | **2.8** | **4.4** | **1.9** |

#### 1990

| **TREAT** | **cort** | **10** | **0.496** | **1.5** | **2.8** | **0.41** | **63.4%** | **3** | **2.25** |
| **CLAY**   | **cort** | **10** | **0.793** | **1.5** | **1.85** | **0.39** | **63.4%** | **3** | **2.25** |
| **STONE/SLATE** | **cort** | **10** | **0.652** | **1.5** | **1.65** | **1.85** | **2.8** | **4.4** | **1.9** |

#### 2000

| **TREAT** | **cort** | **10** | **0.496** | **1.5** | **2.8** | **0.41** | **63.4%** | **3** | **2.25** |
| **CLAY**   | **cort** | **10** | **0.793** | **1.5** | **1.85** | **0.39** | **63.4%** | **3** | **2.25** |
| **STONE/SLATE** | **cort** | **10** | **0.652** | **1.5** | **1.65** | **1.85** | **2.8** | **4.4** | **1.9** |
Continued

<table>
<thead>
<tr>
<th>Material</th>
<th>kg/m²</th>
<th>Distance travelled by mode (km)</th>
<th>Weight factor (tonne km per m²)</th>
<th>Mode energy intensity (kWh per km)</th>
<th>Material transport energy intensity (kWh per m²)</th>
<th>Mode material percentage mix %</th>
<th>Mode relative energy and percentage mix %</th>
<th>Total population (in units)</th>
<th>Relative energy consumed (in units)</th>
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<td>1.2</td>
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<td>100</td>
<td>0.043</td>
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<td>79.3</td>
<td>25</td>
<td>1.19</td>
<td>1</td>
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<td>3</td>
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<td>12</td>
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<td>0.216</td>
<td>0.4</td>
<td>100</td>
<td>0.002</td>
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</table>

NOTE: All calculations are in units of energy.
<table>
<thead>
<tr>
<th>Source references</th>
<th>App. B steps 1-6</th>
<th>App. H</th>
<th>App. E</th>
<th>Chap. 2</th>
<th>App. G</th>
<th>(1)x(z)</th>
<th>(2)x(y)</th>
<th>(3)x(x)</th>
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<tr>
<td>Event</td>
<td>(A)</td>
<td>(B)</td>
<td>(C)</td>
<td>(D)</td>
<td>(E)</td>
<td>(F)</td>
<td>(G)</td>
<td>(H)</td>
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<tr>
<td><strong>MATERIAL</strong></td>
<td><strong>Roofing weight per horiz. unit of area</strong></td>
<td><strong>Distance travelled by mode</strong></td>
<td><strong>Weight distance factor</strong></td>
<td><strong>Mode energy intensity</strong></td>
<td><strong>Mode transport energy intensity</strong></td>
<td><strong>Material transportation energy intensity</strong></td>
<td><strong>Material material percentage mix</strong></td>
<td><strong>Mode transportation energy percentage mix</strong></td>
</tr>
<tr>
<td><strong>kg/m²</strong></td>
<td><strong>km</strong></td>
<td><strong>tonne km per m²</strong></td>
<td><strong>kwh per tonne km</strong></td>
<td><strong>kwh/m²</strong></td>
<td><strong>%</strong></td>
<td><strong>%</strong></td>
<td><strong>(Million)</strong></td>
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<td>100</td>
<td>7.93</td>
<td>*</td>
<td>6.35</td>
<td>15</td>
<td>10</td>
<td>0.695</td>
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<td>100</td>
<td>7.93</td>
<td>*</td>
<td>6.35</td>
<td>15</td>
<td>10</td>
<td>0.695</td>
</tr>
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<td>*</td>
<td>6.35</td>
<td>15</td>
<td>10</td>
<td>0.695</td>
</tr>
<tr>
<td>rail</td>
<td>*</td>
<td>100</td>
<td>7.93</td>
<td>*</td>
<td>6.35</td>
<td>15</td>
<td>10</td>
<td>0.695</td>
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<tr>
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<td>1.62</td>
<td>3</td>
<td>3</td>
<td>0.198</td>
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<td>100</td>
<td>1.46</td>
<td>*</td>
<td>1.12</td>
<td>3</td>
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<td>0.198</td>
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<td>75</td>
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<td>3</td>
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<td>*</td>
<td>100</td>
<td>2.12</td>
<td>*</td>
<td>1.62</td>
<td>3</td>
<td>3</td>
<td>0.198</td>
</tr>
<tr>
<td>rail</td>
<td>*</td>
<td>100</td>
<td>1.46</td>
<td>*</td>
<td>1.12</td>
<td>3</td>
<td>3</td>
<td>0.198</td>
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<td><strong>CONCRETE TILE</strong></td>
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<td>75</td>
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<td>11</td>
<td>11</td>
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<tr>
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<td>1.2</td>
<td>*</td>
<td>0.96</td>
<td>11</td>
<td>11</td>
<td>0.106</td>
</tr>
<tr>
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<td>*</td>
<td>100</td>
<td>1.2</td>
<td>*</td>
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<td>11</td>
<td>11</td>
<td>0.106</td>
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<tr>
<td><strong>ASBESTOS CLOTH</strong></td>
<td>16</td>
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<td>*</td>
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<td>*</td>
<td>100</td>
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<td>*</td>
<td>6.35</td>
<td>8</td>
<td>8</td>
<td>0.506</td>
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<tr>
<td><strong>TOTAL POPULATION 40K</strong></td>
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<td></td>
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<td></td>
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<td></td>
</tr>
</tbody>
</table>
Appendix E contains three tables; E-1 deals with animal and human powered land transport, E-2 deals with water transport, and E-3 deals with rail and lorry transport. In the first two tables the energy intensity of each mode is found by estimating the load (column 1) and distance (column 2) which could reasonably be handled by the various modes per day. The product of these two factors results in a tonne kilometre (column 3) factor for each mode. This amount is subsequently divided by the modes daily direct energy input\(^1\) for control\(^2\) (columns 4 and 5) and propulsion (columns 6 and 7) to produce an energy intensity for each mode.

The energy intensity for lorry and rail transport (Table E-3) are not calculated but are taken from various sources directly. In all cases the energy intensity is based on good haulage conditions and technology. Appendix F, like appendix C is concerned with increasing the estimated mode energy intensities to reflect the diminishing operating condition and technology of earlier historical periods. Appendix H adjusts the assumed mode mileage for the same reasons.

1 Direct energy is based on the fuel (wind is not considered as a fuel) consumed by a convertor, either man, animal or machine in controlling or propelling a particular mode of transport. It does not include energy required for processing or transporting the necessary fuel, the energy required to make either the vehicles or the infrastructure i.e. roads, rail, ports, etc. associated with them.

2 This represents the energy consumed by man to control, or operate the mode involved. It is particularly relevant in the smaller and earlier forms of transport i.e. carts, wheelbarrows, etc; becoming insignificant with larger and faster carriers of today. It is not considered in the energy intensity of either rail or lorry (Table E-3).
Table E-1  Loads, distances and energy requirements assumed for modes of land transport propelled by men and animals, and their calculated energy intensities.

<table>
<thead>
<tr>
<th>Calculations</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
<th>(6)</th>
<th>(7)</th>
<th>(8)</th>
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<tbody>
<tr>
<td><strong>Mode</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Men back</td>
<td>0.065</td>
<td>(0.05)</td>
<td>32</td>
<td>(20)</td>
<td>4.66</td>
<td>0.46</td>
<td>2.66</td>
<td>(1 horse)</td>
</tr>
<tr>
<td>Wheelbarrow</td>
<td>0.136</td>
<td>(0.15)</td>
<td>32</td>
<td>(20)</td>
<td>4.85</td>
<td>0.46</td>
<td>2.66</td>
<td>(1 horse)</td>
</tr>
<tr>
<td>Peak horse</td>
<td>0.091</td>
<td>(0.1)</td>
<td>64</td>
<td>(40)</td>
<td>5.8</td>
<td>0.182</td>
<td>26.6</td>
<td>(1 horse)</td>
</tr>
<tr>
<td>Oxcart</td>
<td>0.455</td>
<td>(0.5)</td>
<td>32</td>
<td>(20)</td>
<td>14.6</td>
<td>0.182</td>
<td>26.6</td>
<td>(1 horse)</td>
</tr>
<tr>
<td>Waggon</td>
<td>2.75</td>
<td>(3)</td>
<td>64</td>
<td>(40)</td>
<td>175</td>
<td>0.0152</td>
<td>106</td>
<td>(4 horses)</td>
</tr>
</tbody>
</table>

*Recept for the 'wheelbarrows' load factor which has been reduced from 400 to 300 pounds, all the figures for load and distance are the same as those used by Professor Hay in his book Transport Engineering (1961, Table 1-1). His non metric figures are indicated in brackets but have been converted to metric units for this study. To get a rough idea of each mode's speed, the distance should be divided by ten which represents a ten hour working day, i.e. twenty miles covered in ten hours would equal two miles an hour.*

The direct energy input is based on seventy five percent of man's average 3000 Kcal intake which amounts to 2300 Kcal or 2.66 kWh. This is incidentally very close to what Cottrell calculates as the world population's average daily intake. Animal energy is based on the horse and can be estimated in two ways, being approximately ten times man's assumed consumption (Cottrell, 1955, pp 18-21) or 2.66 kWh/day or figured on the mechanical output of a horse times four or five to reflect a conversion efficiency between 20 and 25%. If a horse was capable of producing one horse power for a ten hour day this would amount to 10 horse power hour or 7.45 kWh times 5 for conversion efficiency would equal a 37.25 kWh per day maximum. A minimum value would result from using the output which Watt found that horses produced in his day, which was only two thirds of a horse power. This would mean for a ten hour day a horse would produce 6.6 horse power hours or five kilowatt hour using the minimum conversion efficiency factor of 20% would result in an input energy of 20 kWh/day. The first method of calculation results of 26.6 kWh/day falls roughly between the two extremes of the second method and has been assumed as the input energy for horse powered transport.
### Calculations

<table>
<thead>
<tr>
<th>Load</th>
<th>Distance</th>
<th>Load dist. factor</th>
<th>Control energy</th>
<th>Propulsion energy</th>
<th>Total energy intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>tonne</td>
<td>km</td>
<td>tonne km per day</td>
<td>kWh per tonne km</td>
<td>kWh per day</td>
<td>kWh per tonne km</td>
</tr>
<tr>
<td>(sh. ton)</td>
<td>(sh. ton ml)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Inland Barge

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<th>Distance</th>
<th>Load dist. factor</th>
<th>Control energy</th>
<th>Propulsion energy</th>
<th>Total energy intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>35b</td>
<td>320</td>
<td>1120 (500)</td>
<td>5.2 (2 men)</td>
<td>0.004</td>
<td>25.6 (1 horse)</td>
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</table>

### Sailing Ship

<table>
<thead>
<tr>
<th>Load</th>
<th>Distance</th>
<th>Load dist. factor</th>
<th>Control energy</th>
<th>Propulsion energy</th>
<th>Total energy intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>160</td>
<td>190°</td>
<td>11500 (21600)</td>
<td>15.3 (crew of 5)</td>
<td>0.00043</td>
<td>0.0004</td>
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### Steam Ship

<table>
<thead>
<tr>
<th>Load</th>
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<th>Propulsion energy</th>
<th>Total energy intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>165</td>
<td>300°</td>
<td>50000 (32000)</td>
<td>26800</td>
<td>0.54</td>
<td>0.54</td>
</tr>
</tbody>
</table>

---

*British river and canal barges averaged seventy tons (Williams, E.L., 1911) applying the guide for wooden vessels, in which carrying capacity equated vessel weight (Owen, D., 1911) to this type of barge would give a carrying capacity of 35 tons (40 s.ton). This figure agrees with Christopher Hill's (Hill, 1969, p. 249) reckoning that "one horse could draw eighty times as much in a canal barge as by cart on soft roads, and four hundred times as much as a pack horse". (From Table E-1 cart = .5 s.ton x 80 = 40 s.ton and packhorse = .1 s.ton x 400 = 40 s.ton).*

*Two miles an hour was the average speed of a canal barge, allowing for a 10 hour day would result in 20 miles per day (32 km).*

*Most building materials that were transported by sea went by 70-80 foot sailing barges, 60-90 foot smacks, 80-100 foot schooners or 90-115 foot brigs (Watts, 1911a), the carrying capacity ranging from 100-200 tons, a capacity of 165 tons (180 s.ton) will be assumed for both sail and stern.*

*This figure was based on a 24 hour day at (5 m.p.h.) 8 km/hour or 100 km/day (120 miles) for sail and 12.5 km/hour (8 m.p.h. - 7 knots) or 300 km (190 miles) per day for steam ship.*

*The effective horse power required to drive a vessel between 60-200 feet at 7 knots would be approximately 150 (Watts, 1911b). This times 24 hours = 3600 bhp, assuming a thermal efficiency for a steam engine at 105 the result would be a direct fuel input amounting to 36000 bhp (10 x 3600) or 26800 kWh.*
<table>
<thead>
<tr>
<th>Source</th>
<th>Steam train&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Diesel train</th>
<th>Lorry</th>
<th>Large lorries</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kWh/tonne km</td>
<td>kWh/tonne km</td>
<td>kWh/tonne km</td>
<td>kWh/tonne km</td>
</tr>
<tr>
<td>Meier&lt;sup&gt;c&lt;/sup&gt; (1956, Table 16)</td>
<td>0.8 (4000)</td>
<td>0.2 (1000)</td>
<td>4.2 (6000)</td>
<td>0.35 capacity (1750)</td>
</tr>
<tr>
<td></td>
<td>btu/s.ton mile</td>
<td>btu/s.ton mile</td>
<td>btu/s.ton mile</td>
<td>btu/s.ton mile</td>
</tr>
<tr>
<td>Leach&lt;sup&gt;d&lt;/sup&gt; (1973, Table 2)</td>
<td>0.55 @ 5x diesel</td>
<td>0.11</td>
<td>0.67 small</td>
<td>0.41 diesel truck (1100)</td>
</tr>
<tr>
<td></td>
<td>0.44 @ 4x</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>0.53 @ 3.5x</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>koal/1.ton mile</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Breach&lt;sup&gt;d&lt;/sup&gt; (1973, p. 20)</td>
<td>0.61 @ 5x diesel</td>
<td>0.125</td>
<td>0.41 trucks</td>
<td>0.466 trucks (2350)</td>
</tr>
<tr>
<td></td>
<td>0.49 @ 4x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.43 @ 3.5x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>btu/1.ton km</td>
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</tr>
<tr>
<td>Campbell&lt;sup&gt;d&lt;/sup&gt; (1973, Table 5)</td>
<td>0.56 @ 5x diesel</td>
<td>0.19</td>
<td>0.466 trucks (2350)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.36 @ 4x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.40 @ 3.5x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>koal/1.ton mile</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hirst&lt;sup&gt;d&lt;/sup&gt; (1973, Table 2)</td>
<td>0.67@ 5x diesel</td>
<td>0.14</td>
<td>0.56 trucks</td>
<td>0.56 trucks (2900)</td>
</tr>
<tr>
<td></td>
<td>0.53 @ 4x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.47 @ 3.5x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>koal/1.ton mile</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assumed</td>
<td>0.8</td>
<td>0.16</td>
<td>0.8&lt;sup&gt;e&lt;/sup&gt;</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>The energy intensities indicated in brackets are the way in which the intensities were expressed in the source document. They have all been converted to metric equivalents.

<sup>b</sup>Only Meier (1956, table 16) has an actual figure for steam trains, however various authors have expressed the increase in efficiency between steam and diesel trains. Knowing these differences one can estimate a steam train's energy intensity from diesel performances by multiplying its intensity by the difference in efficiencies. Hirst (1973, p. 37) speaks of diesel trains being five times more efficient than steam trains, Meier from his figures (1956, table 16) indicates an improvement of four times, agreeing with Campbell (1973, table 3). Ayers and Scarlett (1956, tables 6 and 7) estimate a difference of 3.75 and Summers' (1971, p. 153) figures a difference of 3.5 fold. In column (1) energy differences of 3.5, 4 and 5 are applied to the diesel figures in column (2). A review of the figures indicates the lowest value for steam trains to 0.38 kWh/tonne km and the highest 5.8, which is the figure which will be assumed for this study. The reason for this high assumption is that the majority of figures are based on U.S. railroads, which are more efficient in energy terms that British Rail, because of the long distances involved which reduce the stop starts inefficiencies found in British short hauls, and the fact that the waggon weight to load ratio is about 2:1 in Britain while being 5:2 in the States (Ross, 1911).

<sup>c</sup>The energy intensities of lorries varies dramatically according to size, Meier (1956, table 16) estimates the large lorry using about one fourth as much energy as a small one. For this study an average lorry size has to be assumed. Ministry of Transport figures (1970, table 25) indicate that for building materials, 55% of the lorry consignments were under one ton, 33% were between 1 and 10 tons and only 12% being over 10 tons, indicating an average lorry to be about 1 ton, so an energy intensity of 0.8 kWh/ton km has been selected to fall between the extremes but favouring the smaller lorry size.
Areas where energy reductions have been made in traditional material transport systems, and the assumed efficiency factors caused by them

<table>
<thead>
<tr>
<th>TYPE OF ENERGY REDUCTIONS</th>
<th>TYPE OF TRANSPORT MODE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction in direct energy costs</td>
<td>Land</td>
</tr>
<tr>
<td>a) Reduction in dead weight</td>
<td>m</td>
</tr>
<tr>
<td>b) Reduction of losses in energy conversion and braking</td>
<td>Chemical to thermal (engines)</td>
</tr>
<tr>
<td></td>
<td>Chemical to mechanical (animal)</td>
</tr>
<tr>
<td></td>
<td>Wind to mechanical</td>
</tr>
<tr>
<td></td>
<td>Braking energy storage electro/chemical or mechanical</td>
</tr>
<tr>
<td>c) Reduction in resistances</td>
<td>Mechanical friction</td>
</tr>
<tr>
<td></td>
<td>transmission</td>
</tr>
<tr>
<td></td>
<td>Rolling friction (wheels)</td>
</tr>
<tr>
<td></td>
<td>Fluid dynamic forces</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aero-</td>
</tr>
<tr>
<td>d) Reduction in distances</td>
<td></td>
</tr>
<tr>
<td>e) Rationalised loads</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reduction in indirect energy costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>f) Reduction in the energy costs of vehicles, routes and support systems</td>
</tr>
<tr>
<td>g) Reduction in energy costs of secondary energy forms</td>
</tr>
</tbody>
</table>

Efficiency factor assumed reductions in transport energy intensities due to vehicle and route related causes:

<table>
<thead>
<tr>
<th>Efficiency factor assumed reductions</th>
<th>3</th>
<th>1.2</th>
<th>1.5</th>
<th>2.25</th>
<th>2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>to vehicle and route related causes</td>
<td>fold</td>
<td>fold</td>
<td>fold</td>
<td>fold</td>
<td>fold</td>
</tr>
<tr>
<td>from 1600 to 1925</td>
<td>from</td>
<td>from</td>
<td>from</td>
<td>from</td>
<td>from</td>
</tr>
<tr>
<td>to 1925</td>
<td>to</td>
<td>to</td>
<td>to</td>
<td>to</td>
<td>to</td>
</tr>
</tbody>
</table>

Legend:

- Major areas of energy reductions
- Minor areas of energy reductions
- Qualified areas of energy reductions (see text)
- Areas of energy increases
- Areas of energy increases (see text)
APPENDIX F

Changes in Transport Energy Efficiencies and Intensities

Transport energy which is involved in increasing a product's 'place' utility is like the energy involved with 'form' utility discussed in Appendix C, constantly changing due to advances in technology.¹

There are three main aspects of transportation where energy can be reduced (Table F-1) those which are vehicle related, those that are route related, and those that are operationally related. Analysing energy economies or diseconomies which are operationally related will not be attempted in this thesis because of the lack of any data on such items as speed, acceleration and load factors and due to their small contribution to the overall energy demand. The operationally related considerations would apply mostly to lorries anyway.

Reducing energy requirements through vehicle improvements can be achieved in three general areas. First by reducing dead weight or improving the ratio between cargo and carrier; second by reducing energy conversion losses. For example those losses which occur in a conventional engine when chemical fuels are converted to thermal energy, which is subsequently reconverted to mechanical work; and third by reducing resistance which could be due to mechanical friction, or fluid dynamic forces.

¹Technological advances do not guarantee overall reductions in transport energy costs; they may in fact increase them by making feasible mode of transport which is inherently more energy intensive, the automobile and even more so the aeroplane are examples of this. Advances in technology made air freight possible, but it is very energy intensive, so products which would have gone by slower more efficient modes now can utilize a faster but more energy consuming mode.
Resistance can also be reduced which are route related especially with respect to land transport and concern surface conditions, gradients and curves. Table E-1 summarizes the vehicle and route energy saving areas utilized by the five freight modes considered in this study. The following paragraphs arranged by mode, expand upon the information presented in this table and explain the most relevant gains in energy efficiency applicable for each mode.

Horse and Human Powered Land Transport - Cart

Between the periods of 1600 and 1925 the energy intensity of this form of transport is assumed to have decreased by 66% (3Wh/kgkm to 1 Wh/kgkm). The less significant factors leading to this large decrease would include better engineered and lighter waggons, improved wheel bearings, improved harnesses and even improved pulling animals\(^1\). The big differences were not vehicle related, they were route related, that is improved roads with lower gradients and especially with durable surfaces. The latter item reduced the resistance immensely. More importantly, the improved roads resulted in freight being put on wheeled vehicles instead of on the back of man or animal which greatly increased the load factor per unit of propulsion, a point well illustrated by comparing the energy intensities between back pack transport and wheel transport (Table E-1, col. 8).

Railroad

A decrease in energy intensity from 1.2 Wh/kg km to 8 Wh/kg km is assumed for railways between 1850 and 1925, with no further

---

\(^1\)Cottrell (1955, p. 21) indicates that "Watt found that horses in use in England in his day produced the energy equivalent to 2/3 hp... whereas a modern horse weighing 1500 lbs. can produce about 1 hp...".
improvements occurring after that date. The causes of this reduction would include improvements in the ratio between carrier and cargo due to increased waggon size. This can be seen by comparing the waggon weights of England's first train which in 1825 consisted of 34 vehicles having a gross weight of 90 tons or 2.7 tons per waggon. The average goods waggon in 1910 weighed about 16 tons gross, 6 tons being waggon weight and ten tons cargo (H.M. Ross, 1911). We could also assume improvements in reducing engine and transmission friction. The biggest efficiencies were gained in the reduction of energy conversion losses, but these might not have been as great as one would expect.

This is inferred by H.M. Ross (1911) when he speaks of the Stevenson brothers 'Planet' built in 1830, only five years after the introduction of steam to rail, as closely resembling the modern type steam locomotive and by which the "main features of the steam locomotive were established, its subsequent development chiefly being a history of gradual increases in size and power, and of improvements in design, in material, and in mechanical construction tending to increased efficiency and economy of operation".

Lorry

An energy intensity decrease of 20% from 1 Wh/kg km to 8 Wh/kg km was assumed between the introduction of the lorry and 1925, with the energy intensity remaining constant after that date. Like cart and waggons, lorries probably benefitted less from vehicle related

Conversion savings for the transport of building materials would be far greater if they were still transported by rail today for they would have benefitted from the significant increases in energy conversion efficiencies (3.5 - 5 times, see Table E-3) effected when steam engines were replaced by diesel in the 1950's and 60's.
improvements than from route related ones. Macadam and metalled roads helped greatly in achieving early energy efficiencies, along with early engine, transmission, and rolling friction reductions. Lorries have also benefitted from a reduction in dead load by the more efficient use of materials. Large savings in this area are usually due to increasing the capacity of the lorry; but the potential for this reduction with respect to material transport is limited because of the small consignment sizes usually involved and already mentioned in more detail in Appendix E (Table E-3).

Reductions in energy conversion would naturally be expected as a result of the automotive industries overall effort in research; however experience in the States does not bear this out. Summer's (1971, p. 153) mentions that "the thermal efficiency of the 1920 engine was about 22%; today it is about 25%". Ironically, the energy economies related to both route and vehicle conditions are more than offset by diseconomies related to operational factors, particularly with respect to increased speeds. These speeds produce much higher aerodynamic drag; "it takes about 8 times more energy to push a vehicle through the air at 60 m.p.h. than at 30 m.p.h." (Summers 1971, p. 152) Rice (1974, p.49) and Summers (1971, p.153) both indicate the fuel consumption rate for automobiles is higher than at any previous time since 1920, Hirst (1973, p. 36) shows the same trend over the last 25 years for lorries in the U.S. ¹

¹D.O.E.'s survey of the transport of goods by road 1967-68 (1971, p. 9) indicates a gradual shift to diesel propulsion for U.K. lorries which would help in producing fuel economies.
Because the principles of reducing energy intensity for both ocean going ships and inland barges are the same the two will be discussed together. At the end of this section there will be a brief discussion of the energy intensity increase which resulted from the propulsion of ships from sail to steam. A few inland barges were also converted to steam but their appearance was so late that their effect on the transport of roofing materials can be disregarded. The energy intensity reduction assumed was 2.25 fold for ships and 2.5 fold for inland waterways. These increases in efficiency being spread over a roughly 300 year period. One might ask that since the period and principles are the same for both modes, why the energy intensity efficiency factors would not also be the same? The difference is due to the fact that inland waterways were benefitted from route related reduction in resistance, whereas the coastal ship did not. In the late eighteenth century gradient and current problems associated with rivers were reduced with the introduction of locks and canals. Both systems benefitted from some reductions in the energy losses through conversion; sailing riggs undoubtedly improved not only in aerodynamic terms which would have increased speed per unit of sail area, but also in the ease of handling, an important factor when only crew energy is being considered. River and canal barges would have benefitted from improved harnessing and as discussed in the beginning of this appendix, and 'an improved horse'. But the real savings in water borne transport are brought about by increasing the capacity of

The capacity of canal barges probably doubled from 20 tons which Derry and Williams (1960, p.440) referred to as being typical with the introduction of canals, and 35 ton barges (70 ton gross) mentioned in the Encyclopaedia Britannica (Williams, 1911). It is hard to determine the increase in capacity of coastal ships which would be dealing with most building materials traffic, but shipping capacity in general increased tremendously between the seventeenth and late nineteenth century. The East India Company used vessels of six hundred tons, whereas the schooners of the late nineteenth century were often over the two thousand ton mark.
It is the same principle as discussed in processing energy, roughly speaking surface area increasing by the square while volume by the cube. This has two advantages, the first is the reduction of skin friction in relation to load, much more relevant at the very low speeds encountered by both coastal and canal boats¹, and secondly it also means an improvement in the dead weight ratio². Increasing capacity can also result in a longer, thinner vessel, particularly with regard to canal boats which would reduce bow and stern turbulence in relation to overall capacity. Larger capacities reduce overall crew requirements as well, for example the crew requirements of a hundred ton ship would not be much larger than a crew for a fifty ton ship though the cargo hold would be doubled; a factor especially important when sailing ship energy intensities are considered solely on crew requirements.

The introduction of steam increased the speed of sea transport (an increase from 5 to 8 m.p.h. was assumed) which would result in increased ton miles per day, and also would reduce crew requirements;

¹This would have been especially the case with canals, for barges doing more than 3½ m.p.h. tended to wash away canal banks. More importantly the resistance of a displacement type craft increases roughly with the cube of speed, unlike wheeled vehicles whose resistance is more directly proportional to speed. In other words if it takes one horse power to move a barge at 2 m.p.h. it would take 8 horse power to move it at 4 m.p.h. Since most barges were restricted to one or two animals they quite literally did not have the horsepower to go any faster.

²The introduction of metal hulls which had dead weight ratios of 2:1 instead of the wooden vessels 1:1 could have reduced transport's energy intensity, the overall effect would be hard to determine but canal barges would have been more likely to have used metal hulls than the smaller sailing vessels usually involved with building materials. If the processing energy of the metal itself was included it is doubtful whether any overall savings would have been made.
but even with these advantages the introduction of steam increased the energy intensity of sea transport by 1350 fold. Even so sea transport still remained far below the energy intensities of all forms of land transport, at .45 Wh/kg km. The figure 27 Wh/kg km in 1900 indicates an assumed conversion to steam of about half the fleet involved with the transport of building materials.

General Review of Changes in Transport Energy Demands

The changes in energy intensity of the various modes of transport discussed are summarized Table F-2 (p. 476).

When the general mode shifts in freight transport are analysed a very general patterns seems to emerge, which is defined by opposing energy and operational thresholds. Below is a diagram which illustrates this phenomena.

<table>
<thead>
<tr>
<th>Operational Positive Qualities</th>
<th>Mode &amp; Year</th>
<th>Energy Negative Qualities</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>Water 1760</td>
<td>-</td>
</tr>
<tr>
<td>+</td>
<td>Rail 1860</td>
<td>-</td>
</tr>
<tr>
<td>+</td>
<td>Lorry 1960</td>
<td>-</td>
</tr>
<tr>
<td>Flexibility</td>
<td>Speed</td>
<td>Barge Load Resistance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>.Aero-Grade .Hydro-Curves</td>
</tr>
<tr>
<td></td>
<td></td>
<td>.Route .Operational</td>
</tr>
</tbody>
</table>

Water transport has historically been the cheapest mode for moving large quantities of bulk goods over long distances and at the time
high speed, canals extended these advantages inland. Waterborne transport however eventually hit the speed threshold, even moderate attempts at achieving increased speeds with a displacement haul meant drastic energy increases due to the cube rule mentioned earlier. The introduction of iron wheels and rails, immediately removed most of the resistance encountered in road haulage\(^1\), and more significantly it overcame the speed threshold, rolling resistance being roughly proportional to speed. The power required to run a 1000 ton ship at 20 m.p.h. is the same as that required to run a train (on a straight and level track) at the same weight at 45 m.p.h.\(^2\) and the power required by the ship at 25 m.p.h. would propel the train at about 70 m.p.h. Railroads, eventually ran into a threshold of their own, one of flexibility being confined to a very rigid infrastructure. The lorry, provided all the operational advantages, large loads, fast and flexible. Unfortunately this was not achieved without additional energy expenditures. Each threshold had its corresponding resistance threshold to overcome. Waterborne transport was only affected by

\(^1\)The railways success is usually attributed to the steam engine, but it was the rail and not the engine that contributed to its success. 'Roads' lined with rails or 'railroads' were in use long before the steam engine for transporting coal and the energy economies which they brought were well appreciated. Lord North as early as 1676 mentioned that "carriage [on wooden rails] is so easy that one horse will draw down 4 or 5 cauldrons of coal" (H.M. (Ross, 1911). This would amount to about 10.6 - 13.2 tons, road carts pulled by a horse could have managed about one half ton. A hundred years later in 1770 Arthur Young was equally impressed by railways, writing in his book Six months tour through the North of England about coal waggons drawn over railways 9 - 10 miles in length, "by which means one horse is enabled to draw and that with ease, 50 or 60 bushels of coals". (Darby, 1936, p. 511).

\(^2\)An 'ordinary' goods train in 1911 ran at 25-30 m.p.h. and pulled about 430 tons (H.M. (Ross, 1911).
vehicle related resistances, the railway also affected by this resistance in addition had to overcome route related resistance primarily gradients and curves. The lorry had operational resistance as well; curves, speed, grades and acceleration contribute considerably to the energy intensity of motor vehicles. Campbell (1973, p. 201) describes this with respect to an automobile:

"if the 4400 lb car is driven at a speed of 50 m.p.h. on a plus 5% grade and 5 degrees horizontal curve (not uncommon) the gas consumption is 2 1/2 times that required at 35 m.p.h. on a level, straight road. In rural areas, grades, curves and higher speeds increase gas consumption about 40% while urban areas congestion at intersections (losing deceleration, acceleration, idling and low speeds) increase gasoline consumption about 80%"

In summary operational 'improvements or economies' brought about by historical mode shifts were gained only through energy diseconomies.

Table Changes in mode energy intensities and efficiency factors, by year.

<table>
<thead>
<tr>
<th>Mode</th>
<th>1600</th>
<th>1700</th>
<th>1800</th>
<th>1850</th>
<th>1900</th>
<th>1925</th>
<th>1938</th>
<th>1950</th>
<th>1966</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cart</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wh / kg km</td>
<td>3</td>
<td>2.5</td>
<td>2</td>
<td>1.5</td>
<td>1.2</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eff.factor</td>
<td>3</td>
<td>2.5</td>
<td>2</td>
<td>1.5</td>
<td>1.2</td>
<td>1</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Rail</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Wh / kg km</td>
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<td>Eff.factor</td>
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<tr>
<td>Lorry</td>
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<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>Sea</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wh / kg km</td>
<td>0.0009</td>
<td>0.0008</td>
<td>0.0006</td>
<td>0.0004</td>
<td>0.26</td>
<td>0.53</td>
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<tr>
<td>Eff.factor</td>
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<td>2</td>
<td>1.5</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Wh / kg km</td>
<td>0.05</td>
<td>0.04</td>
<td>0.034</td>
<td>0.027</td>
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</tr>
<tr>
<td>Eff.factor</td>
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<td>2.1</td>
<td>1.7</td>
<td>1.35</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NOTE:

a The transport efficiency factors assumed are expressed as a multiple to be applied to the mode's base energy intensity (underlined) developed in Appendix E.

b Sea transport in 1900 was assumed to be powered equally by steam and sail, and in 1925 to be totally powered by steam.
APPENDIX G

Mode and Fuel Shifts and Mixes

In order to estimate the transport mode mix for each material an idea was needed of the general historical shifts in the transport of materials. Before 1700, transport was relatively simple and fell into a natural hierarchy, land transport propelled by horse, ox or human, dealt with the haulage of local materials (up to 12 miles) and the terminal haulage of non local materials. Both types of journey would be restricted to short distances (see Appendix H on distances). Inland waterways would have handled most of the medium distance trips and sea would have been used for long distance haulage. This hierarchy was quite efficient in energy terms using the mode with the lowest energy intensity for the longest journeys, (i.e. sailing ships) medium intensity modes, (i.e. barges) for medium length trips and the highest intensity modes for the shortest hauls, (i.e. carts, wagons, pack animals, etc.) This system of transport not only made energy sense but also made economic sense. British building historians, like Clifton Taylor (1962, p. 22), Salzman, (1967, pp. 119 and 349), Knoop and Jones (1933, pp. 51 - 3) and Bowyer (1973, pp. 167 and 195) are unanimous that up to the use of the railway water transport was the cheapest way to transport building materials over any but the shortest distances. By the late 1960's a hierarchy of long, medium and short distances remained, but instead of fitting the most energy economical form

1Terminal haulage applies to a material's first and last journeys, i.e. quarry to ship, ship or warehouse to construction site.
Figs.
G-1
G-2
G-3
Indicates a transfer of mode due to a shift in material usage or manufacture. Local materials, especially thatch, were replaced by more distant processed and unprocessed materials. This usually resulted in a shift from short distance haulage to either medium length haulages as in the case of clay tiles (aa) or long distance haulage frequently associated with slate (ab) or corrugated metals (ac). Even without material substitution haulage distances could well increase with the replacement of smaller production facilities with larger, more mechanized ones. Clay tiles provide a good example, with kilns moving off site to large capital intensive kilns near a large source of clay and reasonably cheap fuel. In energy terms this probably resulted in overall savings, the additional transport energies being offset by lower processing energy demands as discussed in Appendix B. Material substitution did not always result in longer distances, clay tiles being substituted for slate (ad) would represent such a situation.

b Indicates a substitution of one mode for another both catering to the same mileage range, canal haulage being replaced by rail which itself was replaced by lorries in cases in point.

c Length of line indicates approximate period over which a shift in mode took place.
of transport to the longer distances one mode, the lorry, virtually handled all transport requirements regardless of materials or distance.\(^1\)

What brought about this mode switch? To answer this five basic variables have to be considered: the first deals with chronology, the second with the introduction of new modes; the type of journey (single mode or multimode) is the third, and closely associated with this is the fourth consideration, that of distance; and the last deals with material changes.

Because of the complexity of trying to deal with so many variables, all of which can change simultaneously, a chronological flow diagram (Fig. G-1) has been constructed to graphically illustrate the inter-relationships between these variables. The diagram

\(^1\)The Ministry of Transport study, Industrial Demand for Transport (1970, p. 29) indicated that rail handled 4% of the total 'building material' consignments, the remainder being hauled by road. Nothing was even listed under the "other types of transport" which included coastal shipping, inland waterway and domestic air transport. In fact the British Road Federation's Basic Road Statistics (1973, Tables 11 and 12) show that in Britain in 1972 almost 80% of all freight transport ton mileage went by road and 90% of the total freight tonnage. Material transport in the States is somewhat different. Cox and Goodman (1956, p. 49) analysed the transport requirements of building materials for a typical house built near Philadelphia in 1951 and found that "water transport by ocean, lake and river accounted for only 9% of the movements, but it accounted for 58% of the ton miles. Trucks, which provided 56% of the movements, performed only 12% of the ton miles. Railroads performed 34% of the movements and earned 30% of the ton miles". The reason for the high rail and water figures can be accounted for by the fact that the major portion of lumber came from Oregon 3,000 miles away by rail or 6,500 miles by water. Iron ore shipped through the Great Lakes also accounted for a large portion of the ton miles.
includes notations further explaining the two principle causes for modal shift; the introduction of a new mode, and the change in the building materials themselves.

From the flow chart an overall milage mode mix\(^1\) can be constructed. For comparison, two such graphs have been provided immediately above the flow diagram (Fig. G-1). These graphs (Figs. G-2 and G-3) indicate each new mode of transport introduced picks up a progressively larger portion of the traffic milage, culminating with the lorry, which handles all transport\(^2\) requirements (mainly due to the operational advantages discussed in Appendix F). A 'wave' pattern clearly emerges in Fig. G-2, with one mode replacing another with ever increasing rapidity and magnitude. Figure G-3, the composite mode mix has been shaded to reveal the rapid replacement of 'income' by 'capital' sources of transport energy, as well as the elimination of water transport.

\(^1\)The overall milage mode mix for a particular mode (i.e. mode mix) would represent that mode's share of the total milage involved in transporting all roofing materials in one particular year.

\(^2\)The Department of the Environment's survey of the transport of goods by road (DOE, 1971, Table i) summarizes the change to road haulage since 1938. Another indication of the increasing dominance of road haulage with respect to all types of freight is suggested by the vast increase in the number of haulage vehicles listed below:

\begin{align*}
1909-30,000 & \quad \text{(Government Statistical Service, 1970)} \\
1920-101,000 \\
1930-349,000 \\
1940-444,000 \\
1950-895,000 \\
1960-1,397,000 \\
1970-1,616,000
\end{align*}
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<td>28</td>
<td>9</td>
<td>5</td>
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<td>37</td>
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<td>27</td>
<td>24</td>
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<tr>
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</table>
The overall mode mix has been subdivided into each of the roof types by year, and is summarized in Table G-1 and Fig. 3.7. The mode mix for each material usually differ, for example, out of the total transport milage for stone/slate in 1850, 55% was assumed to have gone by water, 21% by rail and 24% by cart, while in the same year 100% of thatch haulage was done by cart, the differences in modal split being largely due to the nature of the material.

Transport for fuel, involved in the manufacture of processed materials has not been considered, even though in some cases the transport requirements for fuel could exceed those of the material itself. It was also assumed that the raw materials for the processed materials were from domestic sources, and in the same proximity as the plants processing them. In other words, the transport energy requirements are those involved primarily with moving the finished roofing product and not the raw materials required in their manufacture. The transport requirements involved with raw materials will be touched upon in Section One, of Chapter Four.
APPENDIX H

Assumed Haulage Distances by Mode and Year

Before discussing the milage assumed for each mode of transport, a general idea as to the milages involved in transporting building materials can be gained from The Ministry of Transport's study Industrial Transport (1970), which breaks down the consignments of building material into nine distance categories (Table 20) summarized below.

<table>
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<tr>
<th>Miles</th>
<th>0</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>100</th>
<th>125</th>
<th>150</th>
<th>200</th>
<th>300 &amp; over</th>
</tr>
</thead>
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<tr>
<td>Km</td>
<td>0</td>
<td>40</td>
<td>80</td>
<td>120</td>
<td>160</td>
<td>200</td>
<td>240</td>
<td>320</td>
<td>480</td>
</tr>
</tbody>
</table>

(Table 20) 59% 18% 6% 1% 2% 2% 4% 4% 4%

For the purpose of discussion the groupings have been consolidated into three ranges (short, medium, and long) which are indicated above. It is recognized that these divisions are arbitrary, but they appear to be the most logical division points based on a percentage of consignments basis. Of course this breakdown applies to the current situation, the terms would be related to prevailing conditions; a 'medium' distance in 1966 might be nearer 120 km, while in 1800 it might have been closer to 60 km. The range however is wide enough to accept such differences.

The assumed changes in haulage distance for each mode by year are summarized in Table H-1 at the end of this appendix (p. 488).

1B.T. Bayless in his report The Road Haulage Industry since 1968 (1973) defines 'short' distances as 0-30 miles, 'medium' distances as 30-125 miles and over 125 miles as 'long' distances.
Animal Powered Transport - Carts

The average haulage distance for land transport was assumed to have increased gradually over 300 years from 5 km. (3 miles) to 15 km. (9 miles), providing short journeys involved with either the transport of local materials or the terminal trips of non local materials. Three miles might appear short for land transport in 1600 but it is doubtful whether much improvement had been made from medieval times that Knoop and Jones (1933) describe in their chapter on transport, in which quarries were sought for royal buildings in the range of 4 or 5 miles; Salzman (1967, p. 119) speaks of a medieval situation where "for a distance of 12 miles the cost of carriage would have been equivalent to the cost of the state itself".

These were for earlier periods in history, Darby's *An Historical Geography of England before 1800* (1936) suggests that the roads were actually better prior to the seventeenth century "for the time being (16th century), the highways were able to bear the demands made upon them: the passage of wheeled vehicles and droves of cattle was not such as to ruin them past repair as was to happen a century later." An indication of practical road transport in the late sixteenth and early seventeenth century is also given in the book when contemporary pros and cons of land and water transport were being discussed "iron and coals could be carried upstream, more cheaply than by road to Smithies within a range of 8 or 10 miles" (p. 362). In describing

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1 This ratio of material cost to land transport for stone appears to have remained unchanged even to this day, roughly 600 years later, a Guardian report on stone aggregate states that "by the time a lorry has driven 15 - 20 miles from a quarry with a load of stone, the transport cost equals the cost of extraction". (Hildrew, 1974, p. 13).
'Leland's' England in the late sixteenth century the chapter mentions "building materials owing to their bulk and weight were rarely sought more than ten or twelve miles away", (p. 343). That would be the maximum range, the average distance particularly with materials like thatch would be far less. Terminal trips were also likely to be much shorter, for towns of any significance would be located on water for general communication and trade. These towns were quite compact, so transport of non local materials from a ship or barge to the site would have been small indeed. Villages and homesteads in the hinterland would have been confined to local materials.

The increases in the haulage lengths for carts and waggons would have naturally increased with road and bridge improvements over the years. Material shifts would have also caused increased in animal drawn land transport. Production transport would have increased somewhat with the increases in the number of production steps involving form, time and place utility.

The marketing of materials has also become much more complex with the emergence of material dealers not normally associated with local unprocessed materials. Materials would have had to go from a natural state to processor through a sales distribution system and eventually to the site which would have added mileage to a material's overall journey¹.

The enlarging of production plants to provide for economy of scale and closeness to raw resources would have also contributed to

¹These types of increases would apply to other modes of transport as well.
increases in distances. In addition land transport mileage would have increased with the spread of a compact town into a sprawling city, which in itself was the result of a transport revolution.

Water Based Transport - Sea and Inland Waterway

Inland waterway transport was assumed to have increased gradually from 25 km. (15 miles) to 100 km. (60 miles) between 1600 and 1850. Transport by sea was also assumed to have increased from 160 km. (100 miles) to 320 km. (200 miles) over the same period. Both forms of transport would have benefitted from the overall increase in trade throughout Britain which accompanied the Industrial Revolution. Providing fuel for cities and towns whether it be food for people and animals or coal for heating and industry was dealt to a large extent by water transport. Vessels involved with this trade would no doubt encourage building material haulage on return trips. The estimation of mileage for ships, is hard to determine but an idea of distance can be gained from the transport of coal; Ireland for example "received supplies mainly from Cumberland but coals from the Tyne and Ware were transported by sea around the North of Scotland. Newcastle and Sunderland (coal) practically monopolised the London market and supplied not only all the East coast, but also the South coast as far as Cornwall" (Darby, 1936, p. 510). Fortunately, the accuracy of sea transport distances in an energy analysis are not essential because of the extremely low energy intensitites involved (see Appendix E). Inland water transport distances, like roads, would have naturally increased with improvements in river navigation and the creation of canals. In the sixteenth century river movement was quite restricted, the chapter dealing with Camden's England
(Darby, 1936) contains an amusing description of the "perennial conflicts between those interested in water carriage and those interested in land carriage", but evidence suggested that fish weirs, mills, and water levels all had adverse effects on river movements. Gristmill owners as well as land carriers being opposed to the development of navigation considering the boatman as a mere "nuisance". This situation gradually changed from 1600 to 1760 England's 700 miles of navigable rivers doubled and between 1760 and 1820, 3,000 miles of canals were constructed. Obviously a network of this scope would have encouraged longer journeys. But the reduction of assumed mileage to 75 km. in 1900 for inland water freight was due to the breaking up of the system by competing railroads, who often themselves owned and eventually closed canals.

**Railway Transport**

Mileage was assumed to remain constant at 100 km. (60 miles) from 1850 to 1950. This assumed high initial distance was based on the fact that railroads, even though the network expanded were initially taking over waterway traffic. (see Fig. G-1) which were serving high or medium haulage routes\(^1\).

\(^1\)This is still very much the case today rails carry only 4% of building material consignments, but of this amount 94% is for transporting materials over 200 km. (125 miles) and 61% of rail's portion of material haulage was over 480 km. (300 miles) this being due to rail haulage costs being cheaper than lorry for distances only over 200 km. (125 miles) (Ministry of Transport, 1970, Table 70 graph 3). Up to the 1960's however rail would have been competing more directly with the lorry on shorter runs before the Beeching report significantly reduced rail's coverage and catchment areas.
The assumed lorry journey increased from 25 km. (15 miles) to 100 km. (60 miles) in two increments from 1925 to 1966. This increase is due to road improvements and coverage, most of it though was due to the mode shifts (see Fig. G-1), the lorry initially taking over short terminal journeys served by waggon and cart, then picking up medium range traffic from the railways and finally long range waterborne haulage, 100 km. might appear high when compared to the figures shown on page 483, but it must be remembered that this represents number of consignments and roofing materials particularly in the current situation might very well be transported two or three times in the entire production route making the overall journey for a material higher than that involved in an individual consignment.

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<th>1800</th>
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<th>1950</th>
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<td>4.7</td>
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<td>155</td>
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CHAPTER ONE (cont.)


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The Estimation of Roofing Material Processing, Energy Intensities along with Roofing Weight and Pitch Data.


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Appendix C

Changes in Material Processing Energy Efficiencies


Appendix E

The Estimation of Energy Intensities for Various Modes of Freight Transport


Appendix F

Changes in Transport Energy Efficiencies


Appendix G

Mode and Fuel Shifts and Mixes


Appendix H

Assumed Haulage


Fig. 2.3 Percentage mix assumed for roofing materials in the twentieth century

Fig. 2.4 Percentage mix assumed for all roofing materials between 1000 and 1966
Percentage mix assumed for traditional inorganic roofing materials
Fig. 2.1  Percentage mix assumed for unprocessed organic roofing materials, and the percentage mixes between agricultural and non-agricultural population and between rural and urban populations (Hobsbawm, 1969, Diagrams 4 and 13)
NOTES: Fig. 1.2

1. The timber demand shown based on U.S. figures for 1960 (Landsberg, 1964, p.90), timber demand in 1958 would be slightly higher. The figures were also expressed in cubic feet, to convert this to weight a timber density of 55 lbs(16kg)/ft³ or 560kg/m³ was assumed.

2. The processing energy intensities assumed for iron/steel and sand/gravel were 12,600 kWh/ton and 21 kWh/ton respectively (Makhljani & Lichtenberg, 1972, table 1). To allow for a comparison between material and energy, energy has been expressed in 'tonne coal equivalents' (TCE's), using a conversion factor of 1 TCE = 7,560 kWh(26 x 10⁶ Btu).

<table>
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<th>Energy Intensity (kWh/ton)</th>
<th>Conversion Factor</th>
<th>TCE Equivalent</th>
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<td>7,560</td>
<td>1.83 TCE/tonne</td>
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<td>Sand/Gravel</td>
<td>21</td>
<td>7,560</td>
<td>.003 TCE/tonne</td>
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Processing energy

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<td>Iron/Steel</td>
<td>108 x 10⁶</td>
<td>7,560</td>
<td>197.6 tonnes of coal</td>
</tr>
<tr>
<td>Sand/Gravel</td>
<td>823 x 10⁶</td>
<td>7,560</td>
<td>2.47 tonnes of coal</td>
</tr>
</tbody>
</table>

3. The by-product to product ratio for iron production is based on those proportions developed in figure 1.3. The by-products represented in this figure only represent those by-products encountered in the production of iron from primary iron ore, and does not include any by-products from the processing of other basic ingredients such as limestone and coke; nor does it include any by-products from steel production. The portion of iron and steel production from primary sources was assumed at 64% of the total demand (Landsberg, 1964, p.80).

4. No quantitative data could be found concerning the by-products associated with the production of sand and gravel, but the by-product to product ratio of 1:4 assumed would be reasonable to expect, since most sources of this mineral lie at or very near the surface and have been 'dressed' naturally.
Fig. Breakdown of 1968 U.S. demand for major materials by end-use (U.S. Dept. of the Interior, 1970) and the relationship between processing energy and by-products, with respect to iron/steel and sand/gravel.