UNIVERSITY OF SHEFFIELD

SCHOOL OF ARCHITECTURE

DEVELOPING DISASSEMBLY STRATEGIES FOR BUILDINGS TO REDUCE THE LIFETIME ENVIRONMENTAL IMPACTS BY APPLYING A SYSTEMS APPROACH

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The question of questions for Mankind,
the problem which underlies all others,
and is more deeply interesting than any other,
is the ascertainment of the place which man occupies in nature,
and of his relations to the universe of things.

Thomas Henry Huxley
Man's Place in Nature
Macmillan, London, 1900.

ABSTRACT

The negative environmental impacts of buildings are now recognised as being of great concern. Increasingly, these concerns are being addressed in both the construction and the operational phase of a building's lifecycle. The specification of renewable or low impact materials and the criteria for designing for energy efficiency are now commonplace, but what about the final stage of a building's life-the demolition phase?

The construction industry produces 24 kg of waste per person per week in the UK, and the majority of this is caused by decisions taken at the design stage. Conversely most of the current discussion in this area has been focused on dealing with the waste once it has arisen. If we are going to do more than 'end of pipe', remedial clean up of building waste we need to rethink how we design, build, use and demolish our built environment. In effect this means taking the filters out of the pipes and placing then instead in the designers heads.

In addressing this situation, the aim of this thesis is to define guideline strategies that will reduce the negative environmental impacts of buildings by designing for the whole lifecycle.

The research is presented in four parts. In the first part, the literature is reviewed and developed to define buildings within a cyclical systems context. This entails drawing upon relevant debates within the fields of systems thinking, architecture, bio-mimicry, industrial ecology, and industrial product design

In the second part, an investigation carried out with demolition experts is presented. In this study knowledge and opinions were sought via a number of semi-structured interviews with demolition experts. The conclusions of the case study identify strategies, which if implemented at the design stage could reduce the lifetime impacts and increase the reuse and recycling potential of buildings, their elements and material components.

Following the detailed focus on end of life, the research is now expanded to consider the changes that occur throughout a building's lifetime. The aim of this is to determine where the greatest use of resources and major impacts occur throughout the building life cycle. Therefore Part III presents an investigation of the lifetime environmental impacts of office buildings. The building is fragmented into its time dependent layers (foundations, frame, claddings, services and internal fit out) and the impacts of these layers over the building lifetime are investigated. The study also examines the relative impacts of different frames and floors, which allow varying degrees of disassembly. Finally, to complete the lifecycle investigation, the embodied impacts are compared with the operational impacts over a sixty-year lifecycle.

Part IV presents the conclusions of this research, based on a synthesis of the findings of the earlier chapters. Finally those areas that would benefit from further research are identified.

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GLOSSARY OF ABBREVIATIONS USED IN THIS THESIS

BCO	British Council of Offices
BPEO	Best Practical Environmental Option
BRE	Building Research Establishment
BSI	British Standard Institute
BSRIA	Building Services Research and Information Association
CCE	Centre of Construction Ecology
CDM	Construction Design Management
C&DW	Construction and Demolition Waste
CFS	Cold Formed Sections
CIRIA	Construction Industry Research and Information Association
CP	Cleaner Production
CPD	Construction Products Directive
CO_2	Carbon Dioxide
DDT	Dichlorodipenyltrichloroethane
DETR	Department of Environment Transport and the Regions
DfD	Design for Disassembly
DfE	Design for Environment
EA	Environmental Agency
ENDS	Environmental Data Services
EPA	Environmental Protection Act
EU	European Union
GFA	Gross Floor Area
HMIP	Her Majesty's Inspectorate of Pollution
HRS	Hot Rolled Steel
HVAC	Heating ventilation and Air Conditioning
IDE	Institute of Demolition engineers
IE	Industrial Ecology
ICT	Information Communication Technology
IPC	Integrated Pollution Control
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
MIPS	Material Intensity per Service Unit
NFDC	National Federation of demolition Contractors
OPC	Ordinary Portland Cement
PEM	Preventative Environmental Management
PWS	Priority Waste Stream
QPA	Quarry Products Association
SCI	Steel Construction Institute
TMR	Total Material Requirement
TQM	Total Quality Management
UNEP	United Nations Environment Programme

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1 DESIGN FOR RESILIENCE

Developing strategies that will enable the functional lifetime of buildings, their elements and materials, to be increased and so reduce their lifetime environmental impacts.

1.1 Introduction

1.1.1 Context

We live in a rapidly urbanising World. In the past century global urban populations have expanded from 15 to 50% and this is likely to increase to 60 or 70% within this century. These urban centres occupy only 2% of the land area of the globe but already consume 75% of the Worlds resources (Girardet 1992). As the demand for buildings in which to live, work, rest and play increases so will their associated environmental impacts. Not only do buildings consume half of all the primary energy produced but they also, through their construction, operation and demolition, produce 50% of the man made carbon dioxide emissions and 50% of all the materials entering the waste stream (Anink, Boonstra et al. 1996). This is four times that of domestic rubbish. As Herbert Girardet concludes writing in Architectural Design, "the construction and refurbishment of cities for environmental sustainability is one of the great tasks ahead of us" (Girardet 1997).

1.1.2 Linear Flow of Resources

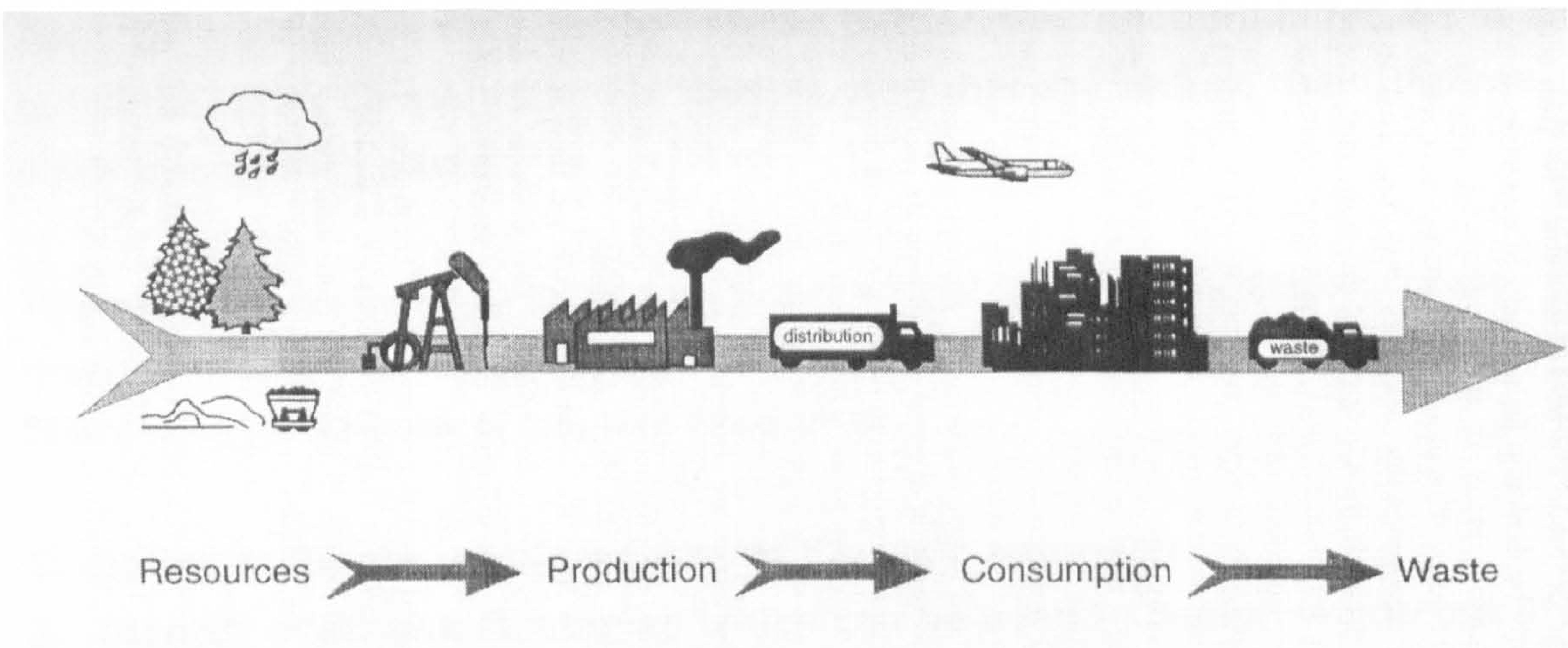
At the heart of the issue is the way we use resources: currently human society extracts, consumes and discards resources in a linear manor (see Fig 1). New strategies in fields such as Sustainable Product Design, Industrial Ecology & Ecodesign, are being developed which question this linear flow path. These offer solutions to redesigning the industrial economy on a more cyclical basis (Jackson 1996). If we are to achieve sustainability in the future it is essential that the built environment is included in this investigation.

1.1.3 Core Issue

Buildings are huge reservoirs of energy and materials, combined in increasingly more complex ways, and generally have life spans of several generations. However, due to a variety of factors, they are becoming obsolete and consequently being demolished long before any structural or material failure (Golton, Hiley et al. 1994). Demolition and subsequent replacement creates wide-ranging environmental impacts. The complex combinations of materials used in the structures cannot be separated and are sent to landfill. New structures are usually entirely constructed of resource intensive virgin materials. These materials are collected from such diverse locations that the resulting ecological footprints of our buildings cover the entire planet (Golton 1994).

Figure 1-1

(Jackson 1996),p3.



In contrast to the current approach of premature building demolition and resource intensive replacement, a new design methodology is emerging. At a philosophical level this is essentially about modelling buildings on natural systems, which are typically characterised by cyclical processes and symbiotic, mutually dependent relationships (Lawson 1996). This methodology sees buildings as dynamic systems, operating at a number of scales, which are readily reusable and recyclable and respond to the changing requirements placed on them (Brand 1994). By adopting this cyclical approach and creating easily adaptable buildings they would become more open and accessible to change (Wyatt and Gilleard 1994). This may result in resource use and wastage being minimized and the useful life of buildings and their components being increased to their theoretical limits (Grammenos and Russell 1997).

1.1.4 Aims & Objectives

In keeping with this dynamic systems approach, the hypothesis of this thesis is that:

Appropriate disassembly strategies can extend the functional lifetime of buildings, their elements and materials, and thereby reduce their lifetime environmental impacts

This is explored at different scales through, system adaptability, elemental disassembly and reuse and material recycling. In order to make this global objective more manageable it has been divided into a number of core aims these are to:

1. **Define buildings within a systems lifecycle approach**
2. **Identify proactive strategies which can be used to design waste out of the system, not simply mitigate the effects of waste once it has been created**
3. **Determine where the greatest use of resources and so impacts are throughout the building life cycle**
4. **Draw together the findings of the first three parts and recommend further research opportunities**

These four aims require four distinct areas of work and so the thesis parallels this and falls into four parts.

Structure of the Thesis

1.2 Part I: Buildings within a systems lifecycle approach

1.2.1 Design and the Environment

Chapter Two examines in depth the idea of Sustainable Development and sustainable design, and the ways in which systems theory helps integrate what is often a very confusing and fragmented set of debates.

The discussion explores the ways in which current researchers from the field have begun to apply systems theory to global issues and highlights the strategies common to all these fields. This entails drawing upon relevant debates within the fields of systems thinking, architecture, bio-mimicry, industrial ecology, and industrial product design. What is revealed is that there are in fact common themes running through these debates, the most significant being the concept of replacing dominant linear flow patterns with circular systems mirroring those found in the natural world. This entails adopting more proactive, life cycle approaches, considering future 'waste' as a resource and reorienting products to facilitate easier reuse and recycling. The conclusions of this chapter are important because they **define system design principles** which can be applied to the built environment and form the basic framework of this research.

1.2.2 Built Environment

With the systems design principles in mind, Chapter three focuses on examining the Built Environment. After identifying the scale and importance of the environmental impacts of the built environment the second theoretical chapter concentrates on the area with least current attention; the demolition phase. Here, the quantities of waste produced, European and British policy on 'recycling' and the disposal of building waste, the views of the research organisations, and the 'state of the art' within the demolition industry are all discussed.

Recycling is a somewhat generic term for a range of activities, which exist in a hierarchy in which the order of preference, subject to the best practical environmental option, is as follows (Hobbs 1996):

- Reduce
- Reuse
- Material recycle
- Recover energy
- Dispose/biodegrade

The reduce option, is a design issue, requiring a proactive, life cycle approach. In contrast to this, most existing research, including the 'state of the art' research, is at the more reactive, material recycle level. However, the majority of decisions about the future fate of an element or material happen at the design stage, and so it is here that the new systems approach must be adopted if change is to occur. (Snow 1999). In searching for a proactive strategy to design waste out of the system, the chapter then turns to examine the concept of Design for Disassembly. Currently, Design for Disassembly has been most successfully applied within the product design sector, therefore, to develop a coherent strategy, examples are drawn from this sector and compared with early ideas and more recent developments from within the building sector.

1.3 Part II: Defining Strategies

1.3.1 Demolition Case Study-Exploratory Expert Interviews

In order to further develop relevant Design for Disassembly strategies, Chapter Four presents empirical findings gathered through exploratory in-depth interviews with fourteen demolition experts. The majority of these experts were demolition contractors, and their inclusion in the case study was important as there is currently little information from the demolition industry itself, and even less feedback from the demolition contractors to the building designers. Addressing this situation and **so defining strategies for designing waste out of the system** is then the core goal of this chapter.

The chapter opens with a description of the methodology adopted for the case study. The questions are then presented along with discussion as to their relevance. This is followed by the findings from the interviews, grouped by respondents reply's to the evolving questions. Information and knowledge from the previous chapter has been inserted in some instances to extend the discussion on the issues raised. The chapter concludes with a summary of the DfD strategies identified through the interviews and arranged within the three systems level model developed in the previous chapters.

1.4 Part III: Lifecycle Building Investigation

After the detailed focus on end of life the research is now expanded to consider the changes that occur throughout a building's lifetime. This builds on one of the strongest themes to emerge from the previous two chapters, which is that buildings are dynamic systems and exist in a number of time dependant layers. These layers are:

- Site
- Structure
- Skin
- Services
- Finishes

Buildings are constructed and demolished in these layers, and also changed during their use in this layered manor. Each layer has a different time dimension and operates at a different physical scales. If sufficiently separated, they can change independently, whilst simultaneously maintaining the function of the whole building. However, continually changing these layers will increase the environmental impacts of any building. Currently there has been little detailed investigation of the environmental impacts of the flux of these layers over the lifetime of a building, therefore the core goal of Part III of the thesis is to address this by:

- **Determining where the greatest use of resources and major impacts occur throughout the building life cycle.**

1.4.1 Lifecycle Methodologies

In order to carry out this investigation, a building type, and methodology must be defined and a review conducted of existing studies, and these are the subject of Chapter 5. Office buildings have been chosen as the building type for the investigation, and after reviewing a number of methodologies Life Cycle Analysis (LCA) has been selected as the method for assessing impacts over the lifecycle.

For buildings, the two most widely used LCA indicators are energy, as an input, and carbon dioxide, as an output. These are considered both in terms of 'embodied' energy/CO_2, that are bound up in the materials, and 'operational' energy/ CO_2, that are used to service buildings. Continuing with this approach this research adopts these indicators. Chapter 5 concludes with a critical review of existing case studies that have also used embodied energy and carbon dioxide to analyse the environmental impacts of buildings. This review identifies the shortcomings and potential areas for further investigation when considering buildings within a dynamic lifecycle approach.

1.4.2 Office Building Lifecycle Investigation

Chapter Six presents an investigation on the lifetime environmental impacts of office buildings, within the framework of LCA. This addresses the core goal of Part III, and builds on the limitations of the previously reviewed case studies.

The chapter opens with a description of the building type to be investigated, the parameters set and the embodied energy and carbon dioxide values adopted. The first two aims are then addressed which are to; identify and compare the impacts of the different building layers at initial point of use and over the lifetime. The impacts of the total building are identified and then the impacts of the different layers, starting with the first to be constructed and last to be removed-the foundations.

The chapter then moves to examines the relative impacts of different frames and floors which allow varying degrees of disassembly. To enable future adaptability and reduce lifecycle impacts, floors and frames might need to be designed to allow removal and replacement or relocation. The section therefore identifies three floor and frame constructions; a composite, a precast, and a lightweight steel, and compares their relative impacts over one, two, and four life changes.

Finally to complete the lifecycle investigation the embodied impacts are compared with the operational impacts over a sixty-year lifecycle. As previously mentioned the operational impacts are related to providing a comfortable internal working environment and have generally been assumed to be far greater than the embodied impacts.

First standard rates of change for the various building layers are used to estimate the increase in the embodied energy over the lifetime. Next a number of operational energy scenarios are defined based around best practice figures. The scenarios range from one which assumes no change in operational energy consumption over the building lifetime to a scenario were the building becomes more efficient with each change of cladding or service plant. These scenarios are then compared with the embodied impacts to indicate where the main impacts occur throughout the lifecycle.

1.5 Part IV: Conclusions and Recommendations for Further Research

This final chapter presents the conclusions of this research, based on a synthesis of the findings of the earlier chapters. It brings together the literature, which was reviewed and developed in Part I with the exploratory and experimental research presented in Part's II and III. In addition, a number of recommendations for further research are made.

1.6 Methodology

The research presented in this thesis is multidisciplinary, covering both experiment investigations and exploratory interviews. An explanation of the different methodological approaches is presented alongside both of these research approaches.

2 DESIGN AND THE ENVIRONMENT

2.1 Introduction and chapter structure

This first theoretical chapter provides the context and philosophical background of the thesis and introduces the premise on which the work is based. Before the impacts of the built environment are investigated it is important to place these within the wider environmental debate. Accordingly, the chapter opens by introducing the background to the current environmental crisis facing humanity. In searching for solutions the international concept of sustainable development is examined and the range of perspectives through which people view human and natural interactions are explored.

The discussion then turns to investigate natural systems. The aims of this section being, firstly, to examine the history and evolution of our understanding of natural systems theory, from its roots in ecology to more general systems theory, and secondly, to compare these dynamic natural systems with those of current human design. The conclusions of this chapter are important because the defined system design principles can be applied to the built environment.

2.2 The Environmental Debate

Over the last two centuries many parts of the World have undergone massive transformations moving from predominantly rural agricultural societies to industrial, urban societies. This shift has brought with it major changes in the way humankind works, rests and plays. To many, these changes are seen as improvements, and in more rural societies (predominantly in countries of the South) where industrialisation hasn't yet happened it is often aspired towards.

However, more recently there has been a growing body of evidence to suggest that these transformations are not without their costs. These costs manifest themselves in numerous forms and range from social deprivation and economic exclusion of an increasing proportion of the worlds poor to the environmental pollution of the land, sea and sky. It is also suggested that unless action is taken at a global, national and local level we may face, in the worst case, an unprecedented global catastrophe, or in the least, growing social unrest, economic instability and environmental degradation.

2.2.1 History of interest in environmental issues

Recognition of the problems caused by expanding societies are not without precedent. Philosophers, scholars and poets have been writing about the impact of the current industrial nations on the natural environment almost since industrialization began (Pepper 1996). Also, casting an eye back though history, one sees that the anthropological records are full of warnings about the rise, fall and death of ancient civilisations. Many of whom over exploited their natural resource base and resorted to extreme measures (in the case of the inhabitants of Easter Island- cannibalism) before extinction (Ponting 1991) (pp1-7). The message from these reconstructed histories seemingly being that forests precede civilisation and deserts follow (Orr 1992). However, whilst many of these cases had clearly defined geophysical limits and dealt with simple resource flows, the scale and complexity of the current 'crisis' has made analysis more difficult. Indeed it is widely accepted that it was not until the publication of *Silent Spring* (Carson 1962) that the modern environmental movement started to galvanize (Wackernagal and Rees 1996) (p31) and recognize the interconnectedness of the problems facing humankind. This was one of the first publications to scientifically, lay the blame for environmental destruction at the visible and invisible wastes of the 'industrial machine'. In this case, Carson linked the use of agricultural chemicals, and in particular DDT[1] with the death of aquatic, land based and airborne wildlife across North America's farm belt.

Since then a burgeoning literature, and a number of high profile, industry related, environmental disasters have substantiated the concern that the Ecosphere,- our life support system, is being eroded at an accelerating pace. The focus initially was on the Earth's continued ability to provide resources (sources) and absorb our wastes (sinks). The Club of Rome's first publication, *Limits to Growth* (Meadows, Meadows et al. 1972) raised questions about the future supply of minerals and fossil fuels for our rising level of consumption and the availability of sinks to absorb our wastes. Whilst the majority of the claims in this text have since been discounted as being both pessimistic and too simplistic, it acted as a wake up call, instigating and stimulating debate on a wide range of human and nature interactions. As well as concern over the Earth's sources and sinks there is now discussion over humankinds increasingly materialistic lifestyles, and its consequences on human health, wellbeing, equity, security, nature and the life-regulating bio-systems.

2.2.2 Sustainable Development.

At an international level the most significant responses to the growing awareness of humankind's dependence on natural systems and corresponding vulnerability to potential environmental 'catastrophe' has been the forming of three United Nations Commissions and a series of global conferences. These have gathered individuals and specialists from all levels and walks of life to report on different aspects of what was coming to be perceived as a

[1] DDT (dichlorodiphenyltrichloroethane) is a chemical hydrocarbon insecticide noted for its high toxicity to insects at low rates of application and for the persistent effectiveness of its residual deposits.

common crisis. This new thinking is most notably documented in *Our Common Future* (Brundtland 1987) more commonly known as the 'Brundtland Report'.

This report acknowledged that the rich are destroying the environment through high consumption and the economic activity needed to support it, and the poor are destroying the environment in their daily struggle to stay alive. The solution offered by the Brundtland Report was to marry ecology and economy, and so was born the international concept of 'Sustainable Development', defined as:

> *"Development that meets the needs of the present without compromising the ability of the future to meet its own needs"(p42).*

Whilst being accepted as a seminal international report *Our Common Future* has been widely criticised, particularly by the environmentalists. Paul Ekins (Ekins 1992) accusations focus on the report's conservative nature and its lack of willingness to rock the established worldview and offer a more radical alternative. This, he concludes, is hardly surprising as the authors originated from within this existing world order (p30). This stance is echoed by the environmental pressure group Friends of the Earth (McLaren, Bullock et al. 1998). They suggest that the current environmental stresses;

> *"are not legacies of pre-industrial society which further growth will eradicate, they are not symptoms of the models failure, but of its success... the better the model performs, the worst these problems will get. They are endemic." (p67)*

These authors, combined with many others, argue that after proposing 'Sustainable Development', the Brundtland Report then proceeded to stand more on the development than the sustainable side of the fence, further maintaining the status quo and placating the world's dominant industrial mechanism (see for example (Wackernagal and Rees 1996)). The Brundtland Reoprt equated sustainable development with *"more rapid growth in both industrial and developing countries" (p42).* This though is just one view of the future and many commentators are cautious in wholeheartedly embracing this form of 'sustainable development' with all its potentially hidden ambiguity. Some in-fact see the term 'sustainable development' as an oxymoron, two words juxtaposed without reason. In a series of in-depth essays David Orr (Orr 1992) has examined the current crisis, traced its roots, and discussed the problems and solutions in searching for sustainability, he is concerned that:

> *"The word sustainable conceals as much as it reveals. Hidden beneath the rhetoric are assumptions about growth, technology, democracy, public participation, and human values" (p23).*

2.2.3 The Human Condition

The overriding message from the likes of Orr is that we must tread carefully, and before assumptions are drawn or recommendations made we must examine the very ground, on which we stand and base our arguments.

He likens the causes of the crisis to the concentric layers of an onion (p5). In pealing back the intellectual layers and asking why, you are leading to deeper levels of causation. These start at the outside with the shallow 'social trap' of thinking only for short term rewards, regardless (and oblivious) of long term consequences. Delving deeper you cross the problems of the dominant Western economic system and our assumptions about science, nature, culture and ultimately human nature. According to Orr central to this is our desire to seek short colourful careers rather than long dull ones. Neurologist Robert Ornstein and biologist Paul Ehrlich (Ornstein and Ehrlich 1989) refer to this as the 'boiled frog syndrome'. Our inability to perceive slow changes, long-term implications, and multiple connections can be compared with that of a boiling frog. A frog, when placed in a pan a water that is slowly brought to the boil is unable to detect the incremental increase in temperature and will sit there quite happily while being boiled to death. *"Like the frogs, many people seem unable to detect the gradual but lethal trend in which population and economic growth threaten to boil civilization"* (p62).

2.2.4 Technology versus Ecology

Thus while there is general agreement that the Earth and its inhabitants are going through unprecedented change due to humankind's industrialisation, there is a wide range of opinion on the suggested course of action. Perspectives differ depending on the philosophical positions regarding conceptions of Nature and the environment (Pepper 1996) (p37). The radicals have polarised at the extremes either supporting technological mastery of the environment or complete symbiosis with it.

> *"Advocates of technological sustainability tend to believe that every problem has either a technological answer or a market solution. There are no dilemmas to be avoided, no domains where angles fear to tread. Resource scarcity will be solved by material substitution, or genetic engineering" (Orr, 1992, p24).*

At the other polar extreme are the deep ecologists, equally self-righteous, they propose a cessation of international trade and modern technology, and a return to islands of local self-sufficiency.

These alternative approaches to sustainability are clearly illustrated when one compares movements in contemporary architecture. The architects underlying philosophies being visible from their design choices. From the techno-centric's we have designs informed by the metaphor of the machine. They use automated management systems to control the microclimate and exotic materials to provide the aesthetic. Whilst they may be energy efficient, the services are from distant unconnected sources, and wastes dealt with equally remotely with no link to the hermetically sealed occupants. The eco-centric's have a spiritual focus which tends to lead to organic buildings, using traditional and vernacular methods and are often seen as the panacea for all environmental ills. This is not always the case, presenting the igloo, the adobe house, or the countryside lodge as perfect examples of bio-climatic, indigenous design, ignores many of the issues and problems facing our urbanising populations (Toy 1997).

2.2.5 Technology *and* Ecology

It is more likely that solutions will come from merging the ideas of both camps, technology being of particular benefit in the short term to halt the degradation and stabilise the planetary vital signs. 'Sustainable Development' being more likely to be interpreted as **living off the interest yielded by our natural resources rather than the capital, i.e. the natural resources themselves.**

One of the latest Club of Rome's publications offers a wealth of technical examples were improvements in efficiency and more appropriate utilisation can lead to at least a four fold improvement in resource use while maintaining income (Weizsacker, Lovins et al. 1997).

Similarly Sim Van Der Ryn and Cowan (Ryn and Cowan 1996), talk in terms of **conservation, regeneration and stewardship.** Conservation slows the rate at which things are getting worse by allowing scarce resources to be stretched further. This is the application of suitable technology. Regeneration repairs the wounds, restoring the biosphere and increasing the natural capital. Finally stewardship improves the quality of our relationships with the living and none living world, it is a process of commitment informed by constant feedback.

Venice, a city sinking under its own weight, has recently considered adopting such a survival strategy, marrying technology with ecology in favour of an out and out heavy engineering solution. The techno-centric solution involved building three huge barriers at the mouth of the lagoon, effectively a metal shield against the waves of the Adriatic. The environmentalists believed that these would provide only partial and extremely expensive flood protection. They argued that the fundamental problem is the breakdown of the lagoon's natural equilibrium with the sea which has been going on, through mans invention, for 600 years. Silt has slowly been drained and with the diversion of its three rivers, no new silt is being deposited, also two thirds of the lagoon has been reclaimed for farming and industry. This has left Venice at the mercy of the waves, with no natural mud flats to disperse the high tides. So what the engineers want to do with steel and concrete the environmentalists propose to do with silt, allowing the natural build up of deposits over time combined with small scale engineering, flood proofing and domestic drainage installations, conservation, regeneration and stewardship in action (Pearce 1999).

2.2.6 Natures Inspiration

Similarly, Janine Benyus (Benyus 1997) writes of the lessons being learnt by the bio-mimics, technologists that are studying Natures models and taking inspiration from these designs.

> *"The bio-mimics are discovering what works in the natural world, and more important what lasts. After 3.8 billion years of research and development, failures are fossils, and what surrounds us is the secret to survival. The more our world looks and functions like this natural world, the more likely we are to be accepted on this home that is ours, but not ours alone" (p3).*

2.2.7 Complex Solutions

Fundamental to the work of all those developing our understanding of sustainability is the recognition that the human system exists within, and as a part of, the larger biosphere and for our survival we need to interact with, not react to this. An important point here being for our survival. Sustainable Development strategies are not inherently altruistic to other species inhabiting the Earth, they are human centred. The Earth existed long before humans and biological life will continue even if we manage to destroy most of the existing species. It has though been realised that for humankind to survive we need to maintain the greater environment, which in turn will shelter, feed and cloth us. This requires a change of direction and an understanding and connection with the complex systems of nature. As John Tillman Lyle comments:

> *"Where nature evolved an ever varying, endlessly complex network of unique places adapted to local conditions, human ingenuity has replaced it with a system of relatively simple forms and processes repeated with bold and consistent regularity over the face of the earth. And most importantly, humans have replaced nature's endless cycling and recycling of materials, processes at the core of the earth's operating system, with an encompassing system of one-way flows, moving the materials that support life in vast quantities from sources through consumption to sink" (Lyle 1992) p4.*

2.3 Natural Systems

The next section looks in more detail at the complexity, and feedback of natural systems. The main aims being threefold. Firstly, to examine the history and evolution of our understanding of natural systems theory, from its roots in ecology to more general systems theory. Secondly, to compare these dynamic natural systems with those of current human design. Finally, to identify the key strategies which support the potential application of systems theory to human design.

2.3.1 Stable Ecological Systems

The study of ecosystems began in earnest at the start of the 20th Century when ecologists began mapping out the locations and relations of herbivores and carnivores within a food chain. It was realised that for continuity there must be connection between predators and pray, and this was provided by the discovery of micro-organisms and bacteria breaking down deceased predators into essential nutrients for future organic growth. From this discovery an ecosystem model was established, in which all organisms had a role for the functioning of the system. Frederic Clements, the American plant ecologist, was the first to describe habitats as a series of closed loops that together form a self-regulating system. He also described how plant communities develop through successive stages, eventually settling into a relatively stable state. From these concepts grew the dominant paradigm that nature tends towards balance and harmony (Ball 1999).

2.3.2 Open Ecosystems

However, the view that nature tends towards balance and harmony has since been discredited. The relationships within an ecosystem are now seen as much more open. They do not evolve into the stable (or climax) systems we once assumed, instead they are in a constant state of flux. In the words of Phillip Ball:

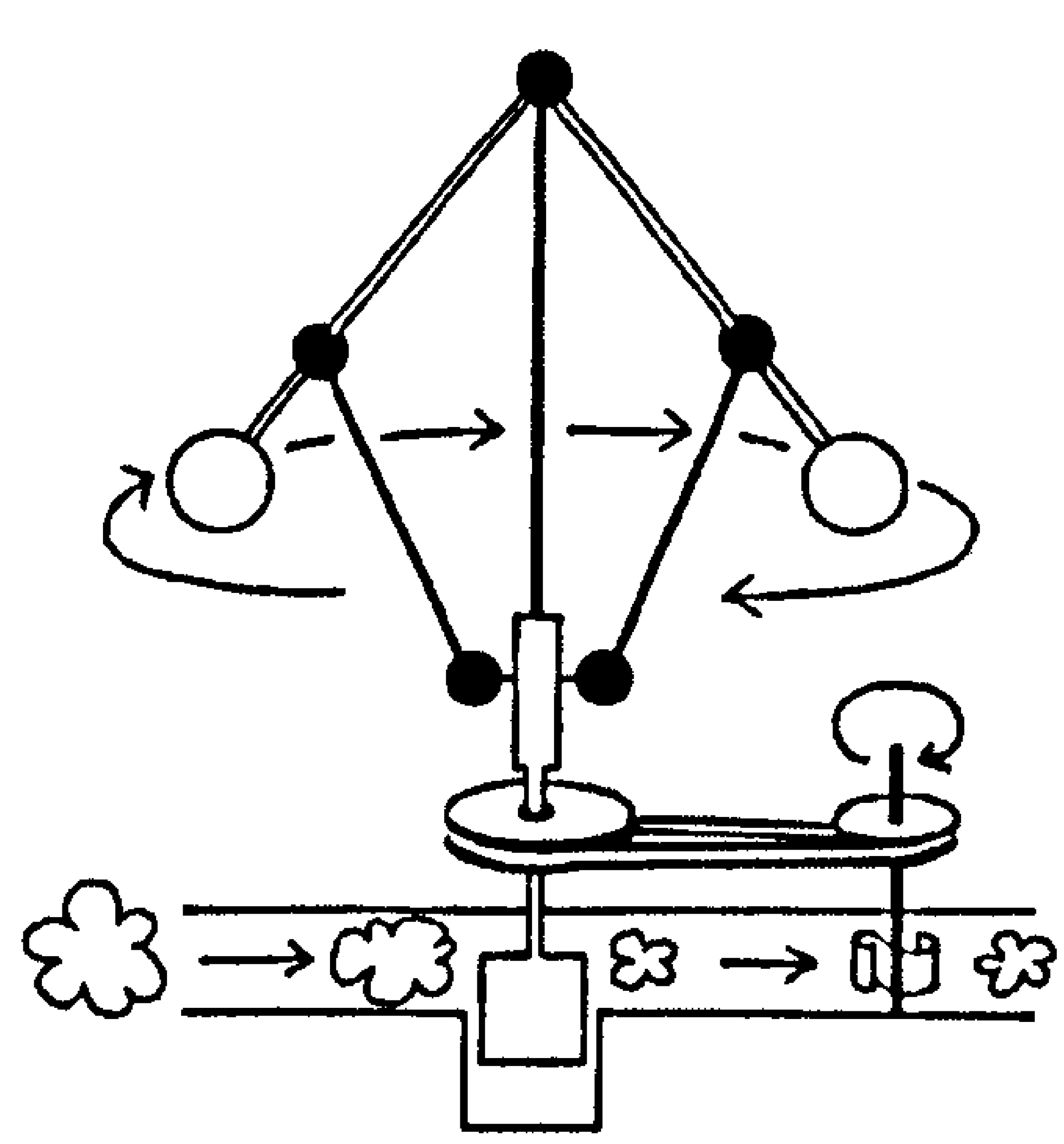
> *"Equilibrium is a dull place. Nothing happens there. If the Universe were itself at thermodynamic equilibrium, it would be a lifeless place pervaded by a uniform, dim glow of just a few degrees above absolute zero. Just about every phenomenon that interests us is an out-of-equilibrium activity. All human activity from shopping to sleeping, takes place in a state that is far from thermodynamic equilibrium. We tend to do all we can to avoid it in the truest sense, since genuine equilibrium is death" (Ball, 1999, p52).*

2.3.3 General Systems

Examining both open and closed systems, we find that we can form some governing rules. Fritjof Capra (Capra 1996) has investigated both and defines a system as *"an integral whole whose essential properties arise from the relationship between its parts"* (p36). An open system requires a continual flux of matter and energy from their environment to stay alive. Unlike a closed system, which settles into a steady state of thermal equilibrium, open systems maintain themselves far from equilibrium, characterised by continual flow and change. They are loosely connected by circular causal links that propagate around the system until the last feeds back to the first. These convey information about the outcome of any process or activity to its source, where it then influences the systems future activity. The returned information will either increase or decrease the open systems amplitude, in effect they oscillate around their source.

Open systems can be both living and non living. One of the earliest and simplest examples of a mechanical feedback system is the centrifugal governor (Fig 2.1) invented by James Watt in the late eighteenth century in response to the necessity to control the pressure of early steam engines.

Figure 2-1 Centrifugal Governor
(Capra 1996), p60



The system is dynamic, it continually oscillates between maximum and minimum limits, but so long as there is no mechanical failure and the engine is refuelled it will never shut down or explode. A closed system on the other hand will proceed spontaneously in the direction of ever-increasing disorder. This would be analogous to the steam engine without the governor, and so no regulating mechanism. It would be likely that it could only be used once, to destruction and disorder otherwise known as thermal equilibrium.

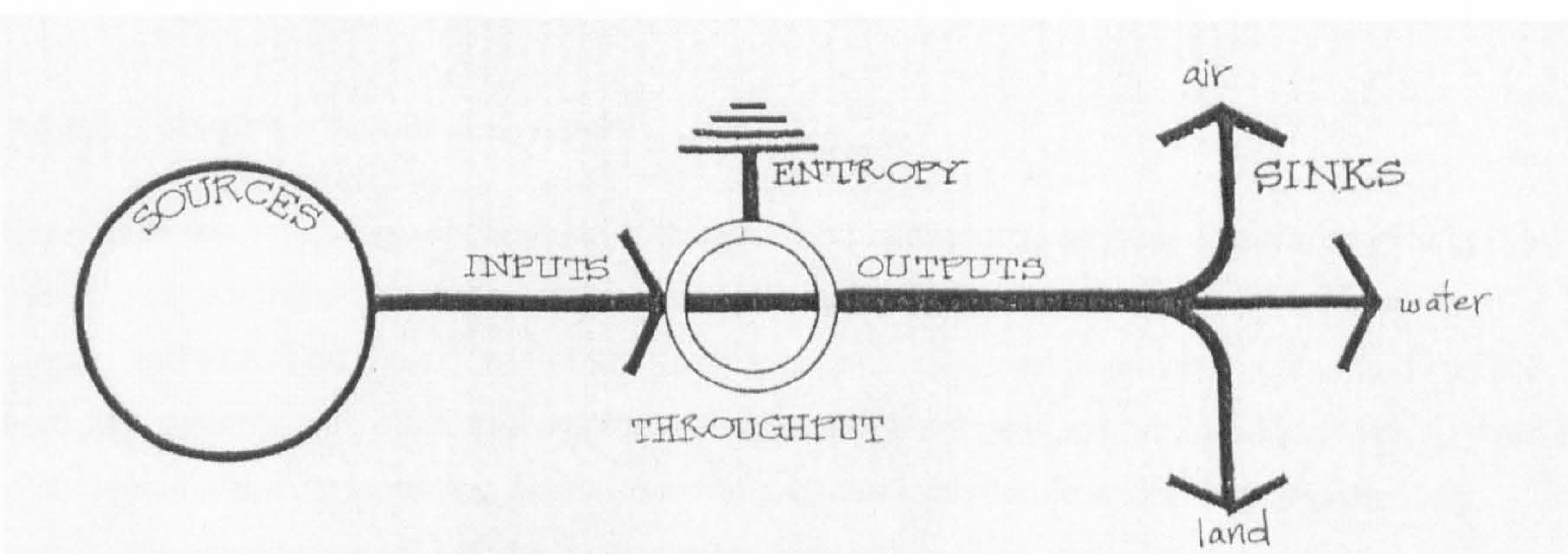
2.3.4 Planetary Systems

At a planetary level, atmospheric chemist James Lovelock has investigated the atmospheric profiles of Earth and Mars. The two are strikingly different, were as Earth's contains massive amounts of oxygen, lots of methane and almost no carbon dioxide, the Martian atmosphere has no methane, little oxygen and mostly carbon dioxide. This lead Lovelock to surmise that Mars is a dead planet, in which all possible chemical reactions between gases in the atmosphere were completed a long time ago. The Martian atmosphere is, in effect, in complete chemical equilibrium, where as Earth's is far from it and in a continual state of flux supported by ecosystem reactions on the Earth's surface. So Lovelock concluded that the Earth's atmosphere is an open system, far from equilibrium, characterised by a constant flow of energy and matter (Capra 1996) p101.

2.3.5 Evolving Systems

Within the dynamic flux of open living systems, it is generally acknowledged that ecosystems evolve through three stages (see for example the work of: (Lyle 1992), (Graedel and Allemby 1995) (Jackson 1996) (Benyus 1997)). The critical points to note with ecosystems are that as systems develop they move from simple linear flows to complex circular flows, with multiple connections and regulating feedback loops. These three stages are:

Figure 2-2: *Stage I: Young Ecosystems*
(Lyle 1992), p5



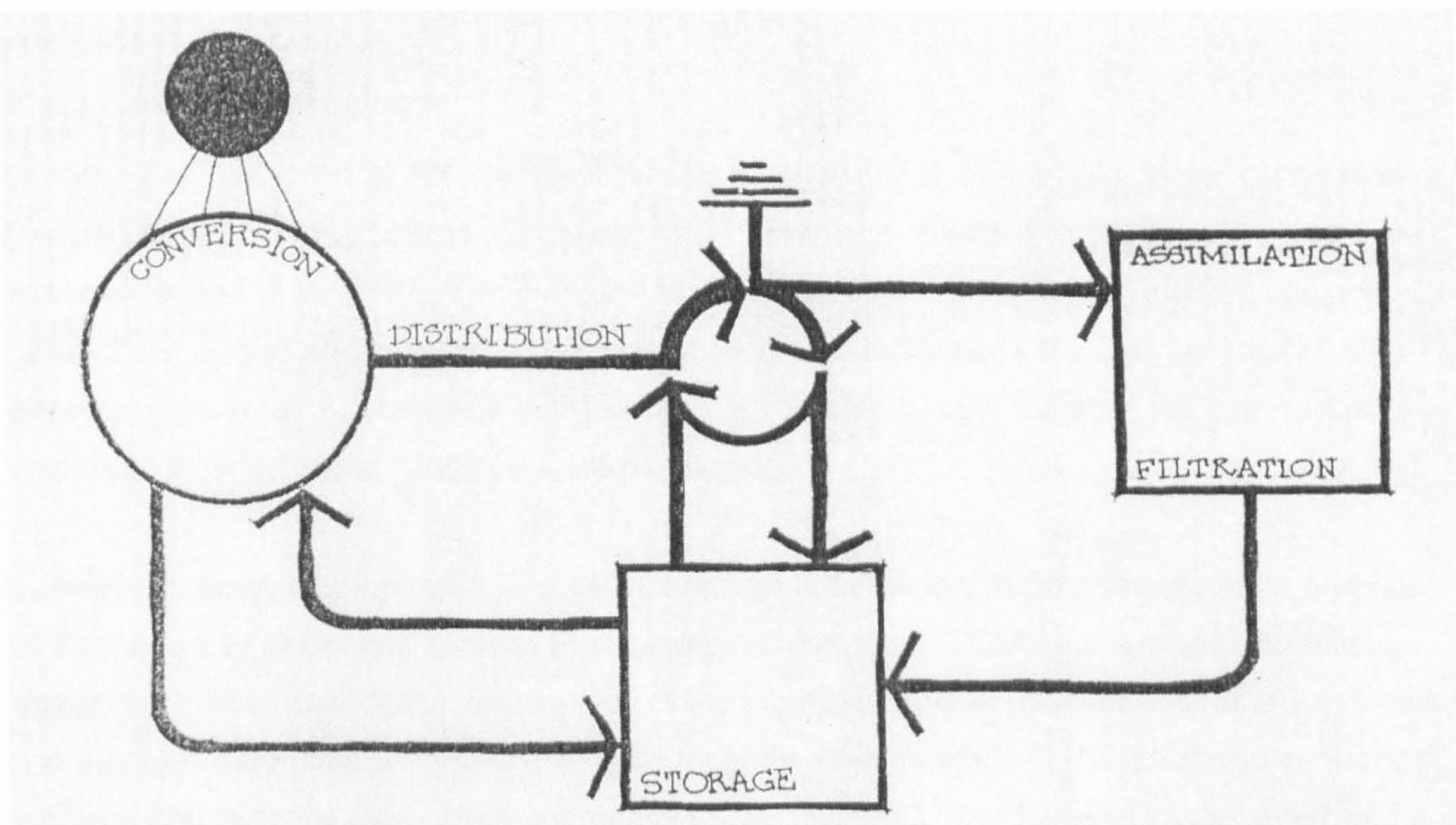
2.3.5.1 Stage I: Young ecosystem

In the early years of development there is a massive throughput of energy and matter, drawing from, and depositing into, the external system in which it is embedded. The species present are relatively simple and spend most of their resource throughput on growing and reproducing.

2.3.5.2 Stage II: Developing ecosystem

As the ecosystem develops new, more complex, organisms sensing the potential to grow and gain an advantage, latch on to the numerous 'wastes' the system is producing and use these as food. As the gaps are filled the species become less interested in reproducing as prolifically as previously and are more content to dig in and establish themselves within the system.

Figure 2-3 *Stage III: Mature Ecosystems*
(Lyle 1992), p26



2.3.5.3 Stage III: Mature ecosystem

Eventually, as it matures, each waste is transformed into energy as new organisms joining the system, increasing diversity and reducing its reliance on the external environment both as a source and sink. The system members are masters of optimisation and efficiency, and live in complex systems with elaborate symbiotic relationships with the species around them. At the global level, the only incoming resource is that of solar radiation from the sun and the only waste- low-grade heat (or entropy as it is often termed) back to space. Even now it is not in a stable equilibrium. Each member of the system is continually diversifying in an attempt to fill new niches, and as individuals succeed, so the system shifts accommodating the new development. Also any moment an external shock or internal vibration could cascade through the system disrupting the order. The most capable and adaptive organisms' will diversify quickly and climb into these new niches, increasing in number. The filling process by which the system occupies new niches is chaotic and therefore would be different if repeated from the same initial conditions.

Current 'systems thinking' proposes that human systems are analogous to stage I, that of young immature ecosystems. In order for humankind to develop along sustainable lines we should aim to move through stage II and to stage III, the mature ecosystem level.

2.4 Comparing Human systems with Mature Ecosystems

The details of this systems analysis have been drawn from a number of fields, two of the most successful being Industrial Ecology and Biomimircy.

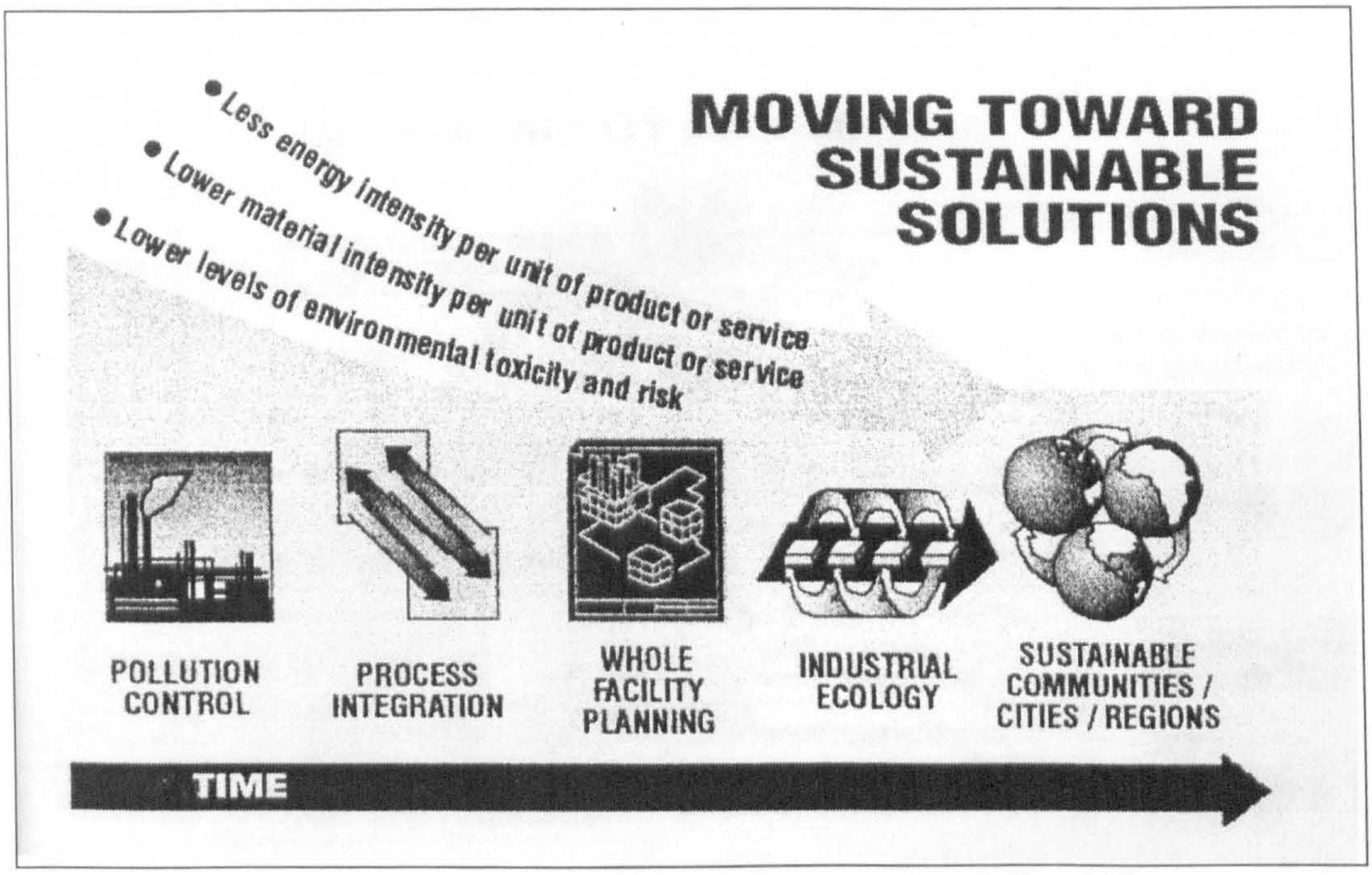
2.4.1 Industrial Ecology

In a key text, Graedel and Allenby (Graedel and Allemby 1995) define Industrial Ecology as a systems view embedded within the greater environment which seeks to optimise the total materials cycles (p9). They go onto adhere to the notion that anthropogenic interactions are generally at stage I and for sustainability we must evolve to stage III, the mature circular ecosystem level (p93). Therefore industrial ecology fully embraces the previously discussed shift, from isolated linear, to whole systems thinking.

Industrial Ecology (IE) emerged as a distinct discipline in the late 1980's, integrating a number of diverse areas of thought such as total quality management (TQM), input-output modeling, design for environment (DfE), and studies of the interface between human and natural systems. It is an organising principle and involves the multi-disciplinary study of industrial and economic systems and their linkages with fundamental natural systems, and Graedal has even termed it 'the science and engineering of sustainability'.

Traditionally industries have responded to environmental degradation in four ways: ignoring the problem, diluting the pollution, controlling or treating the pollution, and preventing pollution and waste generated at source of production (see Figure 2.4). IE is concerned with the development of the latter and an 'industrial ecology' has been defined as an industrial system which is, '*fully integrated within the wider natural cycles of materials. It closes the loops left open in conventional industrial processes and optimises recycling and the use of each material separately, but it also allows for the creation of more complex 'food webs' of materials.*' (Ryn and Cowan 1996) p107. Its influence has slowly grown over the last 10 years both at an industrial and governmental level.

Figure 2-4 From Pollution control to Industrial Ecology and Beyond
(Interagency Workgroup, 1998)



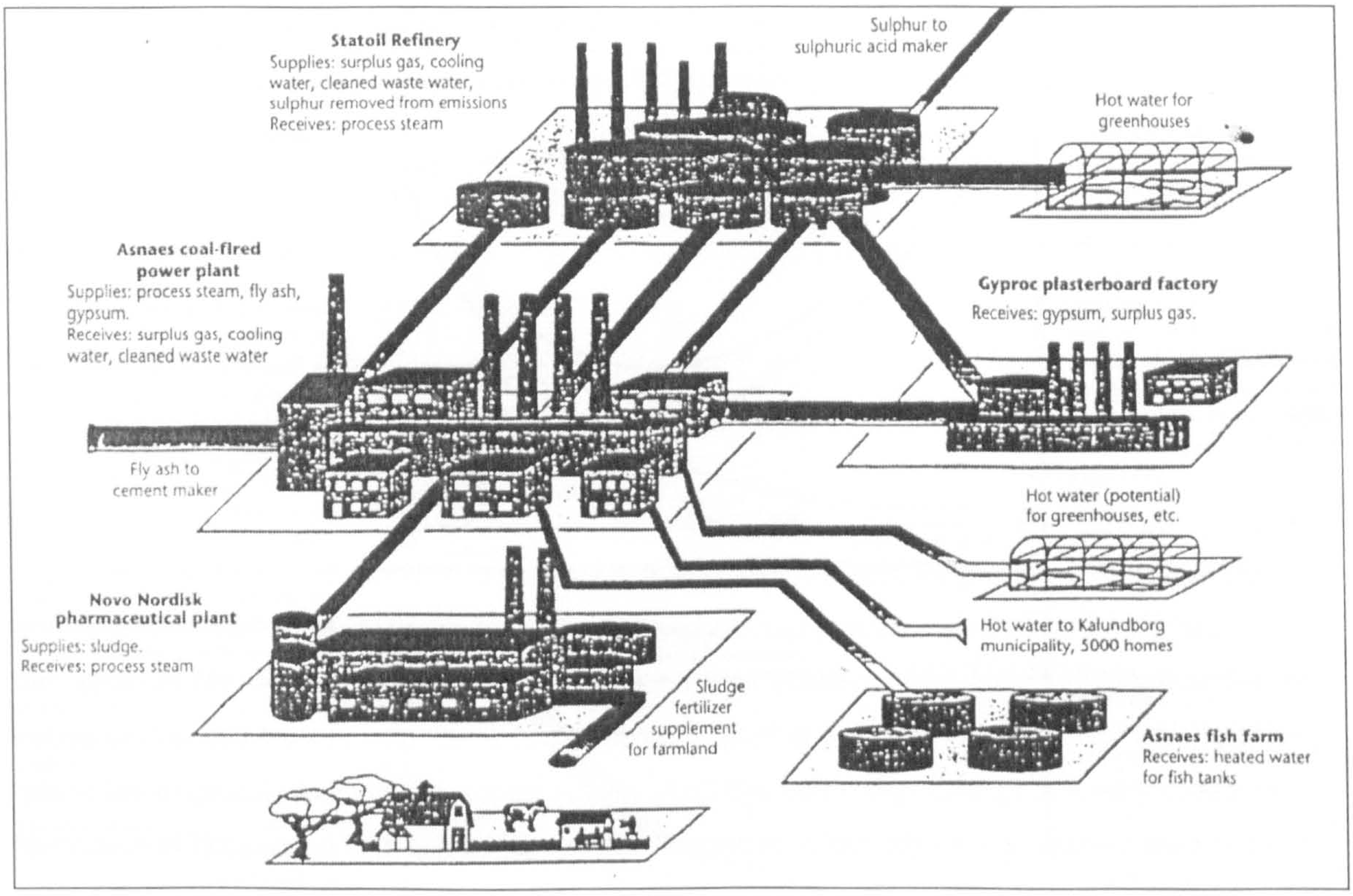
There are four recognised approaches to IE which are introduced below, they are not though mutually exclusive; each emphasises different aspects of the industrial society that can be influenced in order to contribute to sustainable use of natural resources. These four approaches are Macro or Regional, Micro or Individual, Process or Materials specific and Product specific.

2.4.1.1 Macro Level

At a macro, industry wide, or regional level, IE is about creating symbiotic relations between various industries, agriculture and communities, the 'waste' of one becoming the 'raw' material of another. Ultimately it aims to synthesise whole areas with resources on an eternal circular path. In terms of the built environment this is more at the level of a city or community. One of the most widely studied and reported on examples of IE in practice is seaside town of Kalundborg, home to 10,000 people in Denmark (Ayres 1996), (Ehrenfld and Gertler 1997), (Schmidt 1996).

The Kalundborg prototype industrial ecosystem started in the 1960's when the electricity plant modified its operations so as to produce process heat in the form of stream that could be sent to the nearby oil refinery. Once the idea of co-production was taken seriously it was found that the power plant could also sell its steam to a pharmaceutical plant, greenhouses, local homes, and its own fish farm. Co-production is now widely used with electricity generation the world over.

Figure 2-5 Kalundborg-industral symbiosis in operation (Ayres 1996)



The oil refinery then introduced a desulphurization plant and recovered sulphur for sale to a sulphuric acid producer, and cleaner gas to the power plant, replacing coal. Lime scrubbers where introduced at the power plant and the calcium sulphate sludge was sold to a gypsum wallboard manufacturer. Finally, fish processing waste from the fish farm and waste sludge from the pharmaceutical plant where sold to local farmers as fertilizer.

Due to the evolutionary nature of Kalundborg over the last 30 years it is unlikely that its pattern could easily be used as a model or transferred, but the general principles of recycling once perceived 'wastes' around the system are laid down. A number of firms in the US have started to integrate their processes with that of their neighbours, creating new firms to fill niche markets on the way (like an evolving ecosystem). One example is the Chaparrel Steel making Company which has pushed the limits of steel-making to the point where everything they produce is a useful product to nearby enterprises (Interagency Workgroup, 1998).

2.4.1.2 Micro Level

Whilst the macro level deals with the whole system, the micro level looks at an individual product or process within one company or industry, here Industrial Ecology, sometimes termed preventative environmental management (PEM) or cleaner production (CP), is centred around optimising the flow of resources and reducing environmental burdens.

Jackson, (Jackson 1996) provides a plethora of examples where optimising of resource flows has lead not only to reduced environmental burdens but also improved performance and considerable cost savings. This win-win situation, he comments, contradicts the general assumption of most industrialists that economic development and environmental protection are uneasy bedfellows. For increased environmental protection, the assumption was that you either had to reduce economic activity, therefore reducing flows and burdens, or increase it to pay for the extra 'end of pipe' clean up costs or pollution taxes. As the industrial economy shows signs of stress this paradigm is being questioned, preventative environmental management strategies have been shown time and time again to save both money and the environment.

Jackson goes on to examine the causes of pollution, the reasons for profit and their link with quality of life and investigates the limits of PEM, what changes are needed, and ultimately will they provide the levels of protection required for future 'sustainability'. He proposes that the root cause of the industrial economies environmental impact is the demand for goods and services, this is the engine that drives economic activity. And this same demand generates increasing quantities of household and consumer waste. Therefore in looking for the answer we must *"place the consumer at the centre of the complex materials network which comprises the industrial economy"* (p7). As with other systems thinkers he overlays the linear economy on the circular ecosystem and highlights the differences.

> *"The difference between the economic system and the ecosystem is that material dissipation in the economy is independent of the complex balance of natural material cycles which reorganise degraded materials into high-quality resources again." (p32).*

These cycles provide a kind of natural regulatory mechanism between different species within an ecosystem and between different ecosystems. Hence he also sees that the object of the redesigning and reorienting of the industrial system it to try and make it more like the natural system by:

- Creating material cycles
- Improving material and energy efficiencies
- Reducing dissipative consumption, and
- Improving the utilisation of our solar inheritance.

These four strategies are returned to later on in this chapter.

The micro industrial ecology process starts by defining the intended goal, usually the development of a more sustainable product/process, with reduced environmental impacts. Strategies are then used to analysis the problem and propose and test solutions. One of the most important stages is the investigation of the impacts of the product/process over its entire life cycle. This started life as cradle to grave assessment, but more recently it has been expanded to cover cradle to reincarnation, eliminating the end of life and therefore supporting the idea that 'waste' is in fact a future resource. This study is aptly termed Life Cycle Assessment (LCA) and is dealt with in greater detail in Chapter 5. The results of an LCA should indicate areas where improvements are necessary or would be of benefit, and IE strategies are then about instigating these improvements and monitoring the results.

Products and processes are seen as quite distinct and the difference between them is important and these form the last two approaches to IE. Products are what is sold and processes are the techniques by which those products are made, therefore the industry-environmental interaction is heavily influenced by two separate groups of designers. For IE to properly function both of these groups must be involved in future design.

2.4.1.3 Process

The third approach to Industrial Ecology is at the processes level. Processes define most of the resource flows into a manufacturing facility and are responsible for most of the useful, and waste, flows leaving it. They are material specific and generally involve huge amount of capital equipment, and once embedded in an industry it is often difficult and expensive to make more than incremental changes. Therefore whole processes change on rare occasions and are more likely to slowly evolve.

In the context of the construction industry, process design is concerned with the production of steel, cement, pre-cast concrete, aluminium, copper etc and generally beyond the scope of this study. In each of these industries, process efficiency, waste minimisation and dematerialization practices are in place, this generally starts with good housekeeping policies and internal recycling of 'wastes' arising during the manufacturing process.

2.4.1.4 Products

On the other hand, product designers may combine any combination of processed resources when selecting a suitable design. Existing or newly emerging products can relatively quickly be absorbed into designs. The philosophical stance of the design team and social, economic and environmental considerations will influence the direction of any given product. Within the realm of Industrial Ecology *"Solutions are sought through life cycle-based design, which seek to reduce the total environmental burden associated with product systems by balancing* *environmental needs with other design objectives"* (Brezet 1997) p51. It as at this level that most building designers engage with materials. They have been refined from raw materials, through a process outside the designers control, and are generally products in their own right. Any design has to satisfy a whole range of design objectives and so environmental considerations become a key requirement within this. By bringing the characteristics of sustainability to the whole system any product embedded within it will have inherent sustainable attributes. As Allenby notes *"it is the circular process of IE that is important not the individual results. We don't know for definite if we have the right answers" (Allenby 1997).*

2.4.2 Biomimicry

In the field of Bomimicy scientists are taking great pains in attempting to mimic and apply natures solutions to very specific human problems. For example cooling fins on computer main processing boards are now being corrugated to increase their surface area and so cooling potential, copying the wing of butterflies (Ward 1998). Hearing aids are being designed that mimic the acoustic system of parasitic flies, (Lafee 1997), and new types of photo-voltaic panels are being manufactured which more closely copy plant photosynthesis. Although individual plant leaf cells are very inefficient at turning sunlight into useful energy (less than 1%), the shear number of them on any one organism makes them effective. Therefore the new photo-voltaic panels are likely to be made of thousands of tiny collectors which together will give a useful power output (Ball 1999).

From the lead of these 'biomimics', Benyus has presented a set of strategies, or as she put it the 'Ten Commandments' for organisms surviving in a mature ecosystem. These commandments could equally be applied to human systems attempting to evolve to the mature systems level (Benyus, 1997, p252):

1. **Use waste as a resource.**
   One of the key lessons from systems ecology is that as a system puts one more biomass, it needs more recycling loops to stop it from collapsing. Similarly humankind needs to create material cycles, as the Kalundborg example above shows.
2. **Diversify and co-operate to fully use the habitat.**
   The failure of any one element of the system is unlikely to destroy the whole. Research and trade organisations can operate in a similar manor, looking for industry wide solutions without being tide specifically to any one product or building type.
3. **Gather and use energy efficiently.**
   Ultimately all systems on earth require the input of high grade energy to maintain order and balance the low grade energy leaving the system. Nature does this very efficiently

whereas humankind is generally inefficient. There are many examples where dramatic improvements can be made with existing technologies.

4. **Optimise rather than maximise.**
   The lesson is to slow down the throughput of materials, emphasising the quality rather than the quantity of new things. This requires extending the life, maintaining and recycling products.
5. **Use materials sparingly.**
   As with energy, designers are learning to do more with less material and through dematerialisation and recycling policies extend the life of those in use.
6. **Don't foul the nests.**
   Designers are learning that it is far better to design pollution out of a system than to try and clean it up after it has been produced. According toxic materials or those that tend to dissipate during use need to be avoided or used in very small quantities and their release controlled.
7. **Don't draw down resources.**
   There are two main types of resource inputs into the industrial economy, renewable and non-renewable resources. For sustainability we need to learn to make more use of the renewable resources but at a pace which is no faster than they can regenerate. The non-renewable resources need to be used efficiently and contained with recycling loops.
8. **Remain in balance with the biosphere.**
   Human systems should mirror those of the natural world.
9. **Run on information.**
   Use feedback systems to influence current and future designs.
10. **Shop locally.**
    Nature generally uses resources which are produced locally and by adopting a similar practice the human economy could reduce it environmental impact.

This is not the only attempt to offer an operating system for natural systems, both David Orr (Orr 1992), and Peter Allen (1994) have also formulated what they perceive respectively as the 'biosphere laws' or 'evolutionary principles' which nature adheres to. Orr has compared these with the principles on which the modern industrial system are based:

- The logic of **evolution** versus the logic of power. Nature's logic is adaptive, symbiotic, circular were as mans is dominating, controlling liner.
- **Ecological time** versus technological time. Nature works over geological and ecological time of millions of years where as man works in technical time of days and hours. The two do not harmoniously superimpose on to one another.

- **Maintenance** versus unlimited growth. As ecosystems evolve from stage 1 to 3, they test outputs as potential inputs for new processes, and move to reuse and recycling of resources internally. They become more concerned with maintenance than growth. In contrast human systems grow to their maximum extent, or until they face the kind of limitations we are now experiencing. The circularisation of resources does not seem to figure within this. Two of the possible reasons for this are;
    1. Lack of time. As discussed above ecological time and technological time are not compatible. We do not give sufficient time for an ecological response.
    2. The tendency to use dispersion rather than concentration in removing our wastes.
- **Diversity and redundancy** versus homogenisation and fragility. Natural systems fit together in a tangled web of interconnections with a great deal of redundancy and diversity all fed by constant feedback. The system does not become critical with the failure of one particular species within it. Human society is becoming increasingly homogenous and monotonous with industrial globalisation forcing the same patterns the world over. Single failures within the system often have catastrophic results.

To these four biosphere laws should be added a fifth, that of scale linking.

- **Scale linking** versus linear connections. "*Nature's processes are inherently scale linking, for they intimately depend on the flow of energy and materials across scales*" (Ryn and Cowan 1996), p33. These links connect cycles across very different spatial scales, for example, jumping in scale in steps of a thousand, from a millimetre to a thousand kilometres, one encounters a drop of water, a puddle, a lake, and the Antarctic ice cap. Human society by contrast has great difficulty is seeing beyond its own immediate scale.

These five natural laws do not seem to constrict or limit the natural world, on the contrary they allow it the freedom to express itself in ever increasing complexity and diversity. This it achieves under the pressures of constant change and limited resources through its resilience and adaptability. Natural systems may not achieve the greatest efficiency at all times, but by surviving unexpected stress they achieve the deeper efficiency of avoiding catastrophic failures. They are "*resilient enough to withstand external disturbances and internal malfunctions*" (Orr, 1992, p34), but this is not a static condition, systems are equally flexible enough to "*change as a result of the adaptation of its component species to new opportunities or conditions*" (Allen, 1992, p92). "*Resilience implies small, locally adaptable, resource-conserving, culturally suitable, and technologically elegant solutions whose failure does not jeopardise much else*" (Orr, 1992, p34). As oppose to confronting change and stubbornly standing their ground natural systems accommodate change and seek out any benefits resulting from it.

2.4.3 Applying Systems Theory

An early leader and innovator in applying ecological systems theory to design situations is John Tillman Lyle. His work has its foundations in the detailed analysis of ecologist Howard Odum and he has used natural system theory to inform his ecological design strategies for integrated landscape, agriculture and housing schemes.

2.4.3.1 Three Modes of Order

From his detailed work, Lyle has developed a structure for defining the basic order of an ecosystem (Lyle 1992):

Pattern Order	describes the organisation of the system
Structural Order	describes the composition of the living and nonliving elements
Functional Order	describes the flow of energy and materials that distribute the vital requirements of life to all of the species within and through the system

These ecosystem layers can be likened to a house, which is reflected in the word 'ecology', in Greek, 'ecos' means house and 'logy' refers to study. The pattern order becomes the building's location, its spatial layout and planned use and its relation to the existing local environment. The structure is the physical embodiment of the pattern, i.e. the material structure, and the function is the flow of energy and resources through it, which corresponds to its services.

This basic analogy can be applied across the whole spectrum of the built environment. By relating to building in this way, their relationship with the ecosphere, and the flow of resources through them can be more readily perceived. As such, pattern, structural, and functional order form the basic layer and first component of the analytical framework of this thesis.

The leap from natural systems to human systems to buildings is not as great as it first may seem. Buildings are not only the domain of humans; many animals particularly insects build very elaborate structures in which to shelter. These structures like their human counterparts, control the local environment, affecting ventilation, thermal comfort, day-lighting and even food production. Recent research suggests that structures such as webs, nests, hives, burrows, and mats are physiological extensions of their creators (Brown, 2000). They take energy and materials from the environment, including sunlight, water and oxygen, and funnel them to the organisms inside in a continuous flow, typical of a thermodynamic system. This is analogous to human structures, however as identified above the operating principles that these two systems use are very different

While nature uses the sun, wind, gravity and osmosis to power its buildings, humans use fossil fuels. Also, the basic building materials of the natural world are all locally occurring materials or those transformed with the bodies of the builders at ambient temperatures and atmospheric pressures. Human structures are built from materials collected from diverse locations covering the entire planet and are transformed from ores using vast amounts of energy, heat and pressure.

In attempting to provide a new operating system for human systems, the general design strategies of natural systems, as defined by Jackson, Benyus, Orr and Allen above, will now be placed within the three level system framework developed by Capra and Lyle. These start with the organisational level, then the actual structure and finally the flow of resources that turn the structure into a functioning building. As neither buildings nor the natural environment are static the relationships between the individual strategies will change, as may some of the strategies, it is the general systems approach that is important.

Pattern Order	• Diversity, co-operation and resilience
	• Optimise and maintain rather than maximising growth
	• Run on information and feedback
	• Link across scales
	• Think over long time frames
Structural Order	• Create materials cycles
	• Improve material and energy efficiency
	• Utilise renewable resources at replenishable rates
	• Use locally occurring resources
Functional Order	• Gather and use energy efficiently
	• Reduce pollution by avoiding toxic substances and dissipative materials

2.5 Conclusions

Mature natural systems exist is complex web like structures with multiple connections, they adapt readily with minimum fuss to changing conditions and use waste as a resource. Human industrial systems on the other hand are linear, polluting, inflexible, and require the constant input of new resources and removal of wastes to maintain them. Attempting to advance human systems to mimic the 'mature' strategies of natural systems could enable a more circular arrangement of resource use, result in more resilience and adaptability to changing conditions, and potentially reduce the social, economic and environment stresses of our time. As a major component of the human industrial system, and the focus of this thesis, the built environment is now examined within this systems framework.

3 THE BUILT ENVIRONMENT

3.1 Introduction and Structure

This second theoretical chapter focuses on the lifetime environmental impacts of the built environment. After identifying the scale and importance of these impacts the chapter concentrates on the area with least current attention; the demolition phase. Here, the quantities of waste produced, European and British policy on the disposal of building waste, the views of the research organisations, and the 'state of the art' within the demolition industry are all discussed. In searching for a strategy to design waste out of the system, the chapter then turns to examine the concept of Design for Disassembly. Currently, Design for Disassembly has been most successfully applied within the product design sector, therefore, to develop a coherent strategy, examples are drawn from this sector and compared with early ideas and more recent developments from within the building sector. This is further augmented by a case study presented in the next chapter.

3.2 Context

The built environment is the focus of this research and one of the most important areas for investigation within the current sustainability debate. Socially, we now spend over 90% of our time within the confines of the built environment. Economically, although urban centres occupy only 2% of the land area of the globe they already consume 75% of the Worlds resources (Giradet 1999), p15 & 26. Environmentally, buildings consume half of all the primary energy and material resources produced and are responsible for half of the man-made carbon dioxide emissions and half of all the materials entering the waste stream (Anink, Boonstra et al. 1996) p2. As Herbert Girardet concludes writing in Architectural Design, "the construction and refurbishment of cities for environmental sustainability is one of the great tasks ahead of us" (Girardet, 1997).

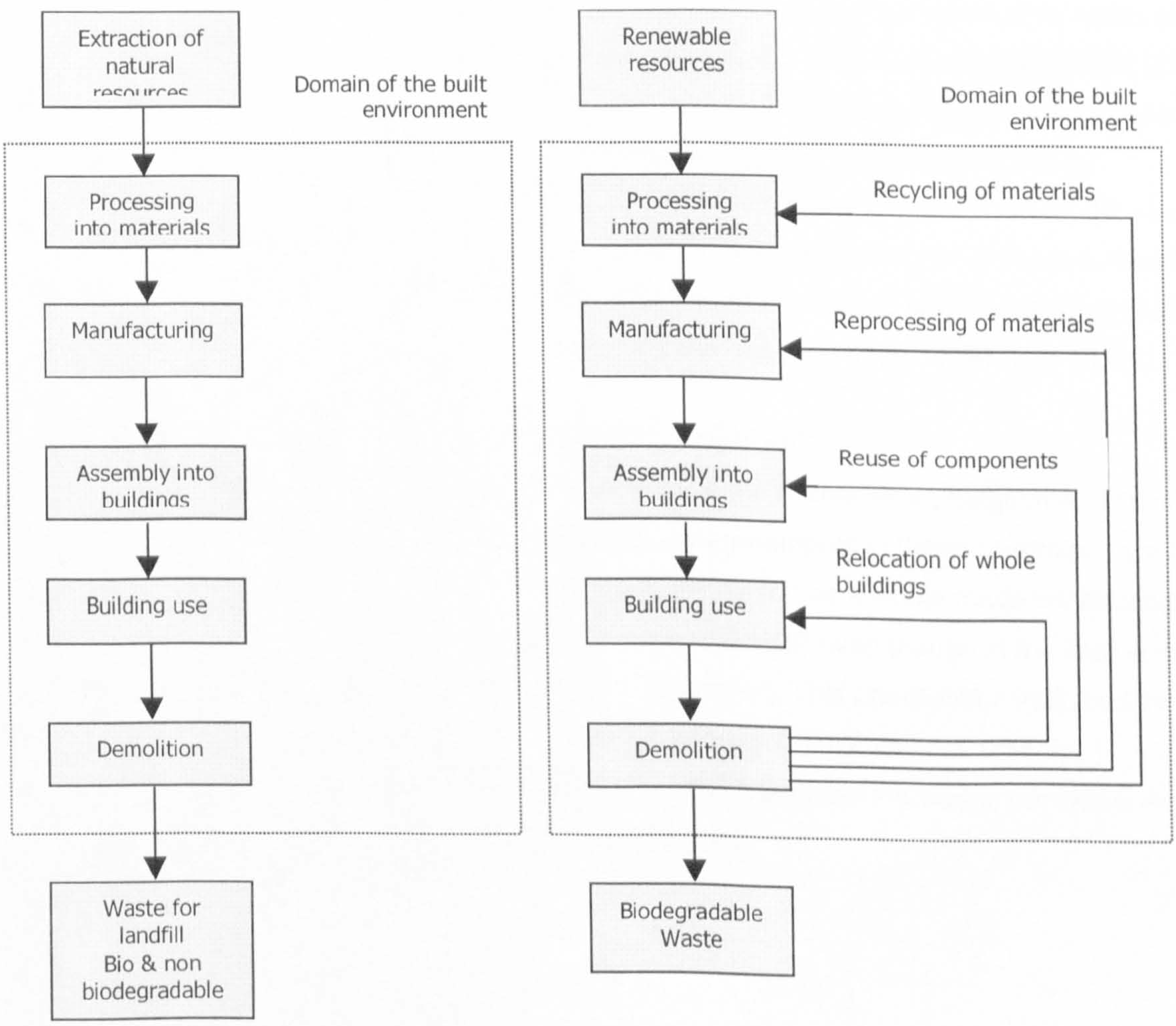
3.2.1 Core Issue

Buildings are (in effect) huge reservoirs of energy and materials, combined in increasingly more complex ways, and have potential life spans of several generations. However, due to a variety of factors, they are becoming obsolete and consequently being demolished long before any structural or material failure (Golton, Hiley et al. 1994). Their demolition and subsequent replacement creates wide-ranging environmental impacts. From the extraction of finite raw materials to the disposal in landfill of exotic and composite materials, the 'ecological footprints' of our buildings now cover the entire planet (Golton 1994).

3.2.2 Linear to Circular Flow of Resources

At the heart of the issue is the way the building industry uses resources; currently it extracts, consumes and discards resources in a linear manor, with little consideration for the entire life-cycle, see Figure 3.1. As indicated in the pervious chapter, new design strategies are being developed which question this linear flow path. These offer solutions to redesigning the industrial economy on a more life cycle or circular basis (Lawson 1994). This more circular approach extends to buildings and sees them as dynamic systems, operating at a number of scales, which are readily reusable and recyclable and respond to the changing requirements placed upon them. At a philosophical level, this is essentially about modelling buildings on natural systems, which (as shown in the previous chapter) are typically characterised by cyclical processes and symbiotic, mutually dependent relationships (Lawson 1996). Adopting such an approach should result in resource use and wastage being minimised and the useful life of buildings and their components being increased to their theoretical limits (Grammenos and Russell 1997).

Figure 3-1 Linear to Circular building System
(Crowther 1999)



Whilst this methodology has not been fully embraced, elements of it are regularly incorporated into current design thinking. Both the construction and the operation (use) phase of a building's life-cycle are increasingly being addressed. The selection of renewable or low impact materials and criteria for designing for energy efficiency are now commonplace and regularly reported on in the building press. However, the final stage of a building's life-the demolition phase has until the last couple of years been outside the consideration of the design profession. The recognition of the scale of the demolition's impacts has though encouraged a growing interest in the demolition phase.

3.3 The current position

3.3.1 United Kingdom Disposal Levels

Figures from 1997 estimate that 70 million tonnes of controlled waste, was directly attributed to construction and demolition waste (C&DW) in the UK. This equates to 6 tonnes of building materials per household per year and is four times higher than the comparable figure for domestic rubbish[2]. Out of the total C&DW some 13 million tonnes has been further estimated to comprise of material delivered to sites and thrown away without even being used (DETR 2000). The majority of C&DW is masonry and concrete, the remainder being wood, metal, paper and plastics. Of the masonry waste, only 4% is recycled to produce high grade secondary aggregates. A further 29% goes to low level uses on or near the site of origin, whilst the rest is used for low grade purposes such as access roads, landfill engineering, or is unaccounted for (Alderson 1997). More recent figures estimate that the UK figures are somewhat conservative, putting C&DW nearer a hundred million tonnes and the recycling figure lower (Kay 1999).

3.3.2 Construction & Demolition Waste across Europe

The recycling picture across Europe is quite varied with the Netherlands, Belgium and Denmark leading the way. Legislation, regulation, and voluntary agreements in these countries have been geared to encouraging recycling. In 1990 the European Union as a whole made construction and demolition waste one of its Priority Waste Streams (PWS) even though at the time very little was known about the nature or volumes of flows concerned. This prioritisation indicated the Commissions concern and the relative importance given to C&DW as an economic, environmental and social issue. The objective of the PWS programme was to develop a waste management strategy that follows the recycling hierarchy.

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[2] Domestic rubbish accounts for 12%, industrial & commercial 38%, and the construction sector 50%.(Alderson 1997)

3.3.3 Recycling Hierarchy

'Recycling' is often used as a generic term for a range of activities (listed below) and the UK Government's policy on waste management recognizes this (in adherence to the EU Protocol on Recycling). The policy is based on a hierarchy in which order of preference, subject to the best practical environmental option (BPEO), is as follows (Hobbs 1996):

• Reduce	Reducing the amount of waste
• Reuse	Putting objects back into use so that they do not enter the waste stream
• Material recovery	Recycling- collecting and separating materials from waste and processing them to produce marketable products Composting- Processing biological degradable organic wastes aerobically to produce a reasonable stable, granular material
• Recover energy	Incinerating waste with energy recovery
• Dispose	Disposal of waste to landfill site or land raised site

The research presented in this thesis accepts and follows this model and refers to 'recycling' as the generic term for these activities. More specific terms are used as appropriate.

The reduce option, is generally a design issue, requiring a proactive, life cycle approach and together with reuse a core aim of this thesis. Reduce relates to good site management policies for waste reduction, and it is also synonymous with making best use of primary materials. Reduce can also be thought of as redesign and covers the much broader issues of cultural values, behaviour and ethics. In order to proactively redesign 'products' it is likely that the values of society will have to change to support this. The adoption of this more life cycle approach by the whole of society is thought beyond the scope of this work.

Reuse can either be of a whole building by extending the life phase, through refurbishment, or, alternatively of individual elements like a pre-cast panel or a steel beam. As it maintains the integrity of the complete elements it is the most energy and resource efficient way to 'recycle'.

Material recovery is where most current activity takes place. It implies a breaking up of the elements into their constituent materials and then reprocessing these to form new materials. Materials go through a 'cascade of use', either being up-graded, down graded or having the same utility, all depending on process type and the input of other (new) energy and resources. Most building materials are cascaded downwards, for example, concrete structures are demolished, crushed and used as sub-base material. It can be less expensive than disposal to landfill and is generally the better option if environmental externalities are taken into account.

Energy Recovery refers to incineration for electricity generation or more typically for heat recovery and dispose to landfill is the least attractive and final option.

3.3.4 Benefits of Recycling

Broadly speaking the main benefits of recycling are recognised as (Edwards 1996) p147:

- Conserving natural resources. Using recycled materials displaces the need to continually extract virgin materials.
- Saving energy, time and money in production and transportation, by reusing existing products, or replacing virgin materials. If elements or products can be extracted in a reusable state these can directly replace new materials.
- Reducing the demand for Landfill sites. Diverting materials from the waste stream reduces the need for extra landfilling capacity.
- Reducing pollution. Landfill pollution and that associated with the manufacture of new products that are replaced by recycled elements.

Plus the additional benefits of

- Conserving architectural history. Many interesting architectural features can be saved and incorporated into new buildings.
- Providing employment. The recycling industry is fairly labour intensive.
- Producing goods more cheaply by embodying recycled material or by using energy from waste.

3.3.5 Impacts of Recycling

Whilst the benefits of recycling are clear it should be noted that recycling of materials is not without its own environmental impacts. These are somewhat similar to quarrying, but as most construction and demolition waste (C&DW) arisings are from urban areas they have the potential to affect more people. The main impacts are; noise, dust & air pollution, surface and groundwater leaching and visual and aesthetic intrusions/pollution. Transport impacts are similar to that of quarrying except where recycled materials are reused on site of origin when they are negligible.

3.3.6 European Commission Report

A recent report for the European Union has reviewed the current C&DW situation and examined the recycling 'state of the art' across the community (Report DGX1 1999). The EU Report was designed to be 'action-oriented', it therefore aimed to highlight practical measures that could be taken to encourage the re-use and recycling of C&DW. It also distinguished between local, regional and internationally applicable strategies.

Table 3.1 below shows the current levels of waste and recycling within member countries of 'core' C&DW arisings. 'Core' arisings are defined as the mix of materials obtained when a building or infrastructure is demolished. This excludes road planings, excavated soil, external utility service connections and surface vegetation. The Scandinavian countries and the Netherlands are leading the way in recycling, with the UK behind these. However judging from the difficulty in even estimating the UK figures, the accuracy of the European wide figures has been questioned (Kay 1999).

Table 3-1: European Waste Arisings

(Report DGX1 1999) (Summary Table, p7)

Member State	Core' C&DW Arisings (m tonnes, rounded)	% Re-Used or Recycled	% Incinerated or Landfilled
Germany	59	17	83
UK	30	45	55
France	24	15	85
Italy	20	9	91
Spain	13	<5	>95
Netherlands	11	90	10
Belgium	7	87	13
Austria	5	41	59
Portugal	3	<5	>95
Denmark	3	81	19
Greece	2	<5	>95
Sweden	2	21	79
Finland	1	45	55
Ireland	1	<5	>95
Luxembourg	0	N/a	N/a
EU-15	180	28	72

The EU report identified three broad levels of recycling technologies and their applications (10.5, p69):

1. Level 1. Lowest level, comprising of mobile crushing and sorting plant. Only really suited to processing of inert C&DW;

2. Level 2. Intermediate, as above but with the inclusion of metal removal and more complex sorting and sieving; and
3. Level 3. Advanced Recycling. This adds hand sorting, washing and facilities for other C&DW streams to level 2 plant. Can deal with any mixed and contaminated wastes as required.

The more advanced level was only identified in a number of Northern European countries. Even in these, all three levels could be found due to regional differences in a number of factors, such as the pricing of primary aggregates. In purely financial terms the costs of moving from a level 1 to level 3 system are, the report noted, quite significant. These are borne at first by the construction industry, then passed on to the owners and users through higher construction costs. These though must be viewed with the wider environmental, economic and social gains made by recycling.

The report goes on to recommend four conditions that must be met if C&DW recycling is to reach significant levels across the community. These are (10.7, p70):

1. Landfills must be well managed, and fly tipping' of waste uncommon and subject to sanctions;
2. Landfilling must be expensive particularly for hazardous or mixed wastes. If high levels of recycling are to be met then as in the Netherlands landfilling of recyclable waste must be banned.
3. The main bulky inert fraction of the waste must be crushed and sorted prior to recycling.
4. Suitably prepared C&DW derived aggregate should be used to replace primary aggregates.

In contrast to this it concludes that relying on a tax mechanism alone will not be sufficient to raise the recycling proportion, as it would have to be set at politically unacceptable levels.

A key element to maximizing recycling yield was the separation of materials at source through selective demolition. This combined with recycling centres, performance specifications, and voluntary agreements, between those within the industry to encourage recycling, where seen as the main strategies necessary to increase the recycling yield.

The publication of such an extensive report indicates the seriousness with which the EU now regards C&DW. The investigation provided a very detailed picture of the current recycling picture within the member states and indicated a number of ways in which the recycling yield could be increased, even if some of the data used was not quite as accurate as suggested. Its main criticism however, was its failure to look in depth at the more proactive issue of reducing waste, the first stage of the recycling hierarchy. The issue of taking a more proactive stance is one of the main threads of this research and will be returned to later in this chapter.

3.4 Waste Legislation

There is myriad of legislation that deals with C&DW issues both from the EU and within the UK itself. The important developments and dates are given below in the table below and then more fully explained.

Table 3-2: Waste Legislation in Europe

Legislation	Area of interest	Date
Directive 75/442/EEC	Cover safe disposal of waste	1975
Recommendation 81/972	Cover safe disposal of waste	1981
Directive 89/106/EEC	Construction Products Directive	1989
Priority Waste Stream	Highlights C&D waste	1990
UK Environmental Protection Act	Bringing environmental protection within a legal framework	1990
91/156/EEC	Concept of Sustainable Development	1991
Environment Agency	Combining the forces of the: EA, HMIP, NRA, LWRA	1996
Landfill Tax	Charging for the disposal of waste	1996
Aggregate Tax	Potential charges for virgin aggregates	2000?

EU Directive 75/442/EEC, and Recommendation 81/972 deal with the safe disposal of waste. These have now been somewhat superseded by Directive 91/156/EEC issued in March 1991, produced in response to the notion of 'sustainable development' introduced in the Brundtland Report (Brundtland 1987) and the Rio Earth Summit (Quarrie 1992). The new Directive obliges governments to encourage recycling and to implement measures that reduce or prevent waste (Edwards 1996) p147. As previously mentioned C&DW has also been classified as a 'priority waste stream' due to the large quantities produced each year.

Plans are also at an advanced stage for a new target driven EU directive for recycling demolition waste that will not follow the EU Recycling Protocol but will give any of the four recycling methods equal merit. Germany and Denmark, two of the keenest recycling nations in Europe, lead the drafting committee for this Directive. This is contrary to the standard waste hierarchy approach (see above) and may be more of a political move by Denmark and Germany to promote their recycling industries.

Another important EU Directive that deals with construction materials and affects reclaimed and recycled materials is the Construction Products Directive (89/106/EEC) known as CPD.

3.4.1 Construction Products Directive (CPD)

The CPD applies to products for permanent incorporation into buildings and civil engineering works and has implications for whole construction industry. It requires that any construction products or components offered for sale must allow the building works (not the product) to satisfy six essential requirements relating to:

- Mechanical resistance and stability
- Safety in case of fire
- Hygiene, health and environment
- Safety in use
- Protection against noise
- Energy economy and heat retention

3.4.1.1 The six essential requirements

The six essential technical requirements of the Directive are explained with the help of Interpretative Documents under Article 3.1. They are aimed at ensuring that building and engineering works are healthy, safe, stable, energy conserving and protected against noise. They are also primary concerned with the removal of trade barriers to allow cross European flow of products.

There is widespread concern particularly within small scale construction and demolition firms that free trade and standardization will lead to the collapse of local materials specification and vernacular building tradition. It might have the effect of discouraging green and 'recycled' product specification as none-standard, one-off or old elements will fail to meet the directive and so using them will be in breach of EU law (Edwards 1996) p21-25 & (Kay 1999).

3.4.2 UK Law

In the UK every local authority is now required to have a 'Recycling Plan' and can enforce the use of better standards of recycling. Waste Management is also a matter of public health, and comes under Section 34 of the *Environmental Protection Act 1990.* Through this a 'duty of care' (Duty of Care SI 1991/2839) is placed upon everyone, (excluding householders) who handles waste (including building sites) to ensure it is disposed of legally and in a *'manor that does not cause pollution of the environment or harm to human health'.* This includes those responsible for leaching or escapes of waste from landfills and ensures transfer of waste is to an authorized person only.

3.4.2.1 Environment Agency

The responsibility for control of waste was with the local authority but this was transferred to the Environment Agency (EA) when it was created in 1996. This joined the forces of the Local Waste Regulation Authorities, the National Rivers Authority and Her Majesties Inspectorate of Pollution (HMIP). The EA is responsible for the control of the flow of materials and wastes in England and Wales through a waste planning system and releases to: water, land and air.

Additionally to these, through the 1990 Environmental Protection Act, the UK has introduced a system of Integrated Pollution Control (IPC) for those industrial processes with most potential to inflict harm on the environment. IPC is now enforced by the HMIP arm of the Environment Agency. Processes coming under IPC are set out in *Part A of Schedule 1 of the Environmental Protection Regulations 1992 (1992/614), 1993 (SI 1993/1749 and SI 1993/2405) and 1994 (SI 1994/1271).* IPC was phased in between 1991 and 1996. There is also a parallel system of Local Authority Air Pollution Control.

3.4.2.2 Landfill Tax

The most significant recent legislation to affect the disposal of waste in the UK is the Landfill Tax. This was introduced in October 1996, and was aimed at reducing the volume of waste sent to landfill and supporting and encouraging increased recycling of all wastes: household, commercial, and industrial. Different types of waste, from inert to hazardous, incur a different disposal penalty.

The effects of this tax so far have been mixed. Four months after its implementation the revenue collected by Customs and Excise was predicted to match the £500 million forecast. There was a reduction in the disposal of inert waste to landfill bringing both positive and negative environmental effects. On the positive side an increasing number of mixed wastes were being separated and sold as secondary aggregates. On the negative side there was evidence that wastes were being diverted to illegal disposal routes and leaking out of poorly regulated activities (ENDS 1997). In 1999 the situation was still very similar. The market for secondary aggregates was growing, as was concern for illegal and unlicensed disposal (ENDS 1998a). The March 99 Budget announced a £1 annual rise in 'active' waste from the 1996 levy of £7 to a 2004 tax of £15 per tonne. However waste industry specialists estimate that the tax would have to rise to £30-40 per tonne to have much of an impact on behaviour. Also prospects for increased recycling of C&DW were further undermined, in light of the new tax exemption for quarries taking inert waste (for groundwork engineering) which will see around 400 landfills fall out of the tax regime altogether (ENDS 1999b).

Legislation regarding landfilling is also emanating from the EU and in April 99 the EU landfill Directive passed its final legislative hurdle, Member States now have two years to transpose the controls into national law. The UK Government and landfilling industry have been busy lobbing against the law and have made little preparation for its effect. The Directive is therefore likely to have a profound impact on UK waste management practices, requiring heavy investment in non-landfill options. It will encourage composting and recycling, ban co-disposal of hazardous and non-hazardous wastes, and place bans or restrictions on landfilling of liquid wastes, tyres and other materials. However, it is likely that most countries will initially fail to comply due to lack of commitment and infrastructure. The EU also has neither the drive or the teeth to impose realistic sanctions for such non-compliance and the overall effect of the law may be watered down (ENDS 1999c).

3.4.2.3 Aggregate Tax

The aggregate industry is also coming under increasing pressure to change its practices and become more environmentally responsible or face an aggregate tax. The Department of the Environment, Transport and the Regions (DETR) has conducted a number of studies to estimate the environmental externalities of aggregate extraction and supply. Originally estimated at £250 million per annum this has now been raised to £380 million. The Quarry Products Association (QPA) has in response presented a range of voluntary measures which it claims would bring environmental benefits worth £159 million per year. The debate is likely to continue as the DETR is demanding that the QPA prove that its proposals will bring environmental benefits "proportional to what a tax might yield". Recycling of C&DW has been steadily increasing and recent research suggests that it is currently at 25 million tonnes per annum. When secondary materials, such as fuel ash, furnace ash and other mineral wastes are added recycled material may account for 20-25% of all aggregate used in England, DETR targets are though 55 million tonnes by 2006. However, the removal from the scheme of the 400 landfill sites which mostly receive inert C&DW is likely to reduce the incentive to recycle (ENDS 1998a), (ENDS 1999b), (ENDS 1999e).

3.4.2.4 Recycling-ENTRUST

From the revenue raised through the Landfill Tax a scheme has been created which permits landfill operators to divert up to 20% of their tax liabilities into environmental projects. This is regulated by Entrust, a private but non-profit body, created at the same time as the tax. It registers and regulates environmental bodies and approves their projects but does not control whom the landfill operators choose to fund. The fund is only allowed to account for 90% of project costs, the rest being raised by the applicants through other means. To date the majority of the funds have gone on amenity and conservation projects near landfill sites, helping operators to improve relations with local communities (ENDS 1999a).

3.5 UK Research Institutions and Initiatives

The building research associations in the UK have shown an interest in recycling and instigated projects to assess, support and advise the industry on appropriate methodologies. The most important of these projects are reviewed below, in order to assess the stance of these research associations

3.5.1 Building Research Establishment (BRE)

BRE has conducted case studies of office dismantling, aggregate reuse and building using mainly recycled materials, it has also instigated reclamation audits and is involved with European wide projects on recycling, Life Cycle Assessment and environmental profiling of all building materials.

Through the construction of its new energy efficient 'office of the future' BRE demonstrated the practical reuse and recycling of building materials (Collins and Hobbs 1997). This involved dismantling an office block on the site and collecting materials from other obsolescent buildings. 96% of the waste generated by volume from the demolished existing building was reused or recycled, and recycled aggregate and bricks were used for the new construction. Important factors highlighted from the project where:

- The need for further information on types and quantities of waste arising from C& D work, waste minimization and disposal options (see smart waste below).
- Greater insight into the role of the reclamation industry.
- Development of quality assurance about the performance of reclaimed and recycled materials.
- Co-ordination of developments in recycled aggregates. BRE has published information papers on the European wide response to this (Collins 1994).
- Research into lime-based mortars
- Setting up waste exchange infrastructure
- Greater awareness of the issues which need to be considered at the design stage of projects.

These all indicate the infancy of the recycling industry and the lack of information, structure and established markets for recycled building products.

As a result of this project BRE has instigated a secondary materials exchange, sponsored by the DETR. This is a prototype web site allowing people to buy and sell used, second hand and unused construction materials over the Internet. Salvo also has a web site directory which lists dealers in antique and reclaimed materials for buildings and gardens.

In response to the lack of information on the types and quantities of waste arising from C&D work BRE has also instigated a project called Smart Waste, which aims to benchmark wastes produced during construction and demolition. So far the construction phase of domestic dwellings has been investigated. By quantifying the average amount and types of waste produced, on site benchmarks can be set and contractors encouraged meeting or improving on these standards.

The work of BRE in investigating and promoting recycled materials is mirrored by the other research organisations. Together they are improving the information on and profiles of recycled materials and it is hoped that these efforts effect the quality, standard and acceptance of these materials.

3.5.2 Construction Industry Research and Information Association (CIRIA)

CIRIA has published a number of guidance documents on waste management and minimisation. These include a series on 'Waste minimisation and recycling in construction' for the boardroom (SP135), the design office (SP134), the site (SP133) and technical review (PR28). In the summer of 1999 it also published 'The reclaimed and recycled materials handbook' (C513).

The 'Waste minimisation and recycling in construction' publications resulted from a project of the same name (RP508) which identified several barriers to reuse and recycling which need to be overcome, these affirm the earlier findings of the BRE and include:

- A lack of demand for recycled materials and absence of a market for their resale.
- A lack of information on and confidence in the appropriate use of recycled materials, and thus of industry and client support
- A lack of authoritative guidance for designers and specifiers on the selection and specification of recycled materials for particular applications.

The main constraints inhibiting recycling and reuse have been identified through a number of projects outside of CIRIA and have been categorised under three headings as follows (Allwinkle and Stembridge 1994):

- Technical. The complex nature of many building elements, the lack of foresight of eventual obsolescence, demolition techniques and quality of waste produced.

- Economic. It is generally considered more economic to extract and convert raw materials than reclaim and recycle waste. There is also a lack of market opportunity for recycled materials.
- Social. The second hand image of recycled materials has discouraged the development of markets. Complex licensing procedures and lack of coherent legislation also affect the potential to recycle.

Following on from these findings, CIRIA has commissioned a further research projects to address these barriers, Funded by the DETR and including a wide number of partners, regular newsletters on the projects progress are produced.

The Reclaimed and Recycled Materials handbook (Coventry, Woolveridge et al. 1999) consolidates available knowledge and provides guidance for designers, specifies and clients. It is a direct response to the barriers identified above and like the recommendations of BRE it addresses issues of quality, acceptance and standardisation. Its aims are to increase awareness of the opportunities for using reclaimed and recycled materials and to provide good practice guidance on a comprehensive range of these materials, particularly for higher-grade uses. As such it is focused on dealing with the waste once it has arisen, there is though some discussion on designing to avoid waste in the introduction to this Handbook and the Design Manual (SP134). Three mechanisms are identified for minimising waste:

- Reducing the resources needed for construction
- Reducing the quantity of waste generated from construction and demolition sites
- Improving the use of materials reclaimed from the waste stream

Improving the use of materials reclaimed from the waste stream was the focus of the handbook. However, the first two 'reduce' mechanisms are design issues and CIRIA's response to these is examined below.

3.5.2.1 Reducing the resources needed for construction.

This addresses issues around the over-design of buildings. Over-design can result in waste, since greater volumes of materials are required for construction and consequently they must be removed with the demolition. On the other hand designing within very specific parameters limits the future flexibility and so longevity of any building. Therefore a balance must be reached which incorporates the above points and the associated cost implications. Whole life costing, both economically and environmentally is needed to properly weigh up the alternatives. The CIRIA report looks at materials, component size, capacity, specification, and design life. It generally considers the multiple layers of the buildings (structure to space plan) as one and assumes that all the impacts are with the structure and happen at the start and end of the life cycle- neglecting the impacts associated with periodic and selective refurbishment. However, recent research suggests that buildings exist in a number of time dependent layers, which have independent lifetimes, see section 3.8.5 for more details of this work. Over-design of the frame, a durable external cladding and short life span interiors, may be more environmentally beneficial

3.5.2.2 Designing to reduce the quantity of waste generated from site.
This is concerned with both the construction and demolition phase. At the construction stage care must be taken to avoid the build up of excess building materials and the likes of surplus excavation soil. Using standard components at standard sizes, both on site or by prefabrication, should minimize wastage and offcuts and allow reuse of formwork and temporary works.

At the demolition stage the CIRIA report notes that buildings could be designed so that at the end of the life cycle the materials are easily reused or recycled, even though such long-term scenarios are difficult for designers to envisage. The report then identified a number of parameters that should be considered to facilitate disassembly and recycling:

- They are easy to take apart; designed for dismantling
- The use of hazardous materials and composites is avoided
- Any polymers used are identifiable and easily separated
- Components of building and any prior treatment these may have had should be identifiable.
- An asset register, which contains information on the materials use and instructions on how they can be dismantled and potential recycling routes should be produced.

These parameters and the issues raised in this section will be further examined later on in this chapter.

3.5.3 Building Services Research and Information Association (BSRIA)

BSRIA as part of its Centre of Construction Ecology (CCE) has produced a number of publications including the 'Environmental Code of Practice' first published in May 1994. This was intended to be a working document for designing environmentally benign buildings from a life cycle approach. As such the stages of refurbishment, decommissioning, dismantling, and disposal were all considered. Within these chapters reuse and recycling of materials were flagged as being of prime importance. For the demolition stage surveys or asset registers of condemned buildings which highlighted the volume and type of materials present and potential recycling routes where also seen as important.

Another publication the 'Standard Specification for Waste Management Services' (78610E/2) was geared at informing those involved with collecting and recycling/disposing of waste.

Unfortunately the CCE has ceased to exist, and its tasks are now carried out by other members of the organization.

3.5.4 British Standards Institute

The British Standards Institute (BSI) has produced the UK standard on recycling/reuse of demolition waste (BS 6187:2000). This is generally geared to supporting increased reuse/recycling rates and a higher standard of environmental protection within the industry. It incorporates 'sustainability' and 'optimal recovery of materials' into the standard (Neale 2000).

3.6 From Reactive to Proactive

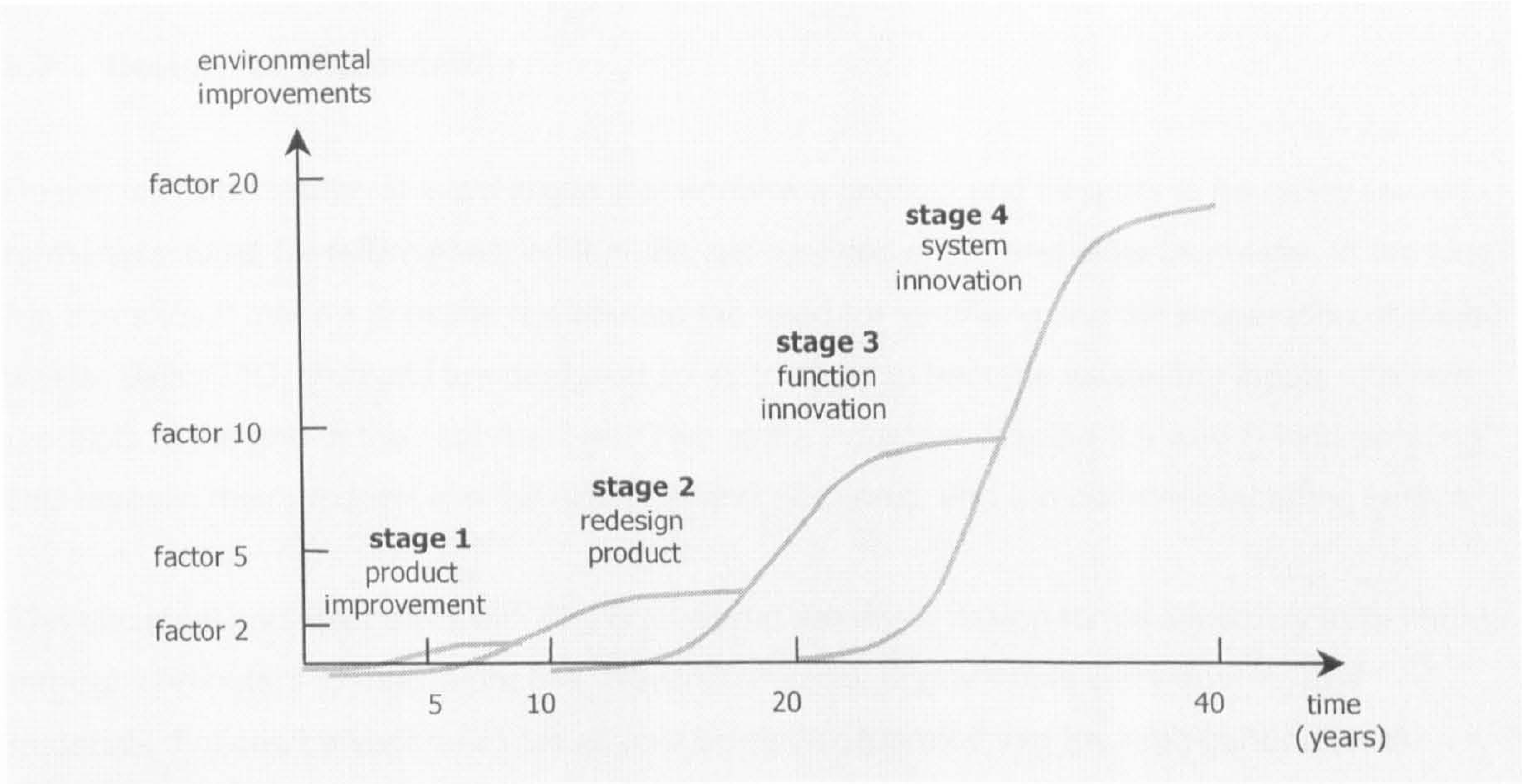
Whilst very valuable, most of the research and reports discussed so far have been aimed at dealing with C&DW once it has arisen. This is essentially a reactive, or 'end of pipe' approach. Most waste however is caused by decisions taken at the design stage (Snow 1999). Indeed, it has been estimated that over 80% of a product, or building's environmental and economic costs have been committed by the final design stage, before production or construction even begins (Graedel and Allemby 1995) p17. '*In many ways, the environmental crisis, is a design crisis. It is a consequence of how things are made*' (Ryn and Cowan 1996) p9. Therefore, if the building industry is going to do more than this 'end of pipe', remedial clean up of building waste it needs to rethink how it designs, builds, uses and disposes of the built environment. In effect this means taking the filters out of the pipes and placing then instead in the designers heads. This more proactive approach requires the designing it out of waste at the conception and through the subsequent lifecycle stages. In the words of Hawken (Hawken, Lovins et al. 1999) "*Everything that shouldn't be in the building process is eliminated by design. Design mentality can then reshape the entire construction process, and even the structure and logic of the way we procure and operate our buildings*" (p72).

The influence of design on the lifecycle impacts of a product or process and designs potential to shape the future has been most thoroughly investigated by the product design industry. The path to future sustainability being divided into four stages as represented by the series of s-curves in Figure 3.2 (Brezet 1997).

Product improvement is the reorientation of a 'product' to consider where resources came from, what are their impacts in use and where they go to at end of life. Product redesign extends this to whole life thinking and functional innovation starts to investigate the social and ethical implications of the 'product'. Systems innovation begins to consider the needs of society in a way that will lead to 'sustainability'. Considering these in relation to the evolving ecosystem model defined in the last chapter, Stage four below is the long term goal- the mature ecosystem, stages 2 & 3 the developing ecosystem and stage one the immature, or young ecosystem. Again this is also analogous to conservation, regeneration and stewardship, as proposed by Ryn and Cowan.

Figure 3-2 Four stages of design-environment innovation

(Brezet, 1997, p22)



Brezet states that the majority of the research community is presently at stage 2, and to bridge the gap to the next s curve, stage 3, and successfully climb it there is a need to innovate. This involves braking away from the existing paradigm and approaching design issues from a fundamentally new direction. On the vertical (y) axis of Brezet's diagram are the factors of eco-efficiency improvement. Factor 4, 10 and 20 are now common terms used throughout the design community to signify the level of impact reduction of a product/process (see for example (Weizsacker, Lovins et al. 1997)).

3.6.1 From Products to Buildings

The lessons being learnt by the product designers can increasingly also be applied to the design of the built environment as buildings and the building process are becoming more modular and standardized -like consumer products.

> *"No longer are (buildings) unique handcrafted artefacts but rather assemblages of standardised components put together by relatively unskilled labour. The design process takes increasing cognisance of the market and seeks to simplify the management of the construction process (Lawson 1994).*

If they are becoming more like consumer products it is on a larger scale. Buildings are more like meta-products, collections of multiple products all with there own characteristics, combined in unique and complex manors (Craven, Okraglik et al. 1994). One of the design tools being adopted by the product design community, as it advances from product redesign towards functional innovation, and discussed by building specialists is Design for Disassembly (DfD).

3.7 Design for Disassembly

Design for Disassembly is a technique that enables a product and its parts to be easily reused, re-manufactured (or refurbished) or its materials recycled at the end of its useful life. In the long run this should make it possible to eliminate the need for landfilling and for incineration of mixed waste. Using DfD, products are designed so as to never to become waste; but inputs into new products at the end of their service lives. Two of the industries leading the way in incorporating DfD ideas in their products are the electrical and electronic, and the car manufacturing sector.

The electrical and electronics industry is investing heavily in design for disassembly from kettles through computers to mobile phones. Reversible joints, upgradeable components, and materials that can be separated are all now being incorporated into the next generation of appliances. For example Xerox have extended their core business beyond selling photocopiers to the service that photocopying provides, re-launching themselves as the 'document company' in the process. Customers pay for the ability to photocopy and for this they get the latest machine, maintained and upgraded by Xerox. At the end of a photocopiers life, or when it is superseded, it is taken back and 'asset striped'. Basically disassembled with many of the elements forming the basis of the new model. For this, Xerox has adopted a limited number of product platforms- the basic structure of the machine, on which to build all the various options available. New models are then designed around the same platform, allowing easy reuse and recycling of the disassembled components.

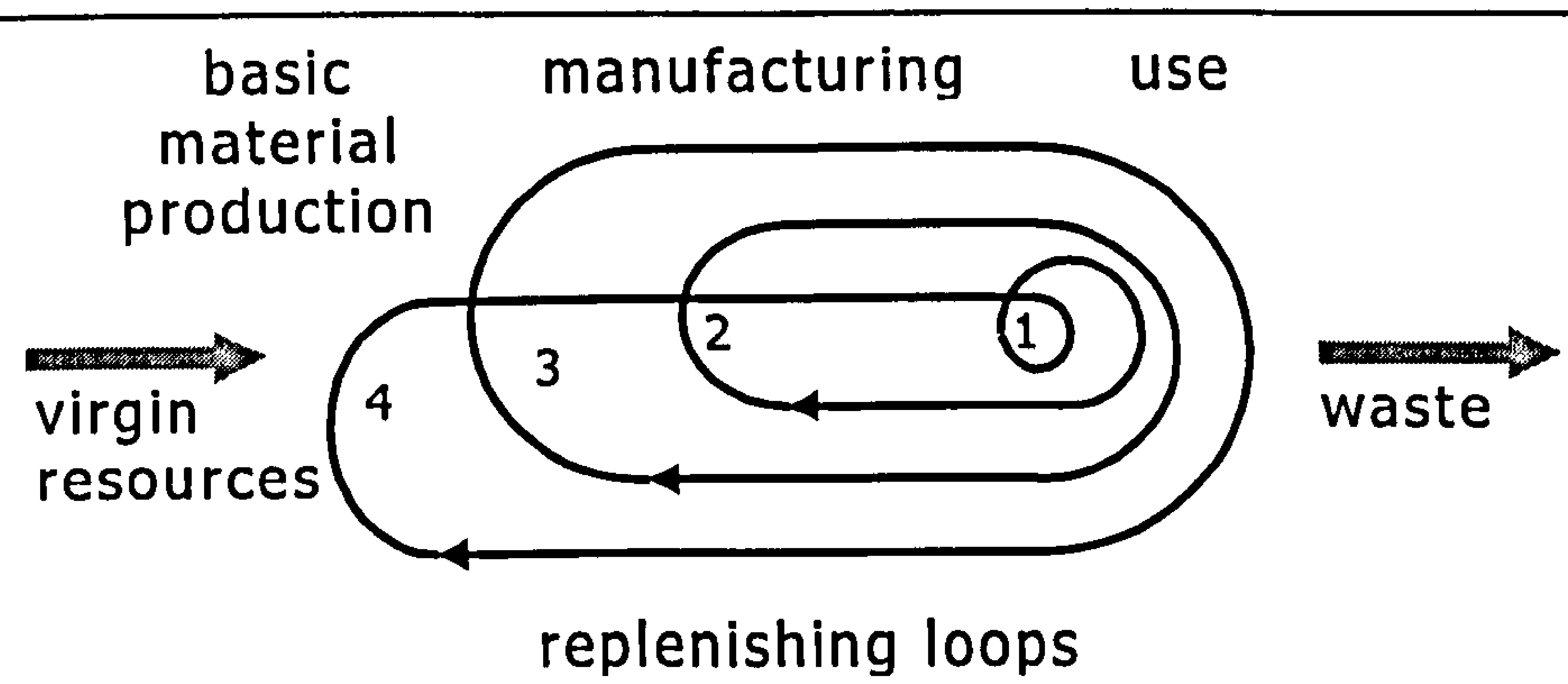
Car manufacturers have also started to consider the eventual end of life fate of their vehicles, encouraged by new legislation and fierce competition. Currently there is an industry-wide effort to reduce the number of materials used down to a recognisable and versatile few; specifically with plastics. Volkswagen are leading the way, vacuum moulding dashboards out of one polymer, and even labelling these with recycling routes. Cars are also being designed to enable dismantling allowing replacement of worn parts and easier recycling. The BMW Z-1 sports car's recyclable thermoplastic skin can be stripped from its metal chassis in 20 minutes on an 'un-assembly line' (Hawken, Lovins et al. 1999) (p79). In the process of this exercise, valuable insights are being made about the initial manufacture. This results in simpler designs and assembly processes with many associated cost savings, and has been recognised as one of the many benefits of adopting a DfD approach.

3.7.1 Disassembly Strategies

There are, in effect, two levels of DfD strategies, the product and the material level. In the first level (Loops 1-3, Figure 3.3) goods are reused, repaired and remanufactured, some disassembly is required, often into component form. Here the identity and function of the product is maintained and this is generally the most efficient use of the resources (its 'maximum utility'). At the material level (Loop 4, Figure 3.3) the product is further disassembled (or 'asset stripped) into its constituent materials and these undergo individual recycling routes. New material and energy resources are now required to turn these into a high quality product once again. This system is equivalent to the five-stage 'recycling' hierarchy discussed earlier in this chapter.

Figure 3-3 Replenishing Loops

(Jackson 1996) (p78)



loop 1: reuse of goods
loop 2: repair of goods
loop 3: reconditioning of goods
loop 4: recycling of raw materials

Whilst investigating the implementation of DfD within the product industry Tracy Dowie-Bhamra (Dowie-Bhamra 1996) identified some general strategies to facilitate disassembly through the replenishing loops, these include:

- Avoiding material composites which inhibit the effectiveness of recycling;
- Promoting modular design so that obsolescence occurs on the component rather than on the product level;
- Where possible eliminating contamination by grouping contaminated area and making its removal easy;
- Avoiding coatings such as paint, this inhibits recycling;

- Marking all parts for ease of identification;
- The recyclable nature of materials or parts. Choosing materials for the initial product with recognised recycling routes will greatly encourage their future circularisation;
- Minimizing the number of different materials, so that common, recyclable materials across and within the product range are selected (in general terms purer materials are more valuable and hence more recyclable);
- The design of fasteners and connections; Easy and quick to take apart products are more likely to be recycled;
- Minimizing the number of fasteners/connectors in a product, this reduces the disassembly time;
- The product structure; Does the product lend its self to recycling, are their obvious ways of doing this; and
- Who will be doing the reclaiming? By the manufacturer or a third party.

It is also vital to know the products intended route through the replenishing loops at the design stage, is it to be reused, refurbished or the materials recycled? As designing for each of these different 'end of life' scenarios can require the consideration of different initial design criteria. The strategies identified by CIRIA (see 3.5.2.2) are very similar to these, the main themes being:

- Label materials and record information about them;
- Use the minimum number of simple materials as possible;
- Avoid the use of hazardous or composite materials;
- Use materials with recognised recycling routes; and,
- Make fasteners/connections accessible and reversible.

Taken together, these strategies offer an overview of DfD and could facilitate the process of taking buildings apart for reuse or recycling. However, there are also a number of existing recognised limits to disassembly, the main ones being as follows:

- Financial – if the costs associated with disassembly are higher than the value of the recycled parts then disassembly won't happen.
- Market – is there a market for the disassembled parts/material? Should alternative (more valuable) materials be specified for which a market already exists? What happens if these materials have a higher impact in production, for example?
- Control over return of goods? Are the goods returned to the original manufacturer, or do they enter more general replenishing loops. If returned have they been 'tampered' with by a third party making repair/recycling more difficult.

In the product industry these issues are starting to be addressed, with the move towards DfD being driven along three main fronts. Firstly, firms in highly competitive markets are seeking a competitive advantage by improving their green credentials. Secondly, it is proving to be economically beneficial to reuse and refurbish elements, particularly compared to paying increasing landfill charges. Thirdly, recently passed European legislation will force all manufacturers of electrical and electronic equipment to take back and recycle at least 90% of their products by 2006 (Knot 2000). Taken together these three drivers are changing the way product manufacturers perceive their relationship with their goods and customers and greatly encouraging the practice of DfD.

3.8 Buildings Designed for Disassembly

3.8.1 Architectural Precedents for Disassembly

Historically there has been a long established culture of reuse and recycling of building materials and in less industrially developed cultures this is still the norm today. The majority of vernacular buildings use local materials; stone, timber, thatch and mud and these are allowed to decay naturally or easily reworked into newer buildings. There are many examples throughout Europe of old buildings that have been constructed from the elements of even older structures. For example, the columns that support the famous underground cisterns of Istanbul are from ancient Greek and Roman structures, and many churches, abbeys and houses were built on the sites of, and incorporating the elements of, older buildings. The reasons for reuse though are complex. Assuming that it is motivated by environmental altruism should be viewed with caution. Social and economic factors have been the main driving force behind much of the World's reuse of materials. John Hudson reached these conclusions while investigating the historical perspectives of reuse; he identified some of the reasons for reuse as follows (Hudson 1994):

- Often reuse of local materials was the simplest and least expensive option and the only one available to most people;
- Ownership and rights for removal and use of materials affected the pattern of building. In some areas 'common land' materials were provided free for the general use of local residents and in others only reused materials were available; and,
- Old materials have an aesthetic or antiquarian value and are often incorporated to add value to a property.

The concept of Designing for disassembly has also been around for some time, even if not called that by name. Certain structures have always been designed with the expressive purpose of being de-mounted, transported and re-erected. Others have been designed for disassembly due to the specification of the client or the desires of the architect. As a technical note for the Royal Australian Institute of architects Philip Crowther has reviewed the history of buildings designed for disassembly, and a summary of some of the most notable buildings designed for this purpose is presented below (Crowther 1999).

3.8.1.1 The Tent

The ancient form of the tent is a good example of careful consideration of resource use, in a way that allows the components to be disassembled for relocation, replacement, and maintenance. Tent like structures have evolved in most cultures with a nomadic or transient tradition. They typically use separate compressive frames and tensile membranes to create a stable structure that can be easily and quickly taken apart by the user. The lightweight and durability of the materials, the size of the components and the ease of re-construction being important design features for any travelling people. Today a whole genre of architecture has grown up around portable and lightweight structures used for everything from music concerts and events to refugee shelters to deployable space structures, see for example: (Kronenburg 1996).

3.8.1.2 Timber pegged buildings

The reuse of timber members in 'permanent' buildings has also been common practice in the distant past. In Europe, in the Middle Ages, the scarcity of suitable building timber led to the regular reuse of large elements. Pegs were used to connect and secure the beams enabling disassembly and reuse. This tradition was also strong in Japan, where farmhouses to temples were constructed without nails enabling them to be disassembled and reassembled like a puzzle. In the Japanese system, a primary frame is built to suit structural requirements, then a secondary frame is built to suit spatial requirements. This allows the secondary frame to be easily altered to suit the changing requirements of the inhabitants without affecting the structural frame. Therefore the structural integrity of the building is maintained, and the waste of building materials is kept to a minimum (Itoh 1972) (Fishbourne 1998). This time layered approach to building design is a reoccurring theme through this style of architecture.

3.8.1.3 Crystal Palace

In the middle of the nineteenth century Joseph Paxton designed the Crystal Palace to house 'The 1951 Great Exhibition of the Works of Industry of all Nations'. The temporary exhibition required a temporary home and the design allowed disassembly and relocation of the building. The entire building was based on a structural grid that was generated from the largest piece of glass available at the time. On this grid, an interconnected framework of cast iron columns and timber and iron trusses was set out. The trusses were slotted into flanges in the columns and held in place with timber or iron wedges. The design was so successful that after being relocated the building was actually expanded (Peters 1996).

3.8.1.4 Dymaxion House

Buckminster Fuller designed temporary portable buildings for wartime that utilised the mass production technologies of munitions factories. After the war, Fuller also had ideas for the use of such technology to make prefabricated houses. He proposed the Dymaxion house, which would be rented to its occupants like a product that would be serviced, repaired, replaced and finally recycled by the manufacturer (McHale 1962). This is very similar to the service concept currently being adopted by industrial and product designers. Whilst a prototype Dymaxion house was built the concept was never fully developed, but Fuller's later design for the Wichita house was built around similar principles. It was intended to be mass produced from standard components, each of which would weigh no more than five kilograms. The house would arrive at its site packed in a single steel cylinder and could be assembled by six people in just one day (Kronenburg 1995). Whilst Fuller might designed houses which addressed his concerns about 'how much does your building weigh' they should not be seen as the panacea to all environmental ills. Imposing a standard-prefabricated building on any landscape raises many other environmental and social questions.

3.8.1.5 Archigram

There have been a number of innovative thinkers in more recent times that have proposed buildings DfD. These include Archigram and the Japanese Metabolism movement. These architects developed schemes that allowed parts of the building to be disconnected from the whole for replacement without interrupting the remainder of the building. Many of these, such as the 'Plug-in City' by Archigram, arranged building parts according to a hierarchy of use, such that parts of the building that require the most frequent maintenance or replacement would be the most accessible (Cook, Chalk et al. 1972). This idea of designing buildings according to a hierarchy of use will be returned to later in this chapter in section 3.8.5.

3.8.1.6 Disassembly at World Exposition's

While most of these ideas never left the drawing board, the international Expo of 1970 in Japan did allow some of these principles to be tested at full scale and the resulting Capsule House and Takara Pavilion were successfully constructed. Like the traditional Japanese timber house, these buildings allowed for the easy removal of parts without interrupting the whole. Continuing with this tradition, the Japanese Pavilion for the 2000 Expo in Hanover, Germany has also been designed by Shigeru Ban to enable disassembly, see Plate 3.1 & 3.2. The structural frame is constructed from cardboard tubes. At the end of life these can be reused, or recycled to make new tubes or any other 'cascade of use' product. They can also be produced *insitu* out of existing waste material and are also being used to provide emergency accommodation in refugee camps (Rogers 1997). A number of the structures inside the Millennium Dome in Greenwich are also constructed out of cardboard tubes. As well as the Japanese Pavilion the Hanover 2000 Expo also featured a number of other buildings that explored the ideas of disassembly. The most notable ones being: The Swiss, Romanian and German 'Green Dot' pavilions.

The Swiss, used lengths of timber, stacked horizontally to form the walls of a labyrinth. These were held in compression by steel rods tensioned by springs. At the end of the Expo the springs are released and timbers could be simply removed and reused for any other building project, see Plate 3.3 & 3.4. The Romanian Pavilion consisted of a steel scaffold frame forming a rectangular building plan, with a laminated timber truss roof, the services being hung around the inside. At the end of the Expo the walls of this building could be easily unbolted and the scaffold reused, see Plates 3.5 & 3.6. The most technically advanced DfD building was the German 'Green dot' pavilion. This building was aimed at demonstrating concepts of reuse and recycling and cyclical thinking. After the Expo it will be de-mounted and go on tour around Germany. The building consisted of an advanced steel frame bolted at the nodes and a spiraling internal ramp. The cladding consisting of glass panels and air filled pillows kept under positive pressure, see Plates 3.7 & 3.8.

While all three pavilions were architecturally very diverse, they demonstrating the wide range of solutions open to the designer of a DfD building. They also embodied some basic DfD principles, they used simple reversible connections, separated the building into layers, used easily identifiable materials and avoided composites.

Plate 3.1 Japanese Expo 2000 Pavilion

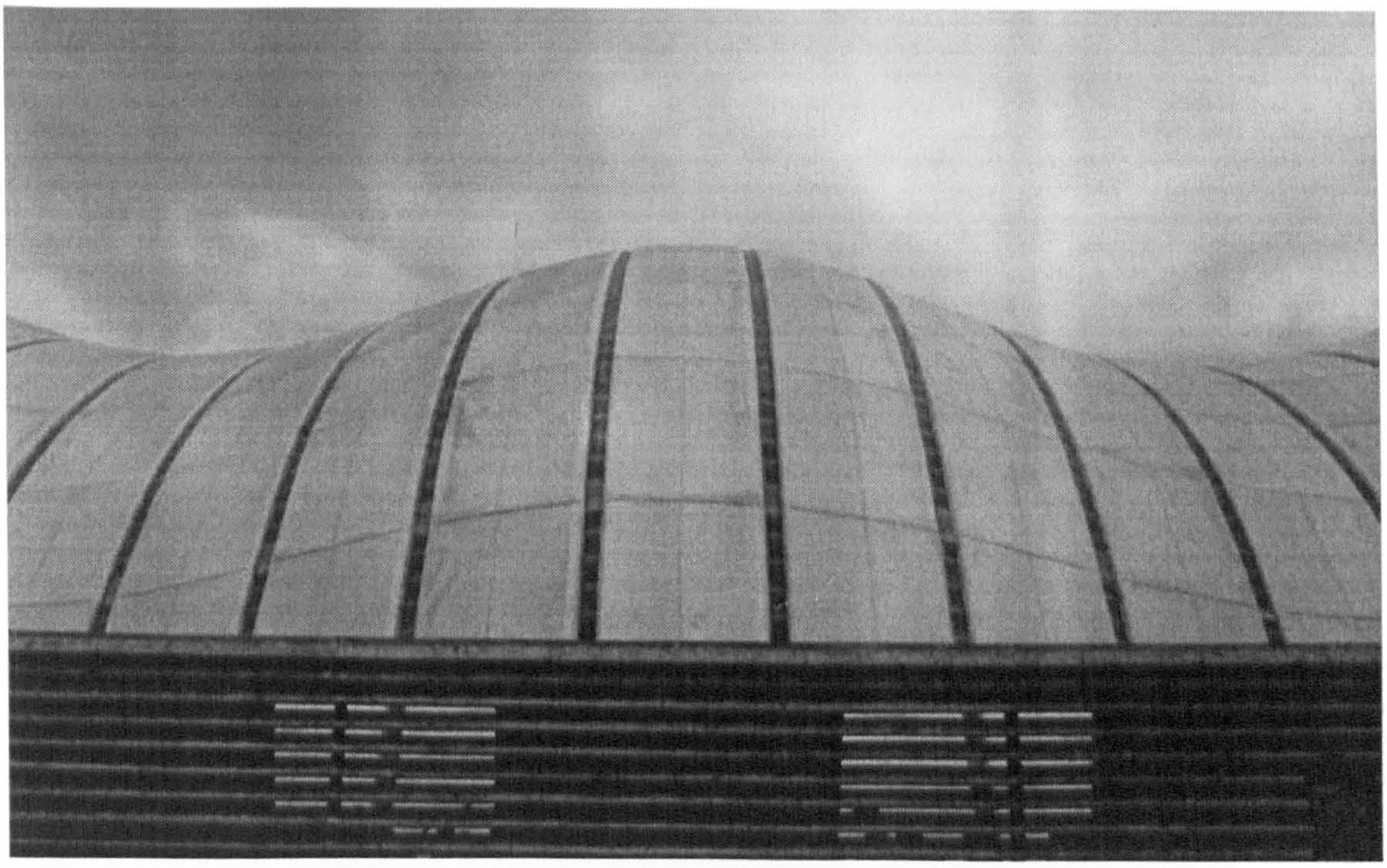


Plate 3.2 Japanese Expo 2000 Pavilion, Internal Detail

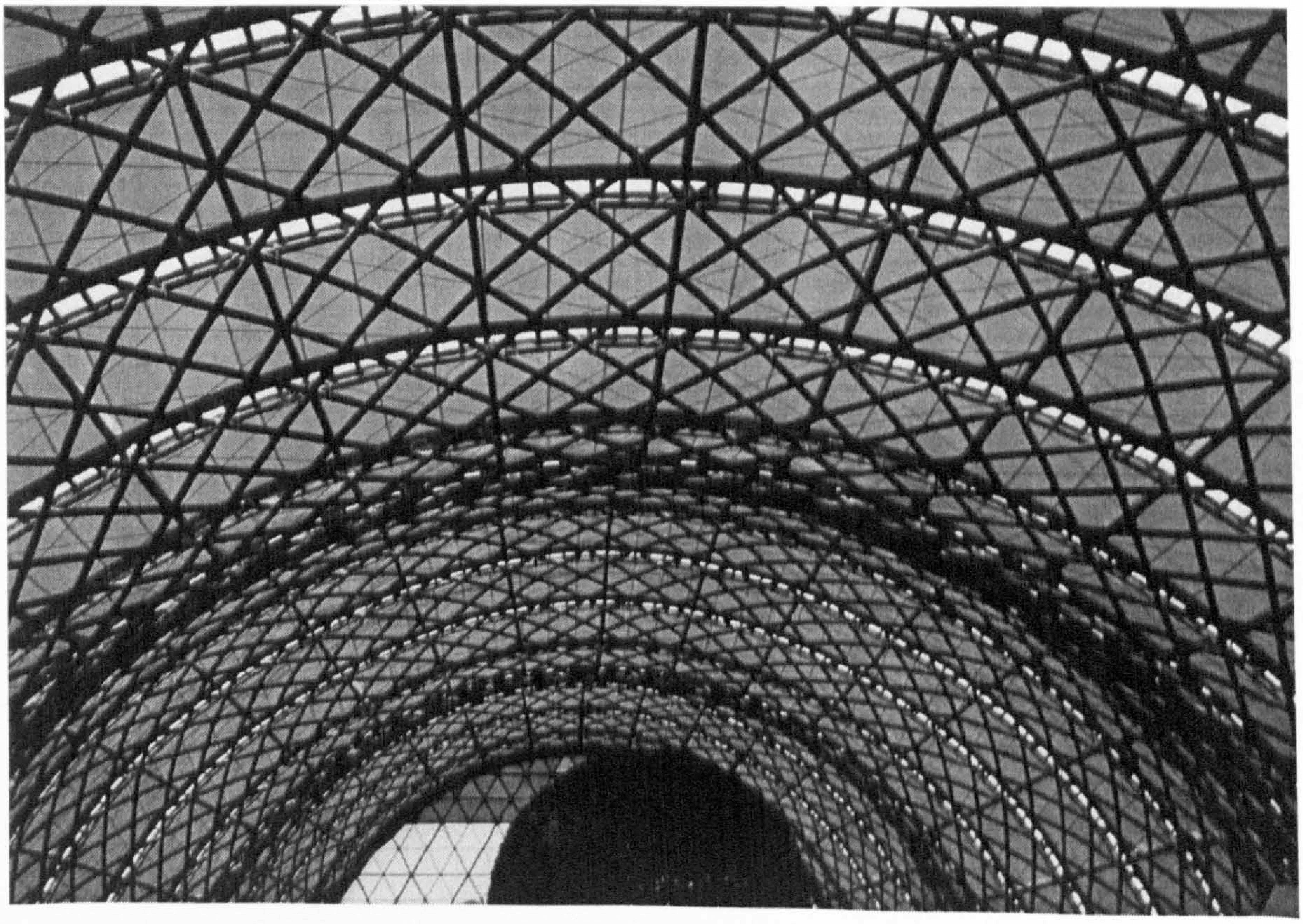


Plate 3.3 Swiss Pavilion

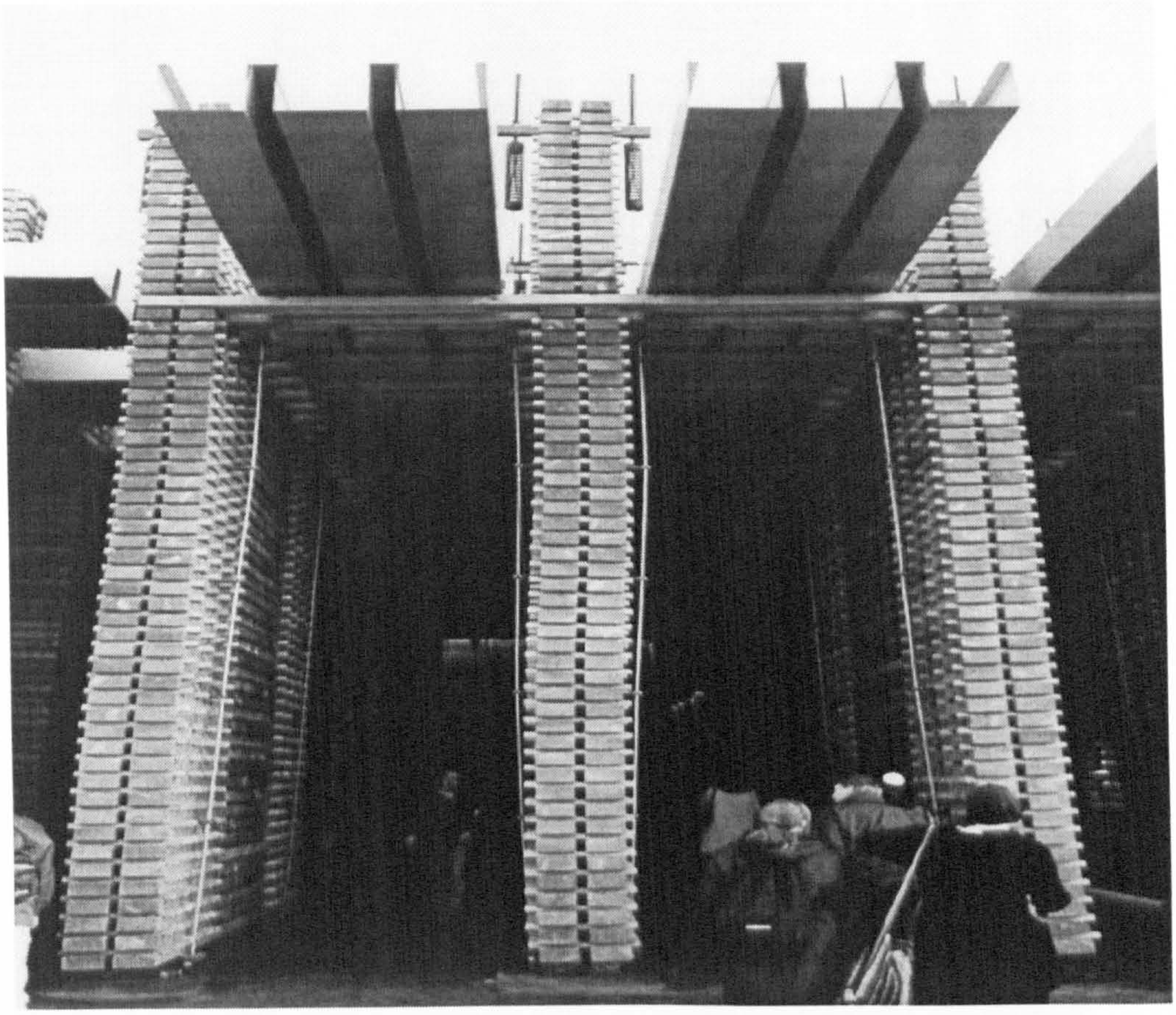


Plate 3.4 Swiss Pavilion, Detail

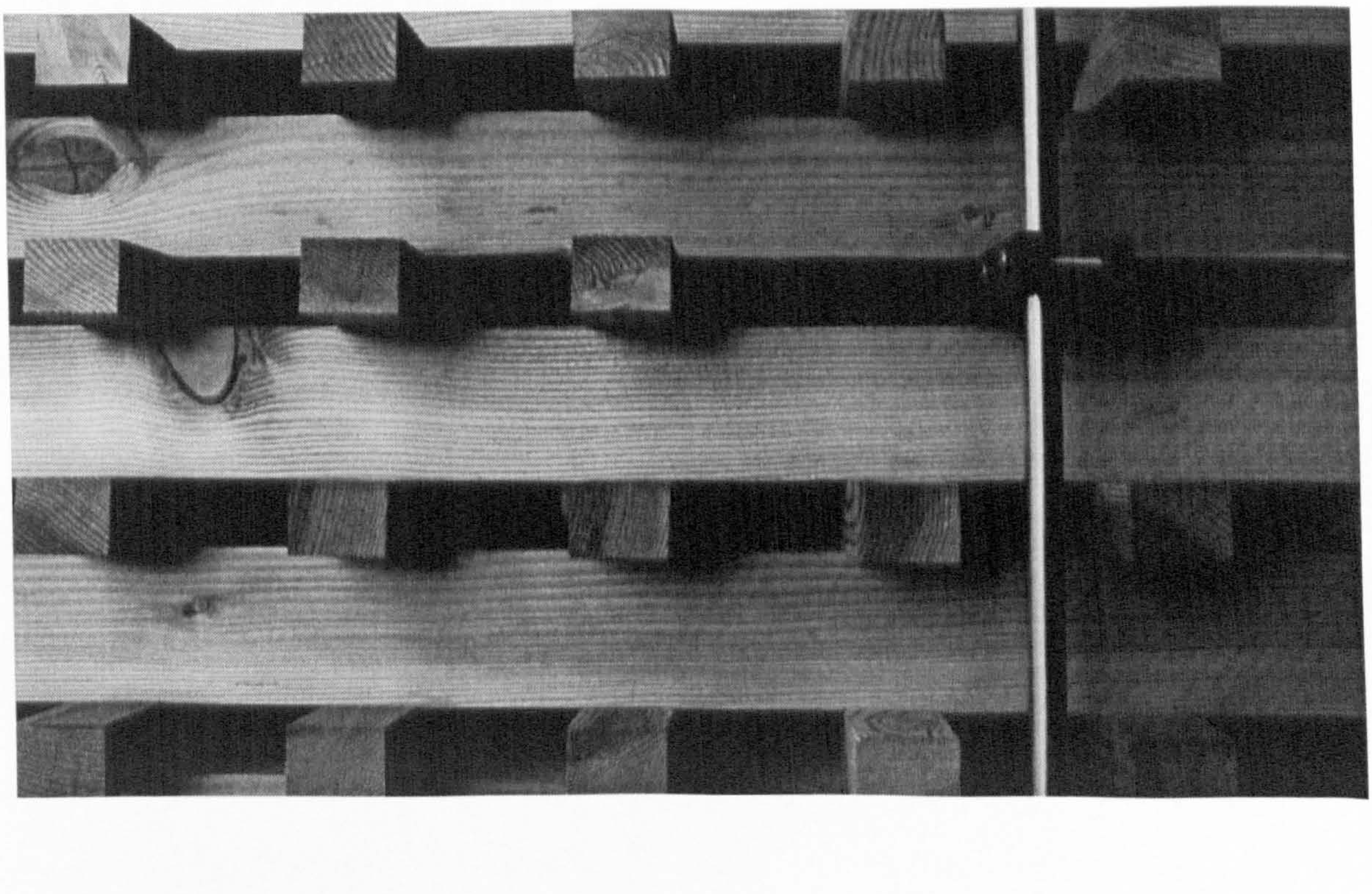


Plate 3.5 Romanian Pavilion

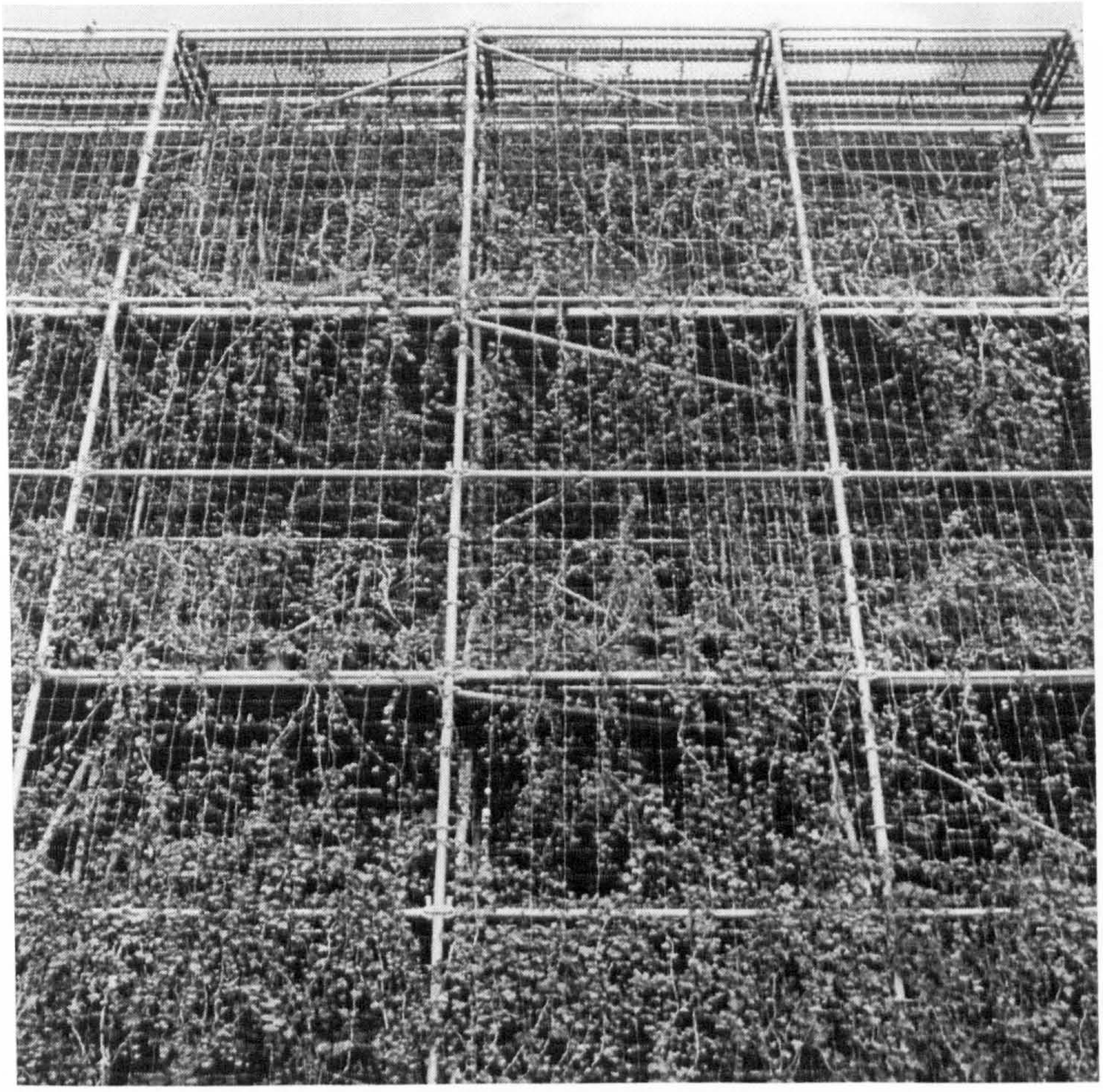


Plate 3.6 Romanian Pavilion Roof Truss

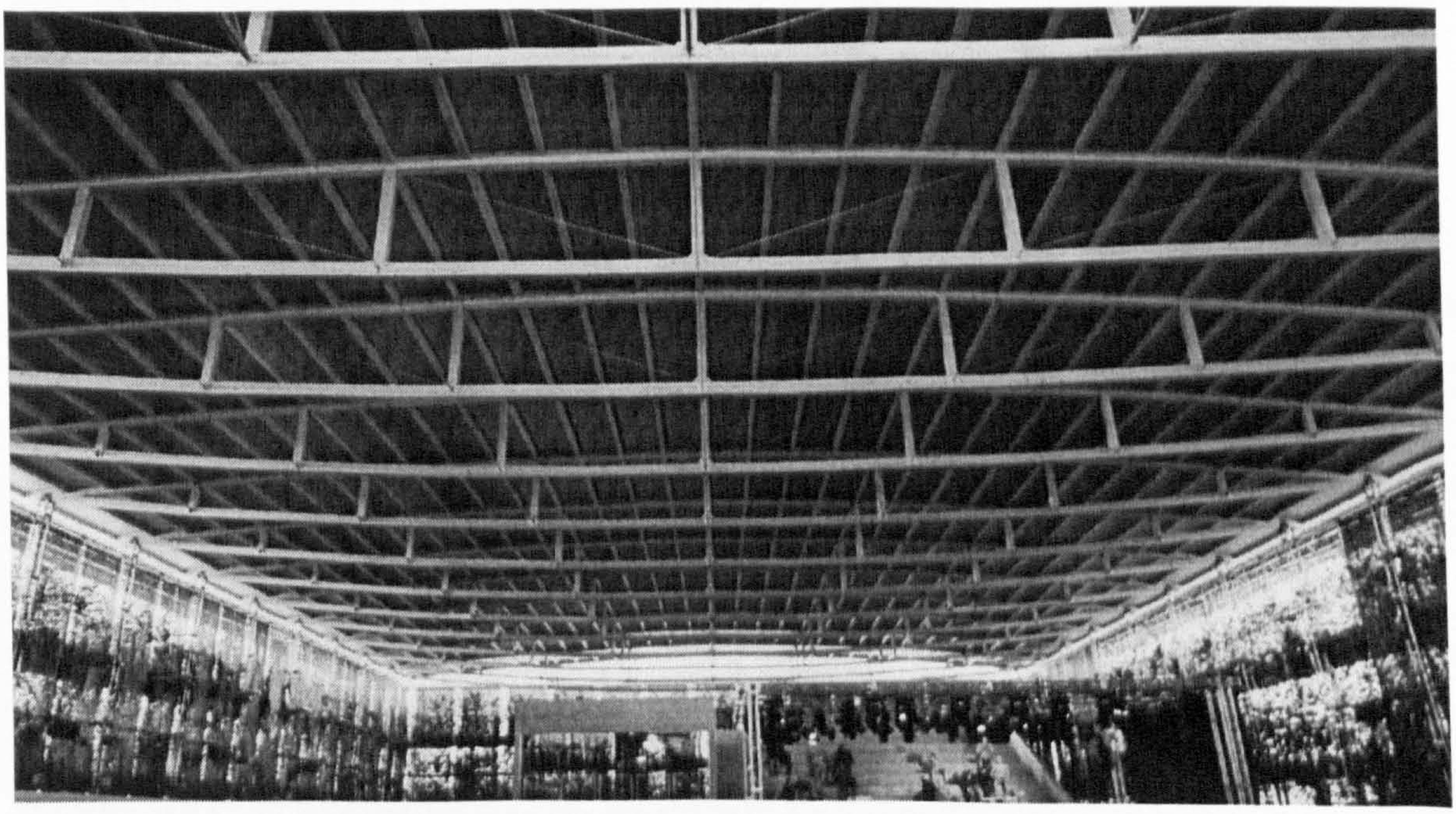


Plate 3.7 German Recycling Scheme Pavilion

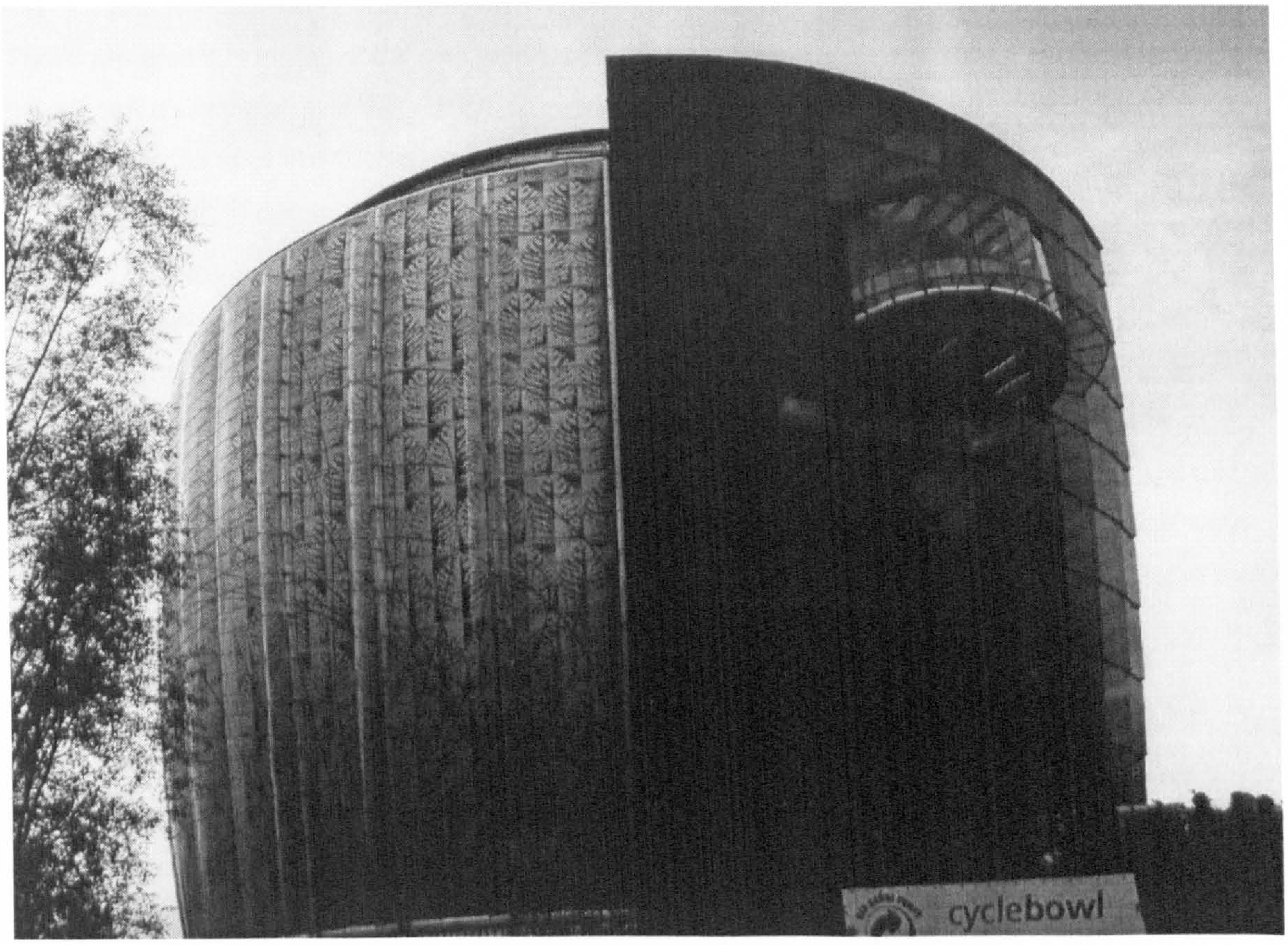
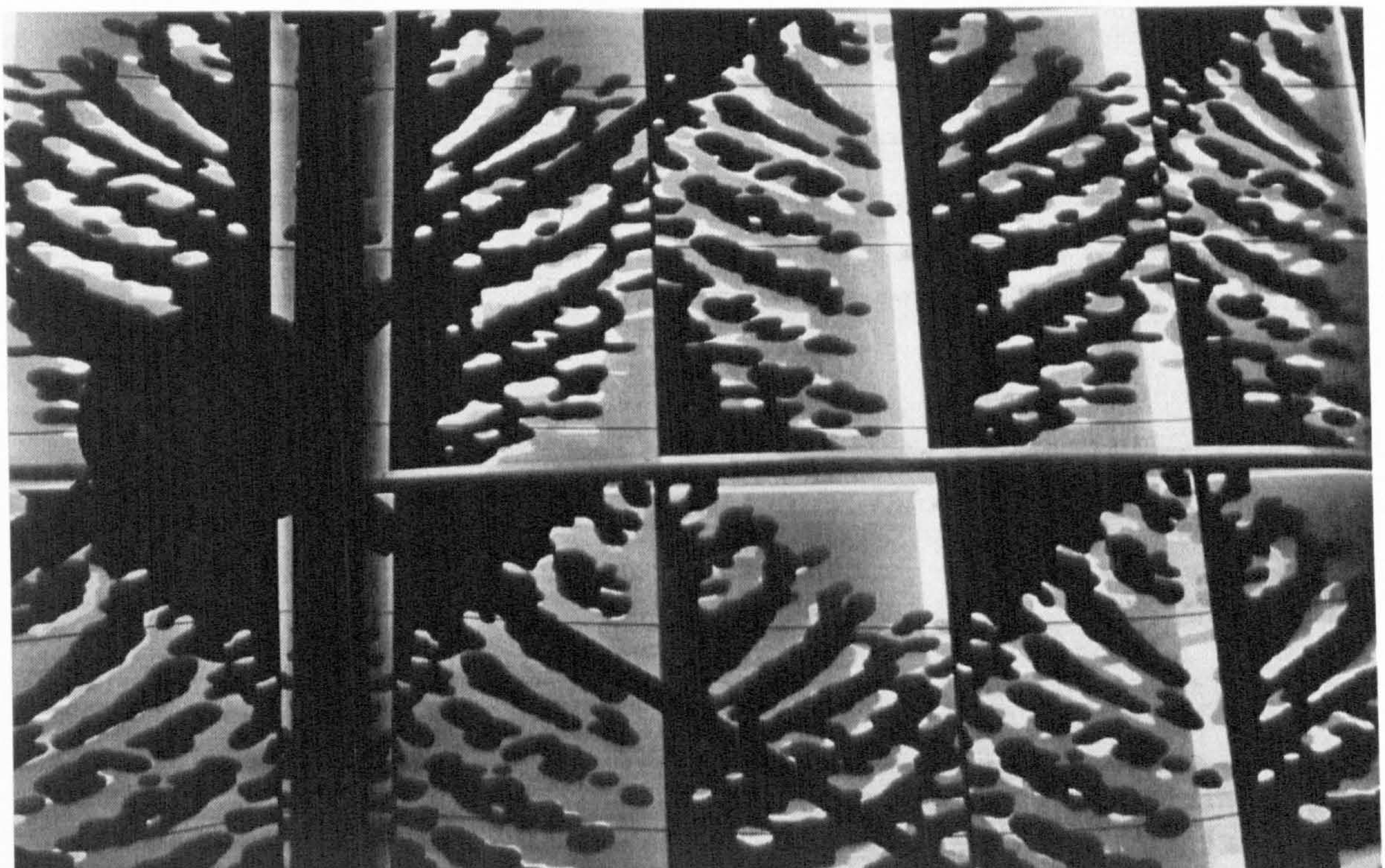


Plate 3.8 German Recycling Scheme, Cladding Detail



3.8.2 UK Examples of Dismantling and Reuse of Materials

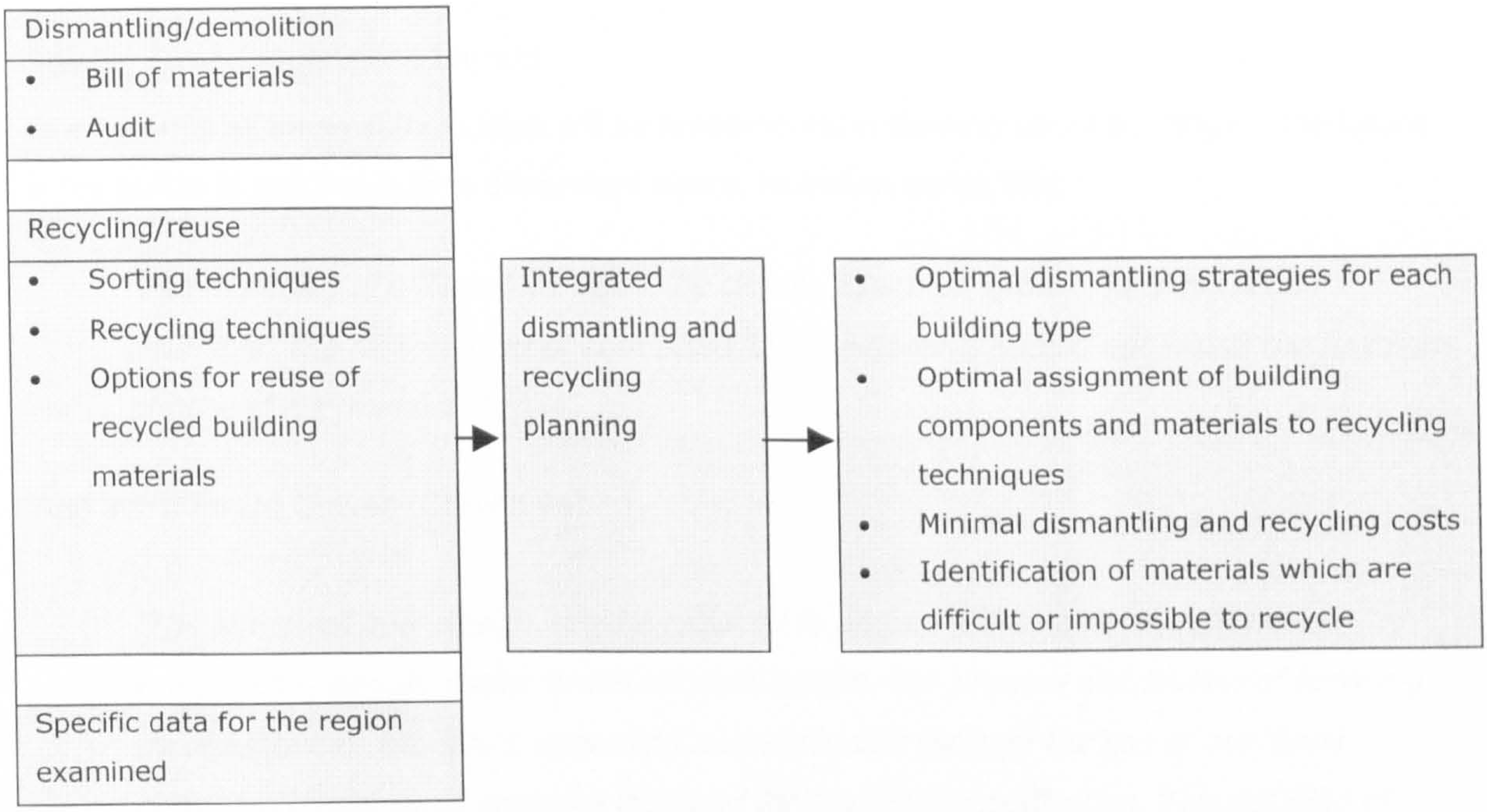
There are also a number of UK and worldwide case studies of recent projects were buildings have been dismantled and the materials reused and recycled. The best-publicised UK projects are the demolition of the IBM offices at Hursley, near Winchester, and the demolition of an existing building to construct the BRE's 'Office of the Future' at Garston, Watford.

In both of these cases an estimated 95% of materials by volume was reclaimed and either reused or the materials recycled at virtually no extra cost to the demolition contract. The extra labour bill being offset by the income generated from recycling credits and the savings from reduced landfill charges. Glass, ferrous and non-ferrous metals, concrete, CFC'c and fuel oil were all recovered, crushed or processed, and only the plasterboard and general rubbish went to landfill. There was very little reuse of elements, most being broken down to their material form and recycled (Evans 1993) (Halliday 1996).

3.8.3 Worldwide Building Recycling Projects

Similar projects in Europe, the USA, Japan and Australia have resulted in comparable recycling rates. A number of these have been discussed at the two 'Building and the Environment' conferences in 1994 and 1997. Marc Ruch conducted a Europe wide study on the state of the art in selective dismantling and compiled the results (Ruch 1997). The main lessons to be learnt from these projects are the need for sufficient time and a sound methodological approach to dismantling. The approach should include a 'reclamation audit', analysis of potential regional and local recycling centres and a detailed schedule of works, see Figure 3.4 below. A 'reclamation audit' identifies the types and quantities of materials present (termed as an asset register above), including fixtures and fittings and suggests recycling options, good as-built records, and maintenance schedules are also necessary for this. However all these examples deal with maximising the recycling yield of existing buildings and not with designing buildings specifically for disassembly.

Figure 3-4 Dismantling and recycling planning system (Ruch 1997)



3.8.4 DfD Methodologies

Several authors have written about this new approach, attempting to define and refine DfD methodologies for the built environment. They all start from the premise that for future sustainability we have to adopt a dynamic circular systems approach, in which the system continually adapts and responds to change. Within this waste becomes a resource, and ultimately the major input into the system (Lawson 1996) p62). Wyatt then goes on to describes the demolition technology as being the antithesis of the construction technology. *"Simply by reverse running the process of construction, (back to the manufacturer if needs be) and looking at a building and its constituent parts we may have far reaching consequences for the transition point of building demolition*" (Wyatt and Gilleard 1994). Craven recommends that a demolition specification should be produced during the design phase along with the construction specification. *"Both would be lodged with the responsible authority, until such time as there was a need to demolish, or alter the building, at which point the document would be made available*" (Craven 94).

However this will not be a straightforward process, as the shear number of elements in a modern building, and the number of bespoke off the shelf processed engineering products is inhibiting to recycling (Wyatt & Gilleard 1994). Not only would the constructional elements need disassembly plans but also all the pre-manufactured components would need identifying and recording along with listings of their suppliers.

3.8.5 Time Dependent Layers

One tool that all these authors think will be fundamental in thinking about buildings in the future is the notion of building in time dependent layers, Hofmann states that:

> *"The materials of different life spans be clearly separated within the construction assembly. The replacement of select building components should not impair the functions of others" (Hofmann 1991).*

And according to Craven (Craven 94):

> *"The structural over-design may be required to accommodate potential expansion without the need for major structural modification; the physical distribution of servicing should allow for the future upgrading and expansion through the use of oversized dedicated cores, again negating the need for structural modification. The detailing of other elements, likely to require upgrading on aesthetic rounds, such as the façade, or internal partitioning should allow removal and replacement without structural disturbance."*

The work of dividing a building up into time dependant layers was initiated by Christopher Alexander (Alexander 1977), and expanded and refined by Francis Duffy (Duffy 1992) and then Stuart Brand (Brand 1994) into the following:

Site	This is the geographical setting, the urban location, site is eternal
Structure	The foundations and load bearing elements are perilous and expensive to change so generally people don't
Skin	Exterior change every 20 years to keep up with fashion, technology etc
Services	The working guts, they wear out or become obsolete every 7 to 10 years.
Space Plan	The interior layout. Commercial changes yearly
Stuff	Chairs, desks, phones etc change daily.
Soul	The person at the centre of all this.

Thinking about buildings in this time-laden way can be very practical as designers can avoid such classic mistakes as solving a five minute problem with a fifty-year solution, or vice versa. Conversely if the ability to change layers independently is not catered for, the slow (more structural) layers with inhibit the quick (internal) layers, and these quick changing layers will tear apart the slow more permanent layers (Brand 1994) p13. This hierarchy of use approach was understood by the traditional Japanese farmhouse, and pragmatic Victorian designers alike, and explored by innovative architects in the twentieth century and is starting to be understood again.

This time layering also defines how a building relates to people, from the individual to society at large:

- Individuals interact at the stuff level
- The tenant organisations (or family) at space level
- Landlord via services and other maintenance levels
- Public via volume of structure and the skin
- And community via site, it does not tell you where to put your desk lamp, the community tells you where to put the building

Thinking of buildings in this was is also about scale linking; from the material, through the product, the room, the building, the city and back again. As discussed in the last chapter, nature operates at all scales and moves effortlessly between them. Human society however, generally interacts only with those on their same scale and time trajectory. Therefore thinking in this time-layered manor may enable greater participation in the design process from the whole of society.

Looking to the commercial world we see that the pattern of time dependant shearing layers is very similar to that described above. The different layers possibly being even easier to identify and give approximate lifetimes to:

Table 3-2 Office Time Dependant Layers (Trebilcock 1996)

LAYER	LIFESPAN
Site	Permanent
Structure	30-100
Skin	15-25
Services	8-15
Space plan	2-10
Stuff	Always changing

Acknowledgement of the time-dependent shearing layers within a building frees us up to think about new ways to save resources. This allows the building to be sensitive to future demands – changing with the ebb and flow of use. Without such a focus, buildings quickly become obsolescent, and are then either neglected and abandoned or eventually pulled down and replaced at significant environmental cost.

In the increasing 'churn rate' world of office buildings, thinking in layers could mean that the external skin could be replaced, with an energy efficient or even energy producing cladding system, incorporating a new corporate image, without destroying part of the structural frame or services. Alternatively the services could be upgraded, to allow more ICT communications, without ripping out all the internal finishes. And these fast changing finishes themselves – the partitions etc. - could be changed with minimal disturbance, as firms move from cellular offices to 'hot desking' (Jaunzens and Willis 1998). There is also the trend to change the function of buildings from industrial to residential and commercial. As a result of this there is a growing perception that buildings must be adaptable to both short-term internal fluctuations and long term external changes in use (Greenberg 1994).

The British Council for Offices (BCO) (Offices 1997) has reached similar conclusions in its best practice document for the specification of offices. This was published to counter the *"mistaken belief that high levels of specification made buildings more flexible to meet occupier needs and created greater value. In some instances the opposite was achieved. Therefore the document sought to revise these standards to match more accurately the needs of the occupier and to provide real flexibility and adaptability for the future."*. The BCO guidelines offer parameters for architects to design within, so providing flexibility for the future. The report does not discuss how this achieved, in order to implement these changes some means of taking the building layers away and changing them is required. This is dealt with by the Design for Disassembly criteria developed in this research.

3.8.6 Durability

Once the time dependant layers of a building have been established there is then the question of how you match material life, with component life with actual product life span in use- the appropriate durability. The life of a building and its elements is determined by a complex array of factors any number of which can render it obsolete. With the exception of historically or culturally important buildings, all become obsolete in time, and Golton (Golton, Hiley et al. 1994) has identified the main influences on their life expectancy, these are: structural, economic, functional, social, fashion and technological.

Looking at these in turn, a building becomes obsolescent structurally if its main frame fails during its use. Economic obsolescence occurs when the building's value decreases to such an extent that it becomes a liability rather than an asset. With function obsolescence the building is unable to perform its required role, this often occurs with organisational changes, ie moving from open plan to cellular office or vice versa. Social obsolescence occurs when a building becomes undesirable for human use, either through failings in its design or a degradation of its neighborhood. Linked to this is fashion, if either the aesthetic of the building or its location become outdated or unfashionable then a building can quickly become obsolescent. Finally technical obsolescence results when a building cannot accommodate the latest advances in services. For example, the increased use of electrical and electronic equipment in offices necessitates a high level of cabling and also increased ventilation to remove the excess heat and many offices do not have the floor to floor height to accommodate such service changes. These range of factors are similar to the obsolescent factors for a product, identified by Tim Cooper, as component, technical, psychological and economic (Cooper 1994).

The regular joining within the same element, of materials with vastly different lifespans highlights the issues of appropriate durability. Taking PVC double glazed windows as an example. The PVC framing has a life expectance of between ten and twenty years, the glass fifty plus, but depending on the vacuuming technology this may be reduced to even five. The cladding system as a whole can have a whole range of life expectancies. The mastics and sealants used usually need replacing between five and ten years (Lawson 1996) p63 & 66. Clearly this is an unsatisfactory position, a more rational and consistent approach is needed, matching materials, fasteners and sealants with a similar life.

Wyatt & Gilleard (1994) define durability as optimum material usage, or the functional capacity of the material, most they comment are not tested to their limits in use. There is a need to exhaust material components useful life before throwing them away, therefore conserving natural resources. They go on to ask how we are to duplicate nature's degradation technology, nature's systems approach? Their proposed answer is to adopt adaptive systems, which are resilient and open to change, instigating environmental stewardship, and resulting in a more positive environmental building action. This is echoed by many authors, all championing dynamic flexible or adaptable buildings and repeats the earlier argument of this thesis:

> *"If the building was originally designed with an inherent flexibility then refurbishment may prove to be an economically viable alternative to demolition and reconstruction, resulting in a significant reduction in the levels of waste generated" (Craven 94).*

3.8.7 Permanent or Ephemeral Designs

There is also the question of choosing between materials for either a short or long term building life span. For example, a new school on the south coast of England has been designed from primary cardboard components. The aim was to build using 90% recycled materials, which are 90% recyclable at the end of the buildings life. The school has a short life expectancy and the technology is intended to be especially for buildings where the waste of high quality, high price materials is particularly inappropriate (ENDS 1999f). Alternatively recycled and recyclable high quality (price & embodied energy) materials could have been used (for example metals), which would be virtually guarantied recycling at the end of life. The debate on the merits of each approach is likely to continue for some time. The merits of the low value recycled materials have been raised recently with the construction of the refugee shelters designed by Japanese Expo architect Shigeru Ban. For these, basic machinery is transported to the camp which then turns local waste fibrous materials into structural cardboard tubes from which the shelters are constructed.

3.9 Conclusions

The environmental impacts of the building industry, during extraction and construction, though use and to eventual demolition are huge and possibly the largest singe area of concern when considering future sustainability. Until recently the final stage, that of demolition, had been given little thought, with most research focusing on minimising the impacts of construction and operation. However, the impact of the demolition phase has also been shown to be of significance and as most decisions about a materials fate happen at the design stage, long before the material becomes waste, it is important to integrate dismantling information into the design process. The advent of the DfD concept enables a more proactive 'designing out of waste' approach to be taken. The two tiered DfD approach adopted by the product industry has been reviewed and expanded to account for the physical scale and variable time dependent layers of buildings.

What is interesting, relating to the systems viewpoint as defined in the previous chapter, is that each approach is looking to move away from a linear and towards a circular system, with 'wastes' being a future building's raw materials. Definitions of specific lifetimes and appropriate durability then become blurred as materials continually flow around the system. For this to work within the built environment the two level concept of DfD must be preceded by a systems level. So DfD then becomes a three level approach:

1. **Systems level: Adaptable buildings which can change to suit changing requirements;**
2. **Product level: The products (or layers) of the building are designed to allow upgrading, repair and replacement. The replaced products can then enter the replenishing loop;**
3. **Material Level: When a product has been stripped back to its constituent materials these can undergo recycling.**

To assist those designing within this new systems approach, a detailed range of strategies must be defined. This is the objective of the next chapter, which presents the analysis of an in-depth case study with demolition experts.

4 DEMOLITION CASE STUDY EXPLORATORY EXPERT INTERVIEWS

4.1 Introduction, Aims and Structure

This chapter presents the empirical findings gathered through exploratory in-depth interviews with fourteen demolition experts. As shown in the previous chapter, most existing research on demolition has generally been concerned with reducing waste after it has arisen, instead of designing it out of the system. Also notable in its absence from current building waste related literature, is information from the demolition sector itself. There is little if any literature on; what demolition contractors actually do, how they do it, and what their views are towards the industry now and in the future. Addressing this situation and so defining strategies for designing waste out of the system is then the core goal of this chapter. This has been divided into the following aims which are to:

- **Identify the pressures and barriers inhibiting reuse and recycling;**
- **Define which materials are reused and reprocessed and which cause problems;**
- **Identify the actual demolition process;**
- **Gain insight into the future of the industry, and most importantly;**
- **Investigate strategies that would ease the disassembly and enable reuse and recycling of buildings, their elements and materials**

The chapter opens with a summary of the research strategy adopted. The findings from the interviews are then presented, grouped by respondents reply's to the evolving questions. Information and knowledge from the previous chapter has been inserted here to extend the discussion on the issues raised. The chapter concludes with a summary of the DfD strategies identified through the interviews and arranged within the three systems level model of the previous chapter

4.2 Research Strategy

4.2.1 Type of Enquiry

This chapter is concerned with providing a contribution to knowledge about the demolition sector of the construction industry, particularly with regard to DfD, which is a major focus of this research. It is intended to develop a detailed intensive knowledge about a number of related cases by asking exploratory 'How' and 'Why' questions. The aim of these is to qualitatively find out what is happening, to seek new insights, and assess the current building demolition situation in new light. Of the three main traditional research strategies listed below the case study approach is the most suitable to this work.

- **Experiment**: measuring the effects of manipulating one variable on another variable.
- **Survey**: collection of information in standardized form from groups of people.
- **Case study**: development of detailed, intensive knowledge about a single 'case', or of a small number of related 'cases'.

A case study being defined as:

> *A strategy for doing research which involves an empirical investigation of a particular contemporary phenomenon within its real life context using multiple sources of evidence. (Robson 1993) p5*

The important points to note from this definition are that; a case study is a strategy or stance, it is concerned with research and reliant on the collection of evidence about what is going on. It is about a specific case, which is examined in situation using multiple methods of data collection. The design of the case study needs to provide the link between the questions being asked, the collected data and the conclusions drawn. If the purpose of the case study is to confirm pervious work then a detailed pre-structured case study is required. If however, as is the work to be undertaken in this chapter, the purpose is exploratory, trying to get a feel of what is going on in a novel situation, then tight pre-structuring is not possible. In practice most case studies fall somewhere between these extremes and to be recognised as an approach to exploratory research its design must consist of the following stages (Robson 1993) (p146-150):

4.2.2 Tactics of Enquiry

The case study has been conducted through semi-structured/focused interviews. Three types of questions were asked of the interviewees: What they know (facts), what they do (behavior) what they feel/think (beliefs & attitudes). This approach allows the interviews to be flexible and evolve as more information becomes available.

4.2.3 Sampling strategy

Interviews where sought with demolition contractors who represent the leading edge of their profession. To identify these, the two national demolition institutions were contacted and requests made for suitable interviewees. The first institution is the National Federation of Demolition Contractors (NFDC) who register approved demolition firms upon reaching and maintaining; quality, health and safety and working practice criteria. The second institution is the Institute of Demolition Engineers (IDE) who register individual engineers, again showing a professional approach to their work. From these two institutions the following demolition experts agreed to be interviewed: The National Secretary, former President and current Vice President of NFDC, the NFDC Demolition contractor of the year (1998/9), the President, current vice president and future president and vice presidents of the IDE.

Interviews where also arranged with the UK's leading private waste management consultants, demolition experts within the three UK research organisations (BRE, CIRIA , BSRIA), the Environment Agency, and the UK's largest producer of construction aggregate and waste material processors.

Altogether 14 interviews where conducted, these represent an in-depth exploratory case study across a sample of demolition experts, as such they are not representative of the whole demolition industry. However, as the interviews developed there was strong consensus of opinion from the interviewees in their responses, and it is unlikely that many differing views would have been gathered from conducting additional interviews. See Appendix A for a list of interviewee's and companies.

4.2.4 Method

The basic questions where first sent with a covering letter confirming the arrangements. The interviews were themselves recorded on tape with the consent of the interviewees and additional hand written notes made. The opinions and stance of the interviewer were made known at the start of the interview to avoid confusion or conflict. The tape was left running after the questions had all been asked, and the interviewees where asked to give any more comments, opinions or additional contacts. This information is included within the transcriptions of the interviews, which where sent to the interviewees afterwards for verification before being included within the text. None of the interviewees requested any changes to the transcripts. Two of the interviews where conducted via email, which involved discussion of the questions two at a time.

4.2.5 Set of questions

In keeping with the aims of the research the questions where focused on identifying;

- the pressures and barriers to recycling,
- the construction types which inhibit recycling,
- the demolition process,
- the likely future of the industry, and,
- strategies to enable DfD.

In the first-pilot interview questions were asked on these five topics, these were then refined and expanded to the 14 listed below. As the interviews were semi-structured the topics under discussion were not always addressed in order and in some instances they focused on particular areas that the interviewees had in-depth knowledge about. Questions missed were returned to later and checked off against the list. However some questions were not relevant to all the interviewees and so not discussed in detail. The questions asked are listed below along with explanation's concerning their relevance to this research:

1) **What are the pressures on demolition contractors?**
2) **What are the barriers to increased element and material reuse & recycling?**

These first two questions were aimed and acquiring an overview of the interviewee's knowledge of the demolition industry. They also encouraged interviewee's to begin to focus on the issues concerning the current reuse and recycling of materials.

3) **How has the Landfill Tax influenced the demolition procedure?**

One of the primary aims of the Landfill Tax was to increase recycling rates by raising disposal charges, however it has been reported to be of mixed success. This question asks demolition contractors directly for their experience with the tax and examines whether tax alone will be enough to encourage increased recycling rates.

The design and construction of buildings is becoming more complex, the next two questions assess whether this is reflected in the approach of the demolition industry.

4) **Is the nature of demolition changing?**
5) **What are the differences in demolishing Victorian to more modern buildings**

Questions six and seven are aimed at discovering first hand, the pre-tender role and actual stages of a demolition project. This is important as it indicates how and when disassembly strategies could fit into the overall demolition programme.

6) **How do you approach a demolition project?**
7) **What are the stages of a demolition project?**

The questions now turn to focus on more specific details, with a view to identifying possible ways to take buildings apart. Question eight looks at the disassembly of the two main structural building materials, steel and concrete. If these materials are to be more effectively disassembled then it is important to understand the current techniques used.

8) Describe the different Demolition techniques and approaches for different building frame types ie steel, concrete or composite?

Question nine identifies existing easy to take apart elements and question ten the opposite- those that cannot be disassembled. Taken together these two questions offer the polar extremes and a good starting point from which to develop DfD strategies.

9) Which building type is quicker to demolish, and results in less waste?

10) What are particular problem elements?

Question eleven aims to discover which buildings change structurally over their lifetime, this has implications for DfD and the concept of building in time dependent layers.

11) Do buildings structurally change over their lifetimes?

Question twelve looks to the future and the likely changes to demolition practice to see if this will increase recycling rates.

12) How do you see the demolition industry operating in the future?

In question thirteen the interviewee's are asked to identify strategies that, from their experience, they think would enable dismantling and reuse of elements and recycling of materials. This is the main goal of the research and it is included at the end of the interview to ensure that the interviewee's had time to familiarise themselves with the issues and develop their opinions about disassembly.

13) How could buildings be redesigned to enable easier/quicker demolition/dismantling?

Finally in question fourteen the interviewee's are asked for any other information that they see as relevant and not already covered, and also for additional contacts they recommend be included in the research.

14) Any other issues/contacts

4.3 In-depth Demolition interviews

4.3.1 Question 1: What are the pressures on demolition contractors?

A number of different pressures where identified, all interviewees highlighted time and money as the main ones. The next major issues were perception, information, location, and health and safety followed by client perception, and risk.

> *"The main pressures to increased reuse/recycling are those of time and cost, any demolition is a balance between time, the value of the material, and issues such as location (city or rural), country (developed or un-developed economy) and labour (skill and price). For materials to be extracted they would need to be easily removable, maximising the time and minimising the human effort." (Scott-Wilson Kirkpatrick)*[3]

4.3.1.1 Time & Money

Time is inextricably linked to money, both in terms of that allowed for the demolition contract as a whole and as the deciding factor as to any material's fate. No time to dismantle re-useable materials simply means no materials for re-us and recycling.

> *"In terms of running demolition contracts, from the perspective of maximising the opportunities to reclaim or recycle materials, the over riding factor is likely to be the time constraint between receiving a contract and delivering the site for onward development." (Tarmac)*

Due to developer pressure the main emphasis is now on demolishing as speedily as is safely possible. As such demolition contracts have gone from six months to six weeks duration. If more time was available recycling might increase but the bottom line is economic: labour is expensive and new products are now cheap.

In some isolated cases demolition firms have offered two very different tender fees, the difference between them being due to the quantity of material recycled. The first for say a million pounds and down in six weeks and the second for a hundred thousand pounds and down in six months. In the first case expensive plant and a large labour force is used to demolish the building quickly and remove it from site, this allows little time for separating the materials and so these are landfilled incurring heavy charges. In the second, the demolition contractor proposed to use a smaller workforce which, over a longer time frame would methodically strip and reduce the building, salvaging and selling on as many elements and materials as possible.

> *"No time to dismantle re-useable materials, means simply no materials for re-use. It is criminal to see on job after job, massive quantities of valuable and often unique materials being collapsed to the ground and bulldozed into skips, simply because there is not time to do anything else." (Detech Environmental)*

Time is then a key factor in determining a materials fate. To increase the potential for reuse and recycling, either the demolition contract needs to be lengthened or the actual demolition process simplified, enabling faster disassembly. This points to DfD as a key strategy in simplifying the disassembly and therefore reducing the on site time required to dismantle buildings.

4.3.1.2 Alternative Recycling Routes

Two alternative routes were suggested by interviewees to increase recycling rates, both with advantages and disadvantages.

The first was to increase the on site recycling, by allowing more time or legally enforcing the separation of materials. Segregation of recyclable materials by selective demolition is seen by many across the industry as essential to ensure higher recycling rates. Against this will be the increase in contract time and so labour costs (at least in the short term). Also the local environmental impact will be increased with noise and dust levels rising which are a constant complaint to the industry particularly in urban areas. On the positive side recycling on site will provide 'new' resources where they are needed with minimum transportation.

> *"Generally it is cheaper and more economic to crush on site, than sending it away to a recycling facility". (Buttons)*

The second, suggested by contractors with space and facilities at their storage yards and also by firms with waste transfer operations, was to remove the materials from site and sort/separate and repackage these at a remote dedicated recycling site. Issues here are mostly centred around transport and time, this kind of operation would require large numbers of truck loads which particularly for bulk low value materials increases costs and environmental impacts. Conversely it would remove the environmental impact from the site and reduce the time pressures on contractors. However many demolition contractors are sceptical as to the motives underlying this scheme.

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[3] Direct quotes from interviewee's are included in the text, in each instance the company name is given in brackets.

> *Off site recycling centres set up by the quarry industry are maybe more in response to the proposed aggregate tax than a genuine increase in environmental awareness. (Buttons)*

Whilst the benefits of recycling are clear it should be noted that recycling of materials is not without it's own environmental impacts. These are somewhat similar to quarrying, but as most C&DW arisings are from urban areas they have the potential to affect more people. The main impacts are: noise, dust, air pollution, surface and groundwater and visual and aesthetic pollution. Transport impacts are similar to that of quarrying except where recycled materials are reused on site of origin when they are negligible.

4.3.1.3 Perception

Contrary to popular belief, demolition is the start not the end of most building projects, particularly on inner city or brown field sites. As such it needs to be fully integrated with the future works program, not as it often seems, perceived as an obstacle to be quickly overcome before building can commence.

When presented with a brief to design a building, most architects start with the visualisation of a clear site (Plate 4.1) and end with the newly constructed building. If reuse and recycling is to be encouraged there is a need to change this approach and include the demolition phase.

Plate 4.1 Clear Site

Projects should start with demolition phase and consider its incorporation into the new building and end with the potential for the elements of this building to be included within the next reincarnation (redevelopment).

4.3.1.4 *Information*

All interviewees suggested that to increase reuse and recycling rates more information was required. The emphasis here being on the quality not quantity of information available to the demolition contractor. Quality information can speed up both the pre-tender and main demolition contract, and allow pre-determination of waste and recycling routes. This should include:

- As built drawing records;
- Records of all changes to the building;
- Asset registers showing what is in the building and its recycling potential;
- Identification of potentially hazardous materials;
- If prefabricated elements were used details of these plus fixing and carrying points; and even
- Labeling of materials.

CDM regulations are starting to improve this situation. We live in a society that is increasingly geared towards and driven by information and this is equally relevant to the building profession. The question is maybe more, how are we going to store the relevant information so that it can be read in 100 years time?

The growing use of computer aided design drawing packages, email and the world-wide-web can all facilitate this. The future scenario could be that all information for a building is contained on a web site. Whenever it is updated or changed these alterations have to be submitted to the site. At the end of life the demolition engineer downloads the info to find not only the structural plans but also the changes and the quantities of each material within the building.
This site could also contain lists of the suppliers and the product manufacturers enabling links to be established for product take-back. However many issues around management, maintenance security and access to the information and continuity of suppliers would have to be worked out before such a facility could be operational.

4.3.1.5 *Health & Safety*

Health and safety legislation is becoming more restrictive. It has resulted in safety standards being raised across the industry but possibly has had a detrimental effect on reuse and recycling as working practices become more controlled.

> *"Health & Safety has made recycling harder but legislation is there to protect and be adhered to so companies must adapt, it has also improved standards and training of site operatives and managers, courses are now available at every level." (NFDC)*

Working at height or in dangerous places, removing slates from a roof for example now requires full scaffolding and boarding out. This is prohibitively expensive and so most contractors would try and use more remote methods which usually implies less separation and selection of individual materials resulting in less recycled material.

> *"H & S if anything has reduced recycling due to the added restrictions and legislation placed on contractors. These significantly add to the cost of a project. Increased personnel risk is another factor. Particularly with reclaiming roofing materials and bricks at high level, the safety risk to operatives is much greater than simply demolishing remotely. Therefore the potential for accidents must be weighed up when considering recycling." (Connell Brothers)*

However new machines and demolition procedures are being developed all the time, enabling efficient recycling while obeying all health and safety legislation.

4.3.1.6 Location

The location of a site affects the demolition contract in a significant way. It basically controls the type of demolition carried out. For inner city or urban sites full protection from the surrounding area must be provided. Strict site operation times, noise, dust, space and transportation guidelines will be placed on the contractor. This usually results in a more controlled slower demolition but one in which the time considerations are paramount and space on site is at a premium.

> *"For inner city you fully scaffold, and use a tower crane and mini excavators demolishing floor by floor filling skips with separated materials, which are removed by the crane." (McGee's)*

For rural demolition away from urban development control is less onerous. Demolition could be conducted using explosives, bringing the building to ground level very quickly. This involves minimal separation and therefore results in minimal, low quality recycling. Alternatively a slow and methodical approach could be taken, with time and space available to separate out materials and locate potential markets for them. This is often aided by the fact that labour rates are cheaper out of urban areas, therefore skewing the economics in favour of recycling.

"Traditionally and for a site away from the city you can fully enclose the building and demolish mechanically with say ball and chain techniques. This is the more old fashioned method and leads to minimal recycling." (McGee's)

4.3.1.7 Client Perception and Risk.

The perception of demolition as a public nuisance does not help the image of recycling. Clients, in an effort to minimise adverse publicity will usually desire the demolition phase to be as rapid as possible. For the positive perception of recycling to grow the benefits need to be sold to the clients and then through their public relations departments passed on to the public, enhancing the profile of the firm.

In some European Countries, such as Germany, sector wide voluntary agreements (VA's) have been reached with the backing of all developers/clients involved with large projects. These are aimed at encouraging selective demolition on big sites. In some instances they are supported by the threat of regulation if ignored, somewhat forcing the developers hand.

There is also an inherent risk associated with recycling materials. The possibility of finding toxic, or non-recyclable materials bonded to recyclable ones is often very great. This destroys their recycling potential and if the job was priced according to this creates major contractual problems. Who takes the risk for this possibility?

"Currently, I am dealing with the removal of 200 tonnes of aluminium curtain walling framework from a large commercial building; a most valuable and recyclable commodity. However, its overall value as scrap metal has been reduced by more than £40,000 because the hollow sections of the framework are filled with insulating foam, no doubt a design requirement." (Detech Environmental)

"Risk, Who takes the risk associated with recycling materials? If the client is prepared to take it, the demolition contractors will be more inclined to recycle, if contractor must shoulder it the costs will be higher as unknowns have to be covered." (Bagnel Group)

4.3.2 Question 2: What are the barriers to increased element and material reuse & recycling?

All interviewees identified a number of barriers to reuse and recycling, these can be summarised as follows:

- Legislation and control
- Infrastructure, insufficient to support various economic material recycling
- Unstable markets and variable demand and supply
- Lack of Cost differential between recycled and virgin
- Appearance, quality, acceptance, standards.

Many of the issues here are linked and the general opinion was that some level of government intervention was needed to boost the market for reused and recycled materials.

4.3.2.1 Legislation and Regulation

As discussed above, legislation & regulation is not only pressurising the demolition phase of a contract it also currently appears to be inhibiting the amount of material reused and recycled.

> *"One of the main issues is the pressure placed on the contractor pre-tender, Quantity Surveyors and H & S are increasingly prescribing what happens, further restricting reuse and recycling." (Connell Brothers)*

Contractors felt that the amount of pre-tender information required was impeding, detailed reports where needed, incurring great expense before the contract was won. However, the industry traditionally has had little regulation and therefore providing detailed pre-tender information may just be bringing it inline with the rest of the building profession.

> *"The problem of dismantling, recycling and re-using key construction materials do not lie with the practicality of completing the task, that is the easy part. The problem lies with the attitude of the Regulators, the Client and the Architect." (Detech Environmental)*

4.3.2.2 Infrastructure Markets, Quality and Standards

The recycling of building materials and in-fact all materials in the UK is somewhat ad-hoc and lacks the logistical and financial support needed to turn it into a major industry. For recycling to become main stream the infrastructure to separate, store, transport, market and manage the goods must be radically improved.

> *"The industry is old fashioned and has a 'watch your back', self preservation and somewhat dark history, this doesn't help perception of recycled materials. The other main barrier are the markets for recycled materials, at present these are unstable and fluctuate*

wildly as do the reclamation markets, contractors won't spend time separating materials if the benefits are only marginal. There are also no standards which covers the reuse of reclaimed materials, danger of quality and liability in event of failure." (Building Research Establishment)

Due to the lack of infrastructure, the fluctuating price paid for recycled materials and the inconsistent quality of recycled materials, contractors are wary of recycling and using recycled materials, and customers are dubious about buying them.

"There are issues of perception, quality and quantity here.
Perception. Willingness of client, public etc to accept reused/recycled materials
Quality. Reliability and safety of reused/recycled materials, and liability in event of failure.
Quantity. Often insufficient quantity of any one material at time of use and unreliable markets." (Scot Wilson Kirkpatrick)

A number of initiatives were identified which aim to tackle this situation, these include:

- Regional recycling centres
- Funding recycling initiatives
- Tax on virgin resources
- Performance based standards for materials
- Re-definition of the term 'waste'

Regional Recycling Centres

From the aggregate supply industry side, Tarmac is setting up a number of regional centres for the recycling of aggregate in a controlled manner.

"The main barrier to increased use of aggregate produced from demolition materials is client perceptions of inferior quality relative to primary aggregates. This is based on the "cheap and cheerful" on site crushing scenario described above. Clients are understandably wary about the suitability of aggregates produced from these variable sources under these regimes. This negative image reflects on all producers regardless of the quality systems that may be in place. Our preference is to export these materials into permanent recycling sites so that greater emphasis can be placed on quality management. We can encourage better segregation on site through variable gate fees and the contractor has no "risk" associated with marketing the end product." (Tarmac)

Taxes and Subsidies

From the regulators there are also a number of schemes aimed at changing the pattern of recycling

> *"The DTI are looking at a funding programme for recycling but this will tend to skew the picture in favour of recycling, in the waste hierarchy this is the third, with reduce and reuse coming before this and these need addressing." (Building Research Establishment)*

The tax on raw materials is an attempt to increase the cost differential between new and recycled materials, favouring the recycled ones.

> *"The Environmental Agency supports any initiatives to recover C&D waste especially on site recovery. We are aware that over-specification makes it difficult for recycled material to find a place in the market and believe that a Tax on raw materials will help. The DETR is to produce guidance on controlling the environmental effects for recycled and secondary aggregates production. This guidance will seek to increase the use of recycled and secondary materials. It will provide guidance for planners and operators." (Environment Agency)*

Performance Based Standards

The issue of standards is currently being investigated with the possibility of moving to performance related standards for recycled materials. The construction industry is traditionally 'conservative' in nature, and has a tendency only to use specifications that have been tried and tested over considerable periods of time. The majority of these specifications are 'recipe' based rather than 'performance' based. The Symonds report recommends that designers and specifiers should be encouraged to use performance-based specifications. This places the emphasis on the identification of the properties and qualities required of materials appropriate to the intended use.

> *"Although there is some movement towards performance based specifications and an increasing desire from many quarters for greater sustainability in purchasing of aggregates, our greatest problem remains convincing clients that our products are "fit for purpose". We are seeking to counter this through the promotion of our Quality Management System backed up by technical resources and a growing library of "Case Study" material showing how various C&D wastes have been reprocessed into aggregate products and successfully re-used for a variety of applications." (Tarmac)*

Definition of 'Waste'

There are also issues around what and how we define 'waste' materials. The negative connotations that accompany this term do not help raise the profile of materials that have been removed from an existing structure.

> *"There must be a redefinition of the term Waste. Many materials which nobody intended to discard and which require little or no processing before re-use, are being treated by Regulators as waste. Roof tiles, slates, stone pavings, timber, steel sections, even such things as radiators are some of the more obvious materials, which fall into this category." (Detech Environmental)*

The Symonds report supports this view also. It concludes that it would be desirable if European Union guidance note on the interpretation of waste in the specific context of C&DW management could be issued. This should address how these materials which the holder intends to reuse without further processing should be dealt with. Adopting principles similar to the OECD's 'Final guidance document for distinguishing waste from non-waste' would meet most of the requirements. This document concludes by suggesting that

A waste ceases to be a waste when a recovery, or another comparable process eliminates or sufficiently diminishes the threat posed to the environment by the original material (waste) and yields a material of sufficient beneficial use. In general the recovery of a material (waste) will have taken place when:

a) it requires no further processing, and;
b) the recovered material can and will be used in the same way as a material which has not been defined as waste, and;
c) the recovered material meets all relevant health and environmental requirements.

While recognising the potential problems embodied in the phrase *"... all relevant health and environmental requirements"*, it appears that a guidance document based on these principles would meet most if not all of the objections identified in the specific context of C&DW. The potential problems here relate to requirements that are relevant to a recycled material but not to its primary 'competitor' (or vice versa). An example concerns leachates, which may be produced by C&DW-derived aggregates but not primary materials.

4.3.3 Question 3: How has the Landfill Tax influenced the demolition procedure?

Current Situation

The landfill tax has had a mixed response within the industry. Initially its implementation caused contracts to stall as those involved worked out who was to pay. The price differential between inert and non-inert waste has encouraged some additional recycling. On the whole contractors and consultants think its effect has been small with some increase in recycling, the additional costs being on the whole passed on to the client.

> *"I believe that one of the key effects has been a move to segregate inerts and non-inerts to ensure that higher rate landfill is not paid on the inert fraction. This in turn does lend itself to higher levels of inert recycling." (Tarmac)*

> *"Landfill tax has increased the profile of recycling traditional materials, but these have been recycled for a long time, Buttons owned a crusher 20 years ago. It is now cheaper to hire in a crusher than to own one." (Buttons)*

There are also some materials for which landfilling is the only safe option and contractors felt that such materials should carry only a low tax to encourage there collection and disposal.

> *"One problem material is asbestos. This, due to Health & Safety issues, must be specially stripped out, bagged and sent to landfill. It though has a high Landfill Tax associated with it (currently £10/tonne) although there are no alternatives to landfilling, so there is no way of recycling and so avoiding the tax. The tax should encourage greater recycling, penalising the landfilling of recyclable materials not those materials with no other options. Future raising of the levy on asbestos will just encourage stripping out by cowboy contractors, fly tipping and municipal waste tipping." (Law Associates)*

Exemptions

Pressure on the Government by the landfill operators has resulted in some concessions, most notable is the tax exemption given to the disposal of inert waste for landscaping, it is likely that this will account for a vast proportion of the inert waste generated.

> *"Regarding landfill tax, this has obviously had an impact in making landfill the least favoured option. However the existence of loopholes such as tax exemptions for leisure*

related projects (eg golf courses) and the new exemption for restoration of quarries ensures that cheap disposal for inerts remains possible." (Tarmac)

Future of Tax

The Dutch banned the disposal of reusable C&DW in 1997, and only certified crushers and sorters are allowed to dispose of any materials deemed not to be reusable (such as asbestos). Belgium and Denmark also have tight restrictions on landfilling of unsorted waste (ENDS 1999c).

"In the Netherlands all materials are separated and even though it may cost to recycle them it is still cheaper that landfilling which carries a heavy tax." (Buttons)

The European Commission Report proposes that relying solely on landfill tax or primary aggregate tax would not achieve high recycling rates. They reason that the taxes would have to be set at politically unacceptable levels before they changed the behaviour of building professional, particularly in areas with easy access to landfills or quarries. Varying the tax rate to match local conditions is also not likely to help as it would create considerable distortions to trade, and would therefore probably be equally unacceptable.

Instead the European report recognises four conditions that must be met to ensure that C&DW recycling reaches sustained and economically viable levels (Report DGX1 1999):

1. Landfills must be well managed, expensive to use, and fly tipping uncommon and subject to sanctions.
2. Holders of C&DW must face a significant cost for landfilling, with hazardous or mixed wastes facing higher charges. To achieve high levels of recycling (above 75%) some form of ban on landfilling of C&DW must be imposed or enforced. Alternatively legislation could be put in place requiring the separation of waste with each stream being directed to some form or reuse or recovery operation (as in the Netherlands);
3. The opportunity must exist for the main bulky inert fraction of the C&DW to be treated (crushed and sorted) prior to reuse and recycling;
4. There must be at least a tacit acceptance that recycled aggregates can replace primary aggregates.

These requirements while beneficial, all place the emphasis (and onus) on the demolition end of the building lifecycle. As discussed throughout this thesis this is reactive, dealing with the waste only after it has been generated, there is also need to consider the other building stages and design to avoid the 'waste' in the first instance.

4.3.4 Question 4: Is the nature of demolition changing?

The demolition industry has undergone major transformation within the last 20 years. Traditionally it has been a labour intensive, low skill, low technology, and poorly regulated activity, dealing mainly with the deconstruction of simply constructed buildings. It has followed the trend of all major industry and mechanised, replacing labour with machines. This has come about because of the increased complexity in building design, the financial pressures from clients, health and safety issues, regulatory and legal requirements and advances in plant design. The industry now employs fewer, but more highly skilled operators and very expensive specialised equipment. Also, while traditionally much of the demolition contractor's income was from the sale of salvaged and recycled materials, today income is mainly generated from demolishing as quickly as safely possible.

> *"Demolition firms historically have always recycled, for a long time the value of the materials extracted was their main income. Now construction has changed and time is main consideration. (Law Associates)*

> *"20 years ago the industry was labour intensive with poor all round standards. Today with the huge improvements in specialist plant the industry is becoming mechanical with technology driving the future. Training is also greatly improved, as before it was almost none existent." (NDFC)*

> *"In the past most demolition was done with ball and chain, but this is no longer the case. In city centres or on tight sites and those with adjacent properties demolition is now done by scaffold and hand methods, with additional small machines.*

> *The biggest change in the last 10 years has been the introduction of Hi-reach hydraulic machines with inter-changeable 360 degree rotating jaws. These can take down a building of any material in a controlled manor, cutting through steel or concrete, and are the future of the industry. For city centre sites, city breakers, which are less environmentally polluting versions of the above are coming on line.*

> *Above the safe working height of a Hi-reach, hand and small machines are used. Hi reaches then take down the rest, speeding up the job and providing added safety for operatives. Separation of materials then occurs at ground level." (Connell Brothers)*

Whilst the materials being demolished have changed to a degree the main change has been in the degree of technology and sophisticated plant now used on site (see Plate 4.2).

Plate 4.2. Hi-reach Excavators

4.3.5 Question 5: What are the differences in demolishing Victorian to more modern buildings?

Older buildings of non-complex construction are generally simpler to demolish, at least until toxic materials like asbestos appeared. Their elements also often have aesthetic or antiquarian value which, being greater than their material value, results in them being salvaged. As the complexity and size of buildings has risen so have the technical demands placed on contractors taking them down safely.

> *"Older buildings are generally of simpler construction and so easier to demolish, although their lack of structural stability sometimes makes disassembly as oppose to complete demolition difficult. Most large-scale primary industry and manufacturing plants have now been demolished. 60's pre-stressed and post-tensioned buildings are now coming down, these are very difficult to take down. As the range and complexity of materials used increases so does the difficulty in taking down and separating materials." (Connell Brothers)*

4.3.6 Question 6: How do you approach a demolition project?

There was consensus across all the demolition contractors in the general approach to a potential demolition project and the stages undertaken once the job commenced. What was notable was the awareness of the differences between the UK and particularly the Dutch system, which was considered to be more helpful to demolition contractors whilst producing higher recycling rates. There was some variation in approaches to the internal strip out, depending on its reuse value, if elements could be sold on then they would likely be stripped out. However, this is a labour intensive and time-consuming operation and so many contractors demolished the internal layer with the frame resulting in mixed waste and minimal recycling.

> *"Generally the same approach is adopted across the industry, it is the reverse of the construction process; remove hazardous materials, soft strip, then main frame. Some contractors do not even bother with the soft strip, demolishing whole buildings and then extracting materials (i.e. metals) at ground level. The cost implications are always first." (Buttons)*

> *"This (soft strip) is labour intensive and materials will only be recycled if a buoyant market exists for them. Stainless steel and aluminium are recycled. Timber if clean is also recycled but any hidden contaminants incur a cost penalty to contractor. Services generally and electrical fitting particularly are not, as legislation requires testing and compliance with new standards. Potential end users do not pay enough for recycled materials and so it is not cost effective to recycle. (Connell Brothers)*

For most jobs, the demolition firm submits one tender, which includes price and time scale. There have though been a number of high profile dismantling jobs, where two tenders were submitted, one with high cost and short time scale and the other low cost, long time scale, and maximum recycling. This is almost a return to the demolition contracts of old, were the firms made their money from extracting and selling on as many materials as possible. Victorian buildings such as schools and hospitals consisting of simple brick and timber construction are often deconstructed in this way as the elements are easy to separate into their constituent materials and a buoyant market exists for them.

> *"First appraise the job, this requires looking at access, both to site and to building, thinking about scaffolding, and preparing a proposed demolition method. This takes into account core samples, integrity of structure, load-bearing elements, as built drawings, and health and safety. McGee's offer one tender price for a demolition contract which*

includes potential recycling, once accepted debate will then continues on extent of actual recycling with McGee's selling the benefits of increased recycling to the client." (McGee's)

"In some cases the demolition contractor entered two bids one of 1 million pounds, down in six weeks with minimal recycling and the other of 100, 000 pounds and down in six months where the contractor made his money from recycling, and the client went for the latter." (Building Research Establishment)

The Dutch system differs from the UK's in that initially the client invites several demolition contractors to submit tenders for the work, this will include demolition method statements, health and safety considerations and expected recycling rates. These reports are paid for by the client, reducing the time pressures on the contractors and allowing them to give detailed assessments of the project. The client then enters into negotiation with one contractor who's tender is considered overall to be the most beneficial in terms of time, cost, avoidance of nuisance and material reused and recycled. In the UK the lowest tender wins which contractors felt was detrimental the quality of the job and the quantity of material reused and recycled.

"In Europe, particularly Holland several contractors are asked to submit tenders and paid for this, the client then negotiates with the chosen one, resulting in a smoother better job." (Connell Brothers)

4.3.7 Question 7: What are the stages of a demolition project

All contractors agreed on the ideal stages of the demolition process and the types of reuse and recycling activity that happen at each stage. Before the main demolition itself can start there are a number of pre stages to be completed, the ideal procedure for the whole demolition process is as follows;

1. Pretender Health and Safety plan as part of CDM regulations, covers hazardous materials, previous uses and building as built and modified drawings.
2. Client provides adequate information about life of building.
3. Undertake a site visit with someone who knows the building and is familiar with any changes and the Health and Safety Plan
4. Demolition contractor can then make an informed decision as to method of taking down the building. Of course there are many other partial demotion types in addition to complete end of life total demolition. In this one would identify Hazardous materials (ie PCB's asbestos, solvents), inert and none inert waste

5. Strategy for demolition is then:
   - Isolate and make safe services
   - Remove hazardous materials
   - Soft strip, i.e. all internal finishes, partitions, carpets, services etc
   - Remove none-load-bearing elements
   - Remove load-bearing elements, these two in reverse of construction and in a way that you could reuse or recycle materials.
6. Then from all this information contractor would develop a demolition health and safety plan, which would include reuse and recycling 'options'. (Bagnel Group)

Whilst the stages of the actual demolition are adhered to the pre-tender stages are often rushed due to financial and time pressures. Also it is rare that adequate information is provided about the materials in the building resulting in educated guesswork in relation to structural form and location of hazardous materials. Additionally time constraints often limit the amount of materials separated into inerts and none-inerts, contractors being prepared to pay the higher landfill tax rather than incur (even higher) time and so financial penalties to the contract.

> *"The ideal is to separate building into component parts/materials, there is a high landfill tax differential, which separates materials into inert and none-inert waste and so identifying and sorting these is a main priority." (Bagnel Group)*

The order of the demolition process is very important, it is effectively the reverse of the construction process. As such the internal frequent changed layer are removed first, then the services and cladding followed by the structure and finally the foundations, although these are often left behind, just being capped at ground level. Demolition contractors therefore see buildings as a number of connected but distinct layers. This concurs with the layered approach identified in the last chapter, providing additional support to the argument that for resilience and adaptability building should be considered in time dependant layers.

> *"Demolition is in-effect the reverse of construction and as such you demolish from the inside out. First is the removal of all toxic/contaminated material. Second you soft strip the internal layer, any valuable elements are usually already gone, so this phase mostly consists of services, none load-bearing elements etc, some recycling of these elements occurs although limited depending on access, size and complexity of construction. Sometimes cladding is removed at this stage. After the soft strip the main body of the demolition happens, taking out floors and then frame. With concrete or composite you would use a pulveriser to crush and remove concrete, these do not cut steel re-bar or sheet. The steel is then cut out in sections and sent away for recycling." (McGee's)*

4.3.8 Question 8: Describe the different Demolition techniques and approaches for alternative building frame types ie steel, concrete or composite?

Steel or concrete frames presented little difficulty to contractors. The new hi-reach excavators are equipped to deal with either, the material type dictating the mechanical jaw used.

> *"No particular problems, methods change with different material types, steel is removed where as concrete is crushed on site. Pre-stressed and post-tensioned frames are very difficult to demolish but these are rare. Increasing we are moving from demolishing Victorian, brick/block/concrete buildings to steel frames. Partial demolition can also be difficult, increasingly we are asked to maintain the façade and demolish the inside, called façade retention. This involves propping the façade and using hand methods near to this to minimise damage, and machines as you move away from the facade towards the centre of the building." (McGee's)*

Steel

There is a well established recycling industry for most steel products and while the price paid fluctuates it is rare for steel to be landfilled. The exceptions are when steel is contained in small quantities in composite materials were separation is not possible for example in light fittings.

Steel frames are cut with shears fitted to the hi-reach excavators. Beams are generally cut free from the frame near the connections, lifted down and then cut into smaller sections for transportation to recycling facility. On restricted access sites or with very large members hot cutting gear will be used, but as this involves site personnel working at the cutting face this is avoided where possible. Fire cladding if bonded to the steel makes it more difficult to isolate, most contractors preferring the more jacket types of fire cladding. With frames based on simple structural grids which have hi reuse potential, such as portal frames, the bolts may be undone, gas cut, or punched out. This enables the whole members to be reused and indicates that given the right conditions the reuse of whole steel elements is eminently possible. The conditions for this to become more common place appear to be that standard member sizes are used, the connections are accessible and safe to work close to, and that a market exists for the disassembled frame.

> *"Steel has high reuse/recycling value, often through a cascade of use chain. For example structural beams may go from buildings to civil engineering projects where they are used as temporary works. Here section sizes and holes etc, do not matter as large safety margins are used. It is fairly easy to use a crane and dismantle a steel building, though*

this does not mean at joints, usually easier to 'cut' sections apart, most are trimmed before reuse anyway." (Scot Wilson Kirkpatrick)

"Steel, almost all goes for reuse/recycling. Often deformed through demolition so not reused. Also market at any particular time dictates fate. Common used steel elements are reuse. If price of steel is low, customer can buy new but contractor will want to reuse as recycle price is low and the reverse is also true. Bricks can be reused and timber reused or recycled." (Buttons)

Concrete

Demolishing reinforced concrete frames, floors and composite floors is a straightforward procedure using a hi-reach excavator, these effectively chew through the concrete. Depending on the thickness of reinforcement in frames or sheet steel in floors these machines will either chew straight through this or stop here. The jaws will then be changed to the shears and the element separated from the frame. Once at ground level (Plate 4.4) as part of standard demolition procedure the sheet steel or reinforcement will be separated from the concrete by smaller machines, which crush and pulverise the concrete. Precast elements might be lifted down from the frame to be crushed at ground level or crushed insitu.

Plate 4.3 Separating Concrete and Reinforcement

Unlike steel, which can, with the addition of heat, be recycled the creation of concrete is a one way chemical process. Techniques are starting to be developed to crush it and use it as aggregate for new concrete, however, most is crushed and used as fill on or near the site of arising. Its bulk, low value and the abundance of its raw constituents in the Earth's crust mean that it generally not transported great distances.

> *"The recycling of concrete is location specific, if demand is not local it is uneconomic to recycle due to transport charges and cheap primary aggregates, there is no current tax levies on primary aggregates." (Detech Environmental)*

Foundations

Upwards of 90% of foundations are of reinforced concrete. Slabs, footings and ring-beams will be removed in all but a few cases, piles however, present another problem. These are cast into the ground and very difficult to remove. Contractors generally remove the pile cap and cut away the first one to two metres of the pile, leaving the rest in the ground. Particularly in major cities such as London where a site may be redeveloped many times old piles are becoming an increasing problem. There is often no record of their position and it is only when contractors drive new piles that they come across the old ones. These can greatly interfere with the direction and effectiveness of the new piles. Most steel piles used are in the form of sheet retaining walls and these are extracted and either used again or sent for recycling.

Bricks and Timber

Many types of old bricks have a high reuse value and provided they do not crumble will be manually cleaned ready for transportation and resale. More modern bricks are generally crushed with the rest of the mineral waste due their lower structural and aesthetic quality and the cement mortars that make separation difficult (Plate 4.5).

Waste transfer stations will accept and even pay demolition contractors for clean used timber, but if contaminants are mixed with the load the situation is reversed and contractors find themselves liable for the safe disposing of the timber. The effort to selectively separate timber from all contaminants was seen by many as too expensive to justify the return.

Plate 4.4 Brick Crushing

Soft Strip

It was difficult to find much information about the soft strip, this includes the internal configuration of partitions, doors, false and suspended ceilings, raised floors and services. Most of the materials in this layer have been highly processed into specific composite elements with resultant high-embodied impacts relative to the more basic-structural elements of the construction. Also, as most buildings will undergo a number of internal fit-outs through their lifetimes, for fashion to functional reasons it is the layer with possibly the largest overall environmental impact. The fact that little information was available on the fate of these products may indicate that they where already being informally recycled due to their resale value.

As many of these soft strip elements exist in recognised product form they potentially could go for reuse, reconditioning and recycling as described for electronic products and cars in the last chapter. This would require a sea change in the way products are procured and the integration of many manufactures and suppliers. This change has already begun to happen for carpets and office furniture in the USA. Here a number of firms have reinvented themselves changing from product sellers to service providers. At the end of the products life, or when it is superseded it is taken back, assist stripped and incorporated into the new generation of the product. This has resulted in a product de-materialisation of up to a factor of 30 without any loss in quality (Hawken 1999), p125-143.

Pre-cast and pre-assembly

If drawings indicate lifting eyes and these are accessible and in good condition prefabricated panels can be removed. But panels are often flimsy and liable to brake up during dismantling and lifting eyes are often corroded or impossible to locate. Also it is an increasing possibility that on a tight city centre site there might not be a suitable location for a tower crane. Many of the demolition costs are in transport, so reducing the number of journeys or fully loading lorries can be beneficial. Prefabricated units, which can be removed and flat-packed are an advantage here, such as cladding systems, curtain walling, steel beams etc. Dry construction techniques enable potentially easier construction and dismantling with less process waste.

4.3.9 Question 9: Which building types are quicker to demolish, and result in less waste?

Buildings using simple structural grids and basic building materials are obviously easier to demolish and recycle. For example, the current trend for 'retail outlet parks' and industrial units has lead to the construction of a large number of steel-framed buildings with many prefabricated panels. Demolition contractors predict no difficulty in dismantling and reusing or recycling the elements of these buildings. As discussed earlier, easy to identify and separate materials will be reclaimed. Traditional building which mainly consisted of a small number of materials put together in a simple and easily identifiable way are always going to be easy to demolish and reuse/recycle than modern buildings were the structure is hidden behind many layers of claddings and finishings.

> *"Brick and timber, brick and concrete and steel portal frames are all easy to demolish. The time for any one job is project specific. Steel will be cut into five-foot sections and sent for scrap. Other materials could be stored but wouldn't be unless a market existed or the price was high. There are H & S problems with letting subcontractors onto a site to strip-out certain elements." (Law Associates)*

4.3.10 Question 10: Do buildings structurally change over their lifetimes?

Contractors all differentiated between residential, commercial and industrial style buildings. In residential and commercial buildings the major changes are often at the level of the internal finishes and services and so outside the realm of the demolition contractors scope of work. They are only likely to come into contact with such a building if it is either being completely demolished, stripped back to the structural frame, or gutted with facade retention (for a listed or inner city building). Industrial buildings for mechanical and chemical manufacturing processes have major changes when plant is superceded or relocated as processes are modified. This often involves the movement of large pieces of plant around existing and still operating sites and a number of demolition firms specialise in this technically and logistically challenging work. This type of demolition is beyond the scope of this research.

> *"Industrial buildings do change, though these are fairly obvious. Residential change considerably. The likes of offices etc have internal layout and service and external cladding changes but very few structural frames changes." (Buttons)*

> *"Offices are now designed with large open plans supported on beams spanning to the perimeter frame with central core services allowing spatial changes from one use type to another and back again. In the past they where more likely to have a central core with smaller floors hung off this which allowed little change. Design life is now often of 50 years for the total building, but certain elements have a much shorter life than this, for example UPVC windows which have a max life of around 20 years as these are cheaper than say timber they are often used. This brings maintenance and replacement issues into the equation also responsibility and accounting, as in 20 years is likely that others will be responsible for the building so avoiding attending to these issues now. This reduces costs in the short term but is likely to increase them long term, classic examples of short-term mentality." (Scot Wilson Kirkpatrick)*

Maintenance, refurbishment, replacement, and appropriate durability all need to be included on the agenda of building designers to maximise the useful life of the building.

4.3.11 Question 11: What are particular problem elements?

There was a range of issues raised that make demolition and reuse/recycling particularly onerous. These vary from the difficulty in dismantling overly complex designs (systems level) to the bonding of dissimilar materials and contamination of the waste stream (product and material level). Most demolition experts sight lack of foresight on behalf of the design and construction team as to the eventual fate of the building and its materials as the major issue here. By not contemplating the inevitable end of life of the building they are seriously reducing the potential to reuse and recycle the materials. Usually it is only when a building is to be demolished that these issues are raised.

Composites

At the product and material level, two of the major problems which demolition contractors increasingly must face are composites and contaminants. Composites are usually dissimilar materials (chemically) bonded together and are very popular in modern construction. While it might be possible to isolate the composite elements, separating the different layers of these for recycling is proving extremely difficult resulting in many elements being landfilled. One of the main problem materials encountered was polystyrene. Whether this is as a bonded insulation, permanent shuttering or as void filler in precast elements. In all these cases separating the polystyrene from the main structural material is proving difficult resulting in the whole element going to landfill.

> *"Polystyrene as permanent shuttering is and will become a major issue, as will other materials, which although not hazardous contaminate the waste stream resulting in the whole lot being sent to landfill.*
>
> *Other composite materials are also a problem, such as man made mineral fibres, timber framed housing which uses insulation panels and brick cladding all bonded together. Cavity wall injection is becoming an issue, as there is no way of knowing before hand if it has been done and the resulting waste is uncontrollable.*
>
> *Steel and concrete present no particular problems, and there are well-established recycling loops for these. Contamination in concrete is an issue. Steel mixed with concrete is easily separable with magnets but the likes of timber must be separated first, as it is impossible to do this after crushing as it splinters." (Buttons)*

Complex Designs

At the system level, demolition contractors constantly have to invent new practices to cope with complex structures. The difficulty in demolishing pre and post tensioned concrete structures being a recent example were no prior thought had been given to their eventual demolition.

> *"The demolition industry is a great innovator, and the expectation within the construction industry is that technical solution will be found in the future for all current problems. For example eventually it is likely that a machine will be designed that sucks insulation out of walls before demolition." (Buttons)*
>
> *"Pre-stressed and post tensioned beams. Cantilevers, undercrofts, composite materials, bonded and loose insulation, cladding panels and large glass curtain walling. All these make demolition difficult. High tensile steel wire is also just starting to appear on demolition sites. Due to its strength and small diameter it cannot be cut with the hi-reach*

shears and is becoming a major headache. Also steel recycling facilities are refusing to take it as they face similar problems trying to cut it into manageable sizes." (Connell Brothers)

Contaminants

Both contractors and waste processors noted difficulty with contaminates. Contractors have to try and avoid mixing materials or separate them by hand, and the waste processors are reluctant to take 'feed' mixed with timber, plastics, foams or excessive amounts of soils/fines.

"The main problem we get is contamination of the feedstock, usually this consists of wood, plastic, metals, man made mineral fibres and gypsum based materials such as plaster, plasterboard etc. As far as possible these are picked by hand prior to processing. The metals can be sold or at least taken away free of charge for recycling, the remainder is usually landfilled. Obviously we try to minimise the amount of these materials that we accept and typically no more than 1% per annum goes to landfill.

The other main problem we have is with excessive amounts of soils/fines mixed in with the feed stock. This tends to limit the end quality of our products and the range of applications for which they are suitable. Again we try to minimise the amounts we accept; we are also researching into ways of adding value to these materials for example by blending with green-waste compost." (Tarmac)

Recycling centres are in the envious position of being able to select which materials they accept. Demolition contractors on the other hand have little choice, all materials generated from the deconstruction must be dealt with.

Lightweight Concrete

Another problem that was highlighted by contractors was the difficulty in reprocessing lightweight concrete and concrete's which contain cement substitutes.

"There are particular problems with many lightweight concrete materials currently used, as they do not have the cohesive strength to be crushed and so recycled. If these are mixed with general concrete waste they will render the whole lot useless for crushing and recycling. These must then be separated at source before recycling. Generally the construction industry hopes that innovations in the demolition industry will keep up with changing materials. Many of the current materials are chosen because they offer quick cheap solutions now, but these do not take lifecycle into consideration therefore leaving

problems for the future. Under CDM regulations developers have to be more responsible for the future of their buildings". (Buttons)

The waste processors on the other hand with their more advanced machinery, and benefit of being further down the waste separation and sorting chain did not find this such an issue, although aerated blocks did prove problematic.

"I would disagree on the whole re: lightweight concrete. We have successfully processed concrete containing lightweight aggregates such as leca, pfa, fba etc. In some instances we have been able to process these for re-use in concrete blocks, or in the case of slags into sub-base and fill products. The major exception would be aerated concrete blocks, which due to their constituents do turn into powder when crushed. Even so we have some success in handling this material by mixing with other streams (conventional concrete) prior to crushing." (Tarmac)

The difference in attitude between the contractors and processors was notable. Contractors demolish and have to shift all materials that can't be used on site, they are pressured by time and have to pay the process sites to take their unwanted material. On the other hand the process sites choose what material to accept and can reject or charge more for mixed wastes. With less time restrictions they can reprocess the waste and sell this on, landfilling the leftovers.

"We seek to avoid accepting all contaminates into our sites- i.e. the problem really lies with the demolition contractor. I suppose the only answer is to strip out by hand prior to demolition, which is not likely to be economically viable at present." (Tarmac)

4.3.12 Question 12: How do you see the demolition industry operating in the future?

Demolition in the UK is likely to follow the lead being taken by the Dutch. Landfill becoming gradually more expensive and in all likelihood disposal of recyclable materials will eventually be banned. This has been shown in Holland to encourage selective demolition and so increase the recycling rates. For this to happen there must be the political will both at a European and UK level backed up by legislation. Initially moving to a higher level of recycling can incur heavy costs as the economic system adapts to it and the demolition industry must invest in new mechanical sorting and processing equipment. Unless tax or other incentives benefit recycled materials their uptake will be slow as virgin resources are relatively cheap. As noted in the Symonds report only by enforcing the recycling and use of C&DW is the situation like to dramatically change.

"Government policy and legislation influences the future. Construction Line has been set up to save some of the pre-tender qualification requirements. Enabling firms to get on with tendering having satisfied finical, technical and skill, expertise, this is an outcome of the Egan report." (NFDC)

"It is always going to become more expensive to landfill, so recycling is bound to increase. In the future it might become economic to mine landfills for materials, therefore turning them into long term stores for future materials." (Scot Wilson Kirkpatrick)

"Clients are generally not interested in environment issues, money is what drives them. The only way to encourage recycling is to make the costs of landfilling higher than the recycling costs, (as is Holland). Or the cost of new materials higher than the cost of recycled ones." (Buttons)

The innovations within the industry are likely to come from new mechanical plant, which are rapidly becoming more sophisticated and specialised. The next growth market for plant is likely to be in the area of the soft strip, which is still labour intensive. As with the use of hi-reach excavators it will only take a few leading companies to start effectively using the new plant for the whole industry to adopt them.

"It is likely that recycling will increase with the introduction of new legislation to force segregation of all waste streams, and prevention of co-disposal of wastes (within next four years). Technology will be involved with this through the increase of remotely operated hi-reach excavators, and small robotic machines, The Dutch are the leaders in recycling as landfill in Holland is so restricted, legislation forces segregation of all waste streams, and it is their model that the UK is following. Whilst the UK demolition firms are not the most advanced in Europe they are amongst the front runners. The demolition industry needs a few people to take the initiative then effects will snowball." (Buttons)

"Demolition techniques are changing as technology improves and the pressures from H & S and environment (noise, pollution, waste, transport) increase as do those from the clients. These pressures are only going to be greater in the future, there is now a demand for sites to have a full time environmental manager who would deal with issues of noise, transport, efficiency, hours etc. Technology is moving towards small remotely operated robotic machines which can work in areas unsafe for humans and also due to

reduced size and noise levels can run for longer hours per day, speeding up contract." (McGee's)

4.3.13 Question 13: How could buildings be redesigned to enable easier/quicker demolition/dismantling?

All of the interviewee's highlighted the same range of issues, the contractors being more specific about particular problems and the consultants focusing more at the design level. The issues raised have been grouped into guidelines within the Systems, Products and Materials headings developed earlier in this thesis, see Figure 4.1 below. Building solutions that enable disassembly, reuse and recycling are explored within this three-tier strategy. To provide a more definitive list of DfD guidelines the issues raised through the interviews have been compared with, and complemented by, the other DfD strategies identified in Chapters 2 & 3.

Figure 4-1 Design Guidelines

System	Adaptable buildings which can change to suit changing requirements
Product	Element manufacture/construction which allows upgrading, repair and replacement
Material	Reuse, recycling and the natural degradation of materials

Systems Level

This involves designing to enable short and long term flux. Buildings must be adaptable to enable these changes to happen as efficiently and none destructively as possible.

No	System Guidelines
	Design
S1	Separate the time dependant layers of the building to enable adaptability and repair and replacement of the individual layers without affecting the integrity of the whole. Ensure that the short life-span parts are accessible and easy to change.
S2	Consider eventual disassembly at conceptual design stage and plan accordingly. Demolition is the reverse of construction. For example allowing site access for machinery & suitable floor loads to take demolition plant and rubble.
S3	Ensure that a detailed building husbandry plan exits. Routine maintenance, upgrading and refurbishment will increase the lifetime of the building.
S4	Use simple structural layouts and standard components combined in interesting but none complex ways to maximise their reuse/recycling potential.
	Information
S5	Drawings- as built drawings and records of all changes should be kept, CDM

regulations should cover at least part of this. As should the growth of CAD packages in the design office.

S6 Asset register of materials. At end of buildings life it would be useful to have a log of materials used, lifetime refurbishment carried out and eventual fates. This 'whole life accounting' would enable the materials to be followed through their different life phases.

S7 Smart Waste. Need to know more about what and how wastes are generated and then benchmark these. This will enable a database of various building types and their associated wastes to be created.

S8 More case studies are needed of buildings that have been successfully dismantled and recycled.

Market

S9 Change in market to increase the demand for recycled materials.

S10 Giving benefit of recycling to the demolition contractor not the landfill operator is one option. Offsetting tax liabilities against amount of (extra) material recycled in a year would greatly encourage recycling, although as in other industries this might encourage recycling for recycling sake, with no end use.

S11 Redefinition of the term 'waste', to exclude those materials arising from a demolition site which can be reuse or recycled.

Disassembly

S12 Selective demolition programming should be adopted enabling valuable or potentially contaminating materials and fittings to be removed safely and intact for later re-use or processing before the main demolition commences.

S13 Above all there must be more time to dismantle

S14 Older buildings tended to be of simple form and so easy to demolish, newer buildings are more complex and therefore harder to take down. Using advances in structural understanding and knowledge of material properties to create modern but less complex buildings would assist the demolition procedure.

S15 The modern aesthetic of having exposed steelwork wrapped in a cladding layer makes demolition easier, except where complicated and often hidden bracing systems are used.

S16 Lift shafts can be used to move materials down through the building, knocking out partitions between each shaft to make one large lift well would facilitate this. As lifts are structurally massive these are ideal waste chutes. In confined city sites this makes a lot of sense.

S17 Avoid; cantilevers, undercrofts, pre-stressed beams, polystyrene as permanent shuttering or precast/insitu concrete void fillers, man made mineral fibre boards, high tensile steel wire and chemically bonded composite materials with dissimilar

	recycling routes.
S18	Permanent external fixings around the facade should be incorporated with the construction to allow the attachment of scaffold for maintenance and controlled demolition.

Product Level

To allow a building to adapt/change the elements that make up this system must all be changeable. This takes us to the product level. Here the elemental systems that lend themselves to disassembly/deconstruction and reconstruction are identified:

No	**Product Guidelines**
P1	Use elements on hire from a service provider and returned to sender after their useful life. This involves moving towards a service or lease economy and results in massive resource saving and de-materialisation.
P2	Label components for ease of identification and record information about them.
P3	The product structure. Design products that lend themselves to disassembly and reuse/recycling. Use standard construction techniques that can be reversed.
P4	Link component accessibility to life-span. Make components with a short life expectancy readily accessible and easy to disassemble, components with longer life expectancy may be less accessible or less easy to disassemble
P5	Who will be doing the reclaiming? Consider the likely reclamation route and design products accordingly.
P6	Rationalise components. Minimise the number and complexity of components to simplify the recycling operation.
P7	Plug and play. Possibility of making many components modular and so easily interchangeable.
P8	Minimise the number of fasteners/connectors in a product and make them accessible and reversible. Easy and quick to take apart products are more likely to be recycled. Using for example bolted and screwed as oppose to welded and nailed connections. If reversible connections are not possible using clearly identified sacrificial zones can enable quick disassembly with minimum loss of product.
P9	Use mechanical rather than chemical fixings and identify connection points for future disassembly.
P10	Promote modular design so that obsolescence occurs on the component rather than on the product level.

Material Level

Once an element of the building has reached the end of its useful life then it should be possible to separate it into its constituent materials and these can then go for reuse/recycling or natural degradation:

No.	**Material Guidelines**
M1	Label materials for ease of identification and record information about them. This could include; chemical treatments carried out, potential recycling routes, and history.
M2	Use naturally degradable materials and coatings for building layers that are likely to wear out over the lifecycle (for example both external and internal finishes). Otherwise they will pollute the environment.
M3	Use low dissipative and technically recyclable materials for all other cases. Maintaining the integrity of the material through the lifecycle ensures that the maximum quantity (or yield) is available for recycling.
M4	Avoid the use of hazardous materials and those that lead to contamination. This will reduce the potential for human health risk during deconstruction. If unavoidable ensure that hazardous materials are clearly marked and try to group contaminated areas and make them easy to remove.
M5	Use simpler homogeneous materials with recognised recycling routes. Choosing materials for the initial product with recognised recycling routes will greatly encourage their future circularisation. Also in general terms the purer materials are, the more valuable and hence more recyclable they are.
M6	Minimise the number of different materials within any one component and generally within any design. This will simplify the process of sorting materials on site and reduce transport to separate reprocessing plants, and avoid contaminating the waste stream.
M7	Avoid material composites, which inhibit the effectiveness of recycling. If composites are to be used identify and separate them from materials that have recognised recycling routes.
M8	Use recycled and recyclable materials to support the recycling industry and enable future recycling.
M9	Avoid chemical secondary finishings and coatings where possible. These make recycling more labour intensive and so less attractive.

4.4 Conclusions

The demolition industry was founded on, and developed around, extracting and selling 'waste' materials for reuse and recycling. In many older buildings the structural connections could easily be reversed and so the buildings disassembled. Separating the materials was then a simple process as only basic and clearly identifiable materials were used.

Modern commercial (and many industrial and residential) buildings, on the other hand, are very complex, both in their design, and the combinations of many composite materials used. These factors combined with the financial and time pressures placed on demolition contractors significantly reduces the quantity and quality of material for reuse and recycling.

This situation then encourages the further extraction of virgin resources and the landfilling of waste materials which has environmental, social, and economic impacts. To readdress this position this chapter has examined the recycling potential of buildings, their elements and materials by:

- Identifying the actual demolition process
- Defining which materials are 'recycled' and which cause problems.
- Investigating strategies that would ease the disassembly and so increase the 'recycling' of buildings, their elements and materials.
- Gaining insight into the future of the industry

The demolition process is the reverse of the construction process, by separating the various time dependant layers and avoiding complex designs, composite components and contaminating materials the levels of reuse and recycling could increase.

Thinking in this layered approach, and designing the accessibility of the layers according to their hierarchy of use could change the way buildings are conceived, constructed and used. Design for Disassembly offers a framework by which the construction industry could achieve this, moving away from a linear and towards a circular system. In this, what once were the 'wastes' become future building's raw materials. Definitions of specific lifetimes and appropriate durability then become blurred as materials continually flow around the system. The System, Product and Material guidelines outlined above are drawn from demolition experts and those involved with DfD in other industries and would enable this more circular approach to be adopted by the building industry. One of the key factors in determining a materials fate is the time allowed on site to disassemble buildings. No time to disassemble, results in no materials for reuse and recycling. DfD addresses this issue by simplifying and so speeding up the demolition process.

The current European political agenda supports increased reuse and recycling of materials. When combined with the fact that the availability of landfill sites and virgin resources are both becoming more limited it is likely that reuse and recycling will have to increase. In the product industry new legislation means that 90% plus of a diverse range of goods, from cars to computers, must be recycled by 2006, and DfD is featuring heavily in the plans of manufactures attempting to reach this target. If similar legislation is forced on the construction industry then DfD will also become an important technique increasing the quantity of elements and materials reused and recycled.

5 LIFECYCLE METHODOLOGIES

5.1 Introduction, Aims and Structure

One of the strongest emerging themes from the previous two chapters is that buildings are dynamic systems and exist in a number of time dependant layers. They are constructed and demolished in layers, and also changed during their use in this layered manor. Also it was noted that while interrelated, the lifetime of these layers are not dependent upon one another and they may change for a variety of reasons from functional failure to fashion and design swings. Continually changing these layers is likely to increase the environmental impacts of any building compared to a static one. However, allowing change (by using the previously defined DfD guidelines for example) may reduce the lifetime impact compared to demolishing and replacing the building every time it becomes obsolescent. Currently there has been little detailed investigation of the environmental impacts of the flux of these layers over the lifetime of a building, therefore the core goal of Part III of the thesis is to address this by:

- **Determining where the greatest use of resources and major impacts occur throughout the building life cycle.**

In order to make this goal more manageable it has been divided into a number of separate aims. The first three, which provide the context, are dealt with in this chapter. These then lead on to the actual investigation, which is conducted in the next chapter. Hence the aims for this chapter are to:

1. Identify the building type to be investigated.
2. Define the methodology with which to conduct the investigation.
3. Identify and critically review other case studies that have used a similar methodology.

Accordingly the chapter structure follows these three aims, addressing each in turn.

5.2 Building Types to be investigated.

For this study multi-storey steel and concrete framed office buildings have been selected for the following reasons:

1. Office buildings are clearly identifiable by their time dependent building layers and there is a growing perception that these buildings must be adaptable to both short-term internal fluctuations and long term external changes in use.

2. The time periods for the different layers has been previously established.
3. There is a noticeable increasing 'churn rate' (particularly of the internal layers) in offices potentially resulting in much higher wastage of materials.
4. There is a trend to change the function of buildings from industrial to commercial and residential.
5. Modern highly technical and composite materials are used which make disassembly and all levels of recycling more difficult.
6. Design life of office buildings is often greater than actual life, resulting in premature demolition.
7. There is currently a debate within the industry over the environmental benefits of using steel or concrete as the major structural material for office construction. Consequently existing research into office buildings is available.
8. Over the last ten years there have been a number of high profile office developments that have claimed to be 'green'.

A more detailed office building specification will be established later in the chapter. First methodologies on which to base the lifecycle study are investigated.

5.3 Methodology

As stated before, the aim of the research strategy of Part III is to identify and quantify the flow of resources over a building's lifecycle. This requires the manipulation of sets of variables, the measurement of the effects of this manipulation and the control of other variables, best suited to an experimental type of research strategy (Robson 1993). Accordingly, a number of established methodologies, which quantify resource flows are described below and their suitability assessed for an office building lifecycle study.

5.3.1 Total Material Requirement (TMR), The World Resources Institute.

In an attempt to track the life cycle of resource flows through the industrial economy the World Resources Institute (Adriaanse 1997) has developed the Total Material Requirement methodology (TMR). This aims *"to provide a quantitative physical description of all the natural resources directly and indirectly used by the economic activity of the country investigated"* (p3). In keeping with the acknowledgement of stresses to sources and sinks (see chapter 2) TMR was motivated by *the "desire to relate use of natural resources to the capacity of the environment to provide the materials and absorb the wastes"* (p5). The study acknowledged that not all flows have equal impacts, therefore materials can be classified in many different ways and it proposed the following method for impact evaluation:

QUALITATIVE IMPACT EVALUATIONS

Materials can be classified by their degree of mobilisation and whether they pose major environmental hazards. Mobilisation is related to materials that are released to the atmosphere or dissipated to land and water systems these affect larger areas than those controlled in landfills or tailings ponds. Materials that have been chemically transformed generally have a higher environmental hazard than biodegradable materials. Therefore TMR recognises four main categories of materials:

1. High mobilisation, high potential for harm. Of a national concern for long term sustainability.
2. High mobilisation, low potential for harm.
3. Low mobilisation, high potential for harm. Of a local concern for public health.
4. Low mobilisation, low potential for harm

(Adriaanse 1997)

The methodology makes adjustments for imports and exports of primary materials and finished goods and draws the following definition of the Total Material Requirement of an economy:

> *"This is the sum of the total material input and the hidden or indirect material flows, including deliberate landscape alternations. It is the total material requirement for a national economy, including all domestic and imported natural resources." (p8).*

The TMR methodology has been applied to calculate the resource flows of a number of highly industrialised countries, and while they vary considerably in size of population, economy and land area they show very similar overall trends in natural resource use. TMR was an important step as it was one of the first methodologies to acknowledge and attempt to calculate the hidden and indirect impacts of the resources used in the industrial economy. While useful at this scale the methodology cannot be applied at the level of an individual building and is therefore unsuitable for application in this thesis.

5.3.2 Mass Balance

Robert Ayres (Ayres 1996), uses the mass balance principle, which is a direct consequence of the first law of thermodynamics. At each physical stage of any transformation process the material inputs must exactly equal the outputs including wastes. Therefore every tonne of a finished resource involves many tonnes of ores that have to be mined, purified and processed. In fact the quantity of wastes associated with raw material extraction often far exceeds the amount of useful product. For example to produce one tonne of virgin copper, 250 tonnes of copper ore must be processed, this leaves 249 tonnes of 'waste', and still excludes process water which is a another major input. Fundamentally this is the basis of all resource flow calculations but without a more developed methodology it cannot be easily applied to the flows of an individual building.

5.3.3 Material Intensity Per Service Unit (MIPS)

Along similar lines is the work of the Wuppertal Institute. They have established the material intensity per service unit (MIPS) concept (Liedtke and Merten 1994). For all types of goods and services, they estimate and calculate the material flows in tonnes on a cradle to grave basis. As goods tend to represent the availability of services, it is ultimately the service that the good provides that is of interest to the user.

Material intensity is defined as the quantity of resources required to produce one unit of resource. The additional material that must be removed or is wasted in the production process has been termed the 'Ecological Rucksack', this is similar to the hidden and indirect resource flows of TMR above.

Figures 5.1 and 5.2 show the material intensity (including rucksack) of primary and secondary steel and aluminium (Liedtke and Merten 1994). Resources are differentiated into water, air and other natural materials, the energy intensity has been integrated. In its primary form aluminium is far more resource intensive to manufacture than steel, and has a far larger rucksack. Whereas in secondary form the two materials are more comparable, with both showing a considerable dematerialisation. Both secondary productions use 100% scrap, which in its first instance must have come from primary production.

Figure 5-1 Material Intensity and Ecological Rucksack of Steel Production

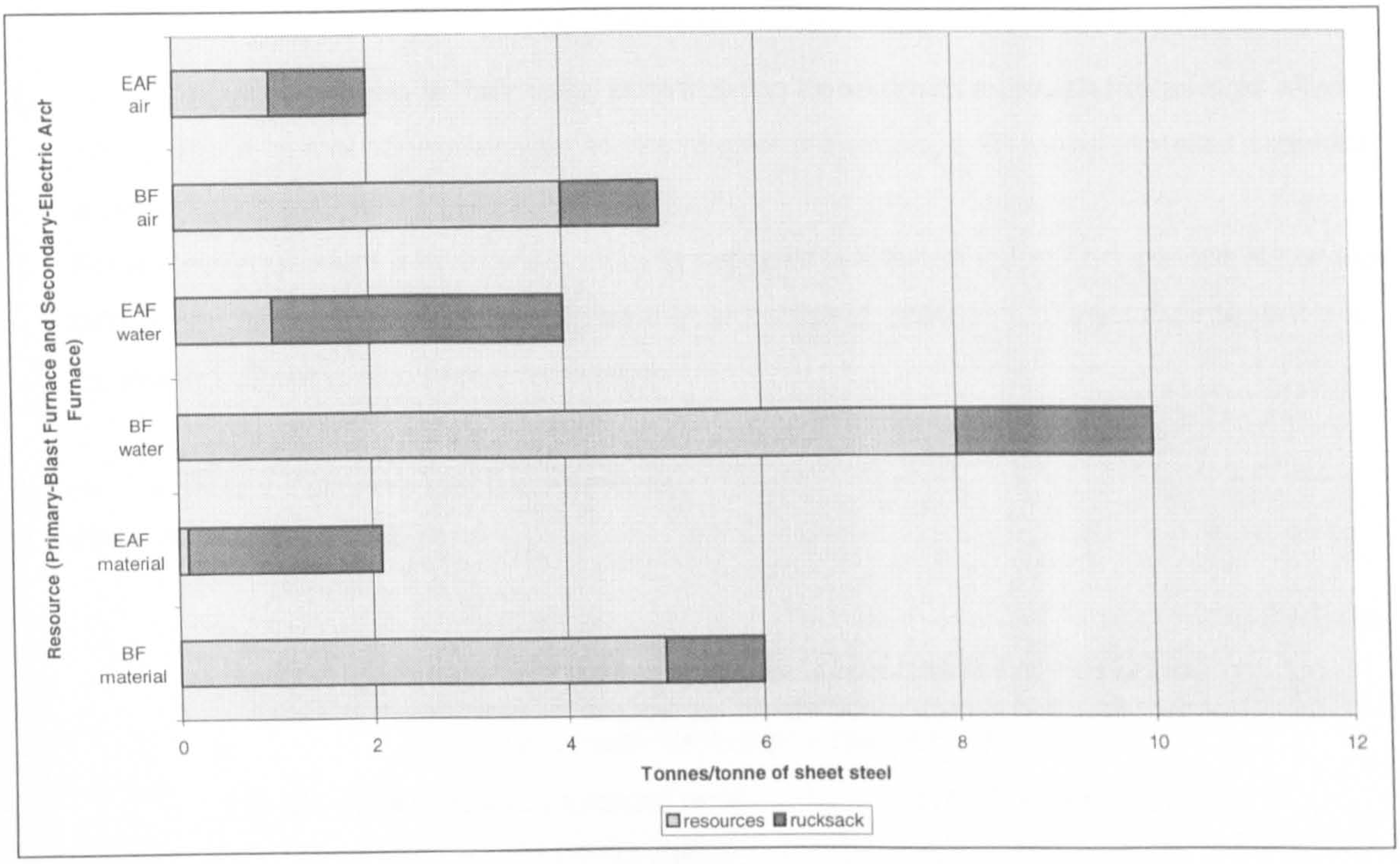
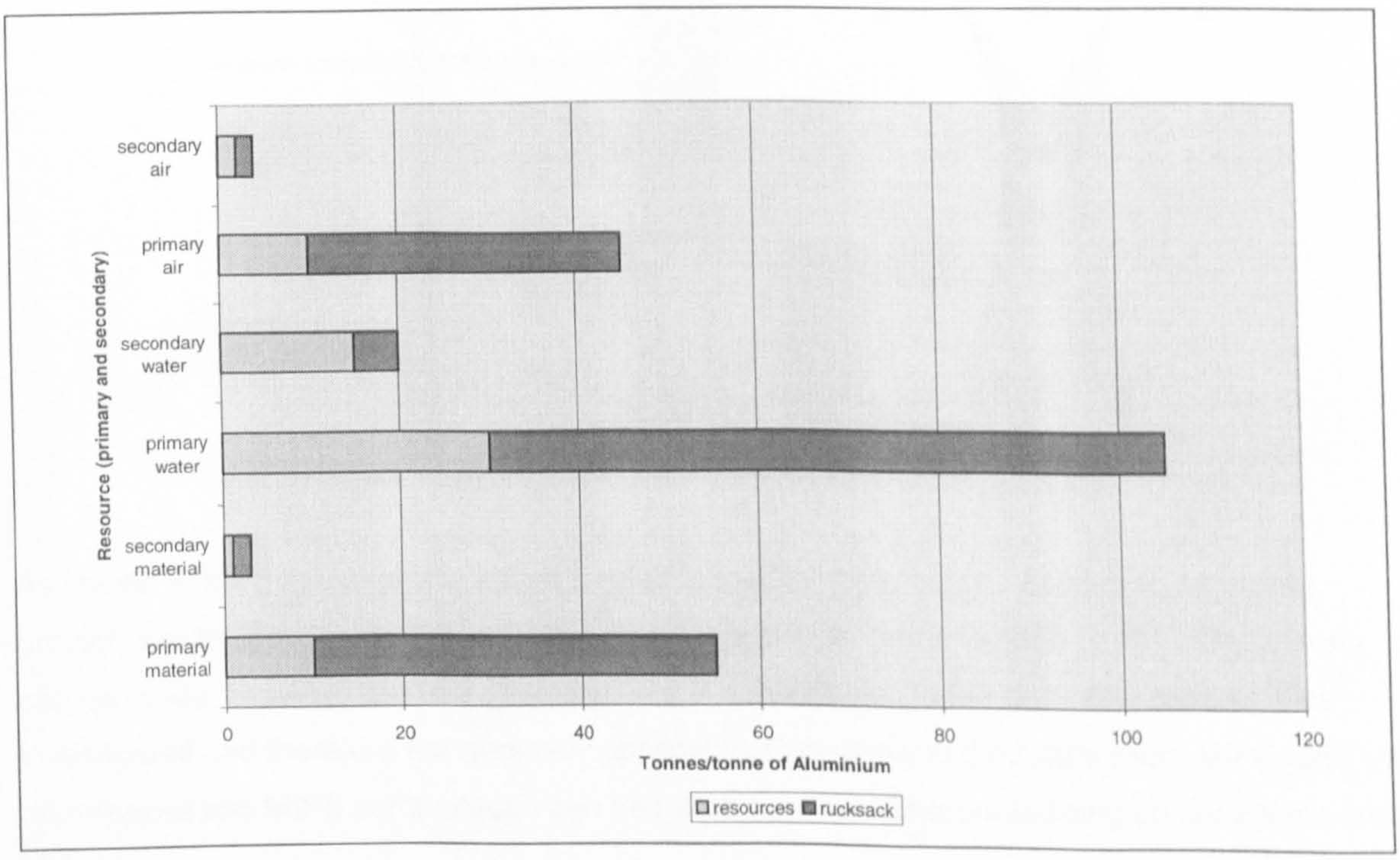


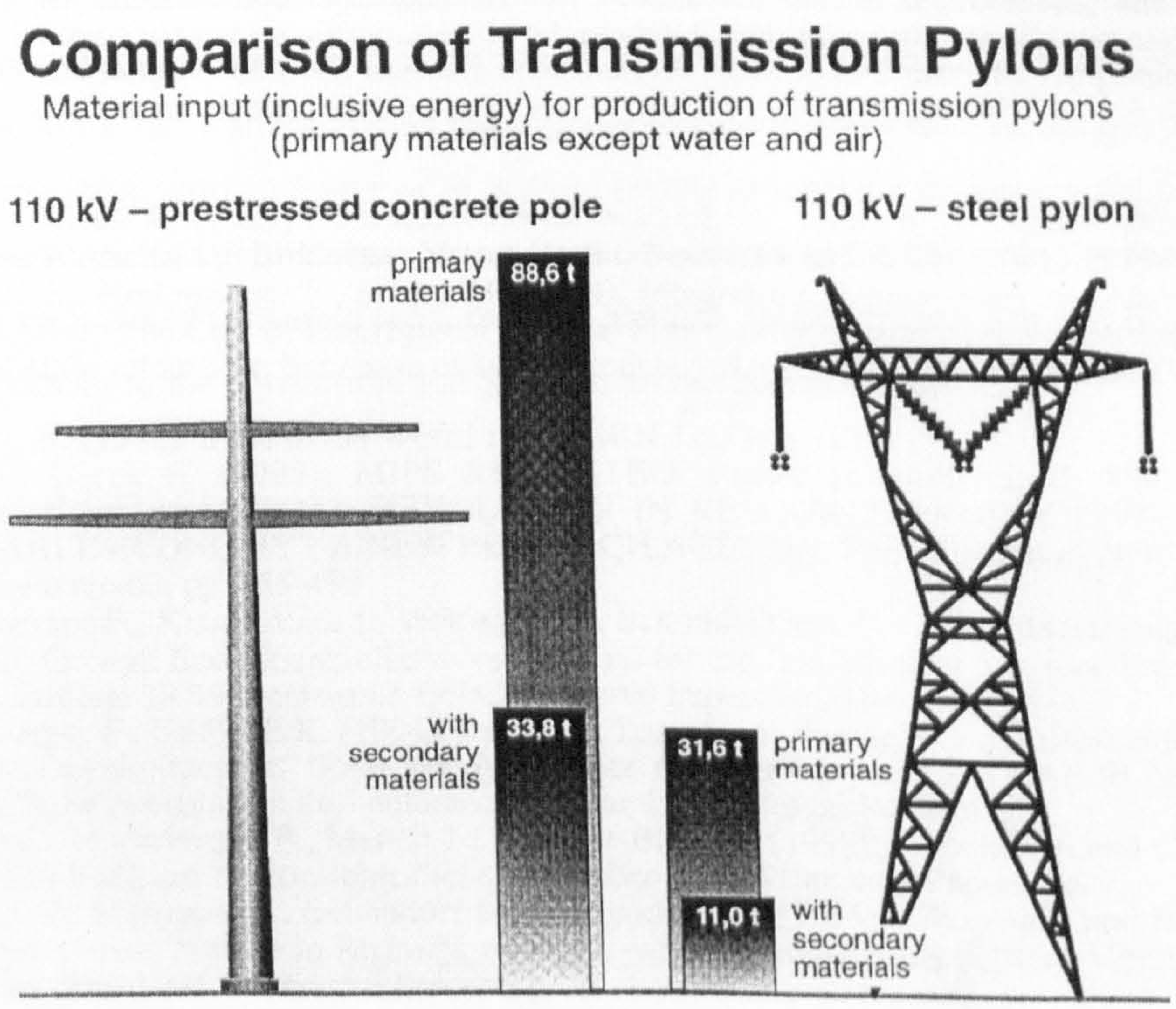
Figure 5-2 Material Intensity and Ecological Rucksack of Aluminium Production



Longevity of goods has a positive influence on MIPS, as it decreases the material intensity per unit time of the respected services. For example a comparison has made between steel and concrete electricity pylons (see Figure 5.3). With their service function being easily defined as carrying mains electricity of 110 kV for a fixed time span of say 40 years MIPS unit can be made. Two main differences make steel a more ecological choice:

1. Concrete pylons require in their initial construction three times as much material as steel pylons. For a typical concrete pylon in use in central Europe, a 90 tonne material rucksack is required for a 45 tonne pylon.
2. For a steel equivalent a 36 tonne rucksack supports a 6 tonne pylon.The service life of steel pylons can be twice or more as long as that of concrete, provided 10 year maintenance is conducted. Steel is also highly recyclable.

Figure 5-3 Steel v Concrete Electricity Pylons
(Liedtke and Merten 1994)



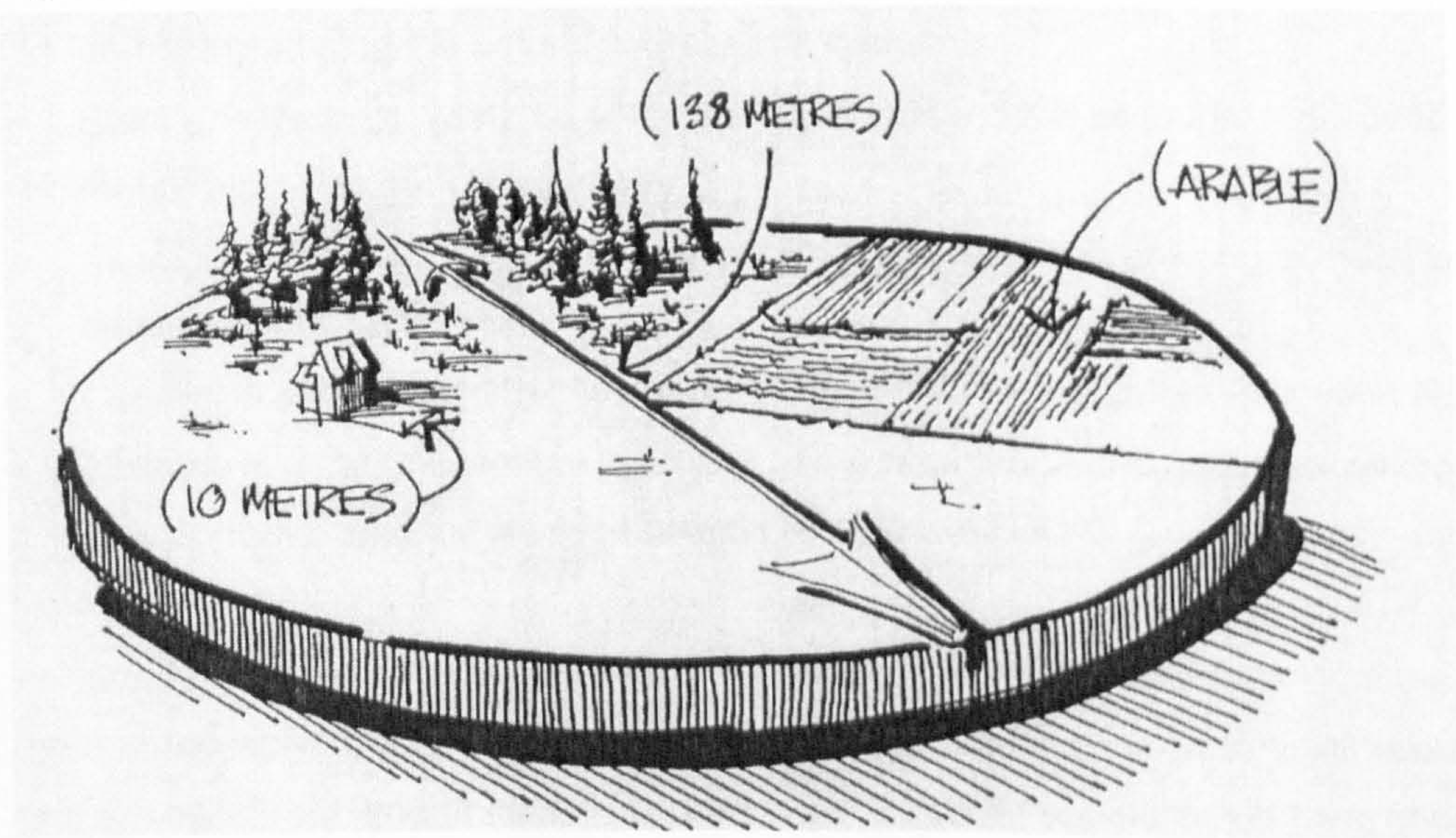
As shown in the pylon example above the MIPS methodology can be applied to a building project, and by looking at the service an element provides over a lifetime useful comparisons can be made. However the raw data available is very specific to the particular case studies investigated and therefore not generally applicable. Potentially in the future more MIPS data will be released and MIPS comparisons can be made between different building constructions and lifetimes.

5.3.4 Ecological Footprints

A different approach to resource flow accounting, is the Ecological Footprint model (Wackernagal and Rees 1996). The methodology relates the resource consumption and waste assimilation of any defined city/region/peoples to an area of ecologically productive land. The ecological footprint of a city is defined as *"the land required to supply it with food and timber products and to absorb its carbon dioxide output via areas of growing vegetation."* For example London's ecological footprint extends to around 125 times its surface area of 159,000 hectares. With 12% of the population, London requires the equivalent of Britain's entire productive land, of course this land stretches around the globe, from the wheat fields of Kansas to the copper mines of Zambia (p92).

Most of the footprint estimates are based on average national consumption and world average yields. This standardisation allows comparisons between regions and countries, however more detailed studies can be carried out. Comparisons can also be made against 'fair Earthshares'. The authors define a 'fair Earthshare' as the amount of land each person would get if all the ecologically productive land on Earth were divided evenly among the present world population. Currently this equates to 1.5 hectares, (down from 5 hectares at the beginning of the 20th Century), one sixth would be arable land, the rest pasture, forest, wilderness and built-up areas (p54). This is similar to the Environmental Space concept explained below.

Figure 5-4 Fair Earthshare



While providing invaluable information and useful analytical tools the Ecological Footprint method is not of direct use in detailed comparative studies of the impacts of the built environment. It is mainly concerned with flows of renewable resources, however, most building materials are from the non-renewable metal and mineral categories, created using fossil fuels. Therefore the Ecological Footprint methodology will not be used for this building investigation.

5.3.5 Environmental Space

Another methodology that attempts to quantify current consumption levels and then set targets for future consumption is the Dutch inspired, and Friends off the Earth developed Environmental Space concept (McLaren, Bullock et al. 1998).

Environmental Space is based on the 'Equity Principle', supply in relation to population. Everyone should have access to a fair share of resources and opportunities to live a pleasant and fulfilling life. For any country you compare the total environmental footprint for each resource with the estimates of the fair share of environmental space available to give a quantitative measure of how far from sustainability we are at present. The resources measured represent the basic material and physical inputs into the national and global economy:

- Energy is fundamental. It is the availability of energy, which has allowed us the freedom to exploit resources, which are unavailable to the rest of the natural world. It is also the direct cause of some of our most intractable pollution problems.
- Land is similarly basic. It provides food, shelter, fuel, and performs many self-regulating functions. Deforestation and soil erosion amongst others are vastly reducing its carrying capacity.
- Water is also vital. Without it there would be no life on Earth. Human intervention is now drastically altering the natural hydrological cycles.
- Steel was the basic material of the industrial age and still accounts for around 90% of all metals input into the UK economy.
- Aluminium is more typical of modern economies. Its use is growing in many sectors from construction to car making.
- Cement is a major construction material especially where timber is in short supply.
- Chlorine is a major chemical input and has a wide range of detrimental environmental effects from ozone depletion to health problems.

As with the other methodologies examined here, this concept also starts from the premise that the anthroposphere is embedded in the larger biosphere. It goes on to acknowledge that through either, our ignorance, or our short sighted human condition, we have chosen to live oblivious to this complex system with its multiple self-regulating feedback's. "*Sustainability is about meeting multiple goals in complex systems, complex natural and human systems*" (p72). The Environmental Space authors recognise that comparing and weighting different environmental impacts is more like comparing chalk and cheese than apples and pears. However, they maintain that there are certain life support systems that cannot be traded away such as the ozone layer or the tropical rainforests.

Similar to the footprint model it investigates the flows of resources through the human economy, and compares these to natural flows and potential future flows for sustainability. For example, flows of copper from the earth's crust to the Ecosphere are today 24 times larger than the corresponding natural flows. The authors comment that *"while there is nothing intrinsically unsustainable about exceeding natural rates of flow of such materials, these figures are indicative of the scale of the interference with natural processes that has resulted from humankind's exploitation of materials"* (p205).

The crux to the concept is in defining the global limits and sustainable rates of resource use. These are based on the premise that the most pressing limits are those of the ability of the ecosystem to supply renewables and absorb our wastes. The rates of non-renewable material consumption being confined more by these, rather than their intrinsic scarcity.

5.3.5.1 Environmental Space Targets for the UK

Accordingly the environmental space targets have been set for the UK, see Table 5.1, reduction is based on 1990 base levels.

Table 5-1 Environmental Space Targets for the UK.
(McLaren, Bullock et al. 1998), 241.

Resource	**Target reduction 2010 (%)**	**Target reduction 2050 (%)**
Energy	30	88
Land	7	27
Timber	65	73
Water	15	15
Aluminium	22	88
Steel	21	83
Cement	18	72
Construction aggregates	12.5	50
Chlorine	25	100

Friends of the Earth along with many other authors argue that these reduction targets are not unfeasible. Methods to achieve overall reductions in resource use, such as increases in efficiency, life extension, reduction of dissipative losses, and increased recycling levels are not beyond the ability of industry with current levels of technology. These reduction targets also provide a scale link between the resource flows in an individual building and the national and global material streams.

In many ways the environmental Space concept works in reverse to the Footprints model. Environmental Space defines global resource flows, calculates the reductions necessary for sustainability and then investigates each countries obligation necessary to achieve these reduced flows. This is a useful planning tool and provides a platform from which to compare any countries performance. However, as it deals with the large-scale flows, those of a whole country, it would be difficult to scale this down to the level of an individual building and project the percentage reductions needed to achieve sustainability. Therefore while providing interesting guidelines on the future rates of consumption of the basic physical and material inputs into the national economy, and so the construction industry, it is of little use in examining the resource flows through an individual building.

5.3.6 Life Cycle Assessment (LCA)

By far the most generally used and internationally accepted methodology for assessing the impacts of any project over its life cycle is Life Cycle Assessment (Clift 1998). Life Cycle Assessment (LCA) consists of four main stages:

- Goal Definition and Scope
- inventory analysis
- impact analysis
- improvement analysis

The first stage of the LCA process is to define the scope and boundary conditions of the study. These limit its extent, detail and accuracy. Next all the resource inputs and wastes resulting from the activity are quantified and tabulated. This is the inventory analysis, often called Life-cycle Inventory (LCI) and is by far the best-developed stage of LCA methodology. In the third LCA stage, an impact analysis is carried out which shows the environmental consequences of the flows being assessed. Impact analysis thus involves consideration of all potential environmental issues – water quality, effects of toxic emissions, ozone depletion, and the like. If two product designs are being compared the environmental impacts must be quantified and prioritised, an inherently contentious process. The final LCA stage, improvement analysis, is where the results of the first two stages are translated into the specific actions that reduce the impact of industrial activity on the environment.

5.3.6.1 LCA in Practice

In practice, it has proved difficult to complete detailed life cycle inventories, more difficult to relate those inventories to a defendable impact analysis, and still more difficult to translate the results of the first two LCA stages into appropriate actions (Graedel and Allemby 1996) ,p105. Table 5.2 below summarises this situation.

Table 5-2 LCA Stages

LCA Phases	**State of the Art**
Goal definition and scope	Defined
Inventory analysis	Defined, understood, needs further work
Impact Assessment	
• Classification	Defined, more work required
• Characterisation	Conceptually defined, partly developed
• Valuation	Conceptually defined, different methods & approaches currently being used
Improvement Assessment	Not yet documented, future uncertain

5.3.6.2 Energy and Carbon Dioxide as Environmental Indicators

As a result of these difficulties, comparisons between impacts are not generally made, and instead a number of environmental indicators are highlighted. Therefore most existing studies are closer to a Life Cycle Inventory (LCI) than a full LCA. For buildings, a single input and output criterion are the most widely used (energy and carbon dioxide respectively). Both in terms of embodied energy/ CO_2, that are bound up in the materials, and operational energy/ CO_2, that are used to service buildings. The reasons for this are as follows (Amato 1996) (Treloar 1996):

- Energy/ CO_2 are commonly used as indicators
- Data for energy/ CO_2 is widely available and it is possible to calculate during the processing of materials into products and the construction of buildings
- Related research uses energy/ CO_2 so results can be compared and data used
- The insatiable global demand in energy and resulting emission of CO_2 is recognised as one of the main issues of sustainability, and since the oil crisis of the 1970's, and the recent world wide interest in global climate change, energy and CO_2 have been perceived as being important indicators.
- Several commercial databases containing energy/ CO_2 information are in existence. This data has been assembled over the last three decades, emerging from the discipline of energy auditing.

Similar to the other studies examined above, LCA is interested in the flow of resources through a project, it defines the system boundaries and then details what flows in and out of this system. Considering the previous example of turning copper ore into copper, the embodied energy would be the amount of external energy required to complete this process. Therefore this would include that used to remove the overburden, extract the ore, process this and any other treatments required transform it into a useful state. This then is analogous to the 'hidden flows' or ecological rucksack' terms discussed earlier in this chapter (see section's 5.3.1 & 5.3.3).

5.3.6.3 Selecting a methodology

The building industry was an early leader in adopting LCA methodology and consequently there have been many papers on its application to building studies and a range of projects where it has actually been applied. Accordingly, this thesis also uses LCA methodology, adopting energy and carbon dioxide as the two environmental indicators. It is though acknowledged that these are neither the only nor necessarily the most important indicators and for a full comparative analysis many more impacts must be quantified. The other methodologies reviewed earlier in this chapter identify some of these other impacts, and as described in section 5.3.6 above, the ultimate aim of LCA is to compare indicators such as global warming, ozone depletion and toxic emissions.

5.3.6.4 Setting Parameters

Internationally, several building related LCA's have been performed at the systems or whole building level (Jonsson, Bjorklund et al. 1998). These all recognise that comparing a mass of one material against another is not enough, what is needed is a means of comparing the environmental consequences of alternative combinations of materials to perform the same function. For example, comparing a tonne of steel versus a tonne of concrete is of little value, as each material is used in (structurally) distinctively different ways. What is of value is to compare the impacts of the equivalent, for example an office floor. This is the **Functional Unit** and for most is taken as a m^2 of building floor plan.

Other parameters to be set include: the boundary conditions, the structural assemblies, the life cycle steps taken into account, the environmental loads addressed, and how the impact assessment and interpretation of results is performed.

The boundary conditions limit the global extent of the investigation. They can be set around the 'product' or 'building' in its final state or can try and include the supply of all resources required for manufacture. This can be further worked back until you get to the impacts for the extraction of the raw materials. Even here one has to decide whether the infrastructure required to conduct this extraction (for example roads, mining equipment and human labour) is included or excluded.

To make the study worthwhile the structural assemblies investigated must be comparable with one another and representative of actual building types. Buildings are operational for a considerable time period and go through a number of lifecycle stages from construction, through use, refurbishment and reuse to final demolition and material recycling or landfilling. All these stages need to be included to get a clear picture of the whole life impacts of buildings. However studies can be conducted for any stage as long this is transparent from the investigation.

5.3.7 Review of Existing LCA Case Studies

Below four existing LCA studies, which use embodied energy and carbon dioxide as the environmental indicators are reviewed. However, the other parameters (see previous section) all vary considerably. Consequently while the results and conclusions of these studies all add to the current level of knowledge about the impacts of the built environment they are difficult to compare with one another (Jonsson, Bjorklund et al. 1998).

5.3.7.1 LCA Study 1, by Graham Treloar (Treloar 1996)

The Environmental Impact of construction – A Case Study, November 1996.

The subject of this case study was a 15 storey commercial office building in inner city Australia. The frame was constructed of reinforced concrete and the exterior clad with precast concrete panels and curtain walling. It has a Gross Floor Area (GFA) of 47,000m2.

The aims of study were to:

- To examine the current state of energy analysis (i.e. embodied energy rates)
- Determine the national average energy intensities for the energy analysis of a case study office building.
- Estimate the likely ranges of variation in the building material embodied energy rates from the national averages.

The report concluded that:

- Embodied energy is a significant component of the life cycle energy requirements of a building. Over a 40-year life cycle the embodied energy requirements of the Melbourne case study office building accounted for 60% of the total energy requirements. It then goes on to note that for future developments the significance of embodied energy is likely to increase due to; increasing efficiency in building operation, increasing use of more energy intensive building materials, and the use of more complete embodied energy assessment techniques.
- The significance of the impact of the building materials decreases rapidly from the main ones. The main structural elements account for 38% of the embodied energy. Therefore while office buildings should be retained as long as possible, significant savings are still possible through the retention of the major structural elements.
- Embodied energy analysis is very complex and includes many variables. The national average energy intensities for Australian building materials were considered to be unreliable due to the assumptions made, and the potential variation from the national average values.

Due to climate variations and so differences in the heating and cooling seasons, and also the fuel mix combinations for primary energy production,direct comparisons between UK and Australian embodied and operational energy figures are very difficult to make. However, even in the UK's colder climate it is now estimated that the majority of an office's thermal comfort energy demand is for cooling not heating (Baker 1997); this is likely to be more pronounced in Australia (however, a more detailed breakdown of the operational energy was not available). Therefore it is interesting to note that 60% of the energy used during the life of the case study building can be attributed to embodied energy. This runs counter to the current perceived wisdom which suggests that operational energy accounts for 80% plus of a buildings total impacts.

It was also interesting to note that almost 40% of the embodied impact was attributed to the structural frame and skin. The author goes on to suggest that it would therefore be environmentally beneficial to retain these layers and extend the life of the building through refurbishment. However it is unclear whether the other layers of the building were studied in any detail and if the lifetime changes to these layers (services, space plan and stuff) were included in the investigation. As these are the relatively quick change layers, compared to the frame and cladding, they could have considerable impact over a 40 year lifetime.

5.3.7.2 LCA Study 2, by Jonsson (Jonsson, Bjorklund et al. 1998)

LCA of Concrete and Steel Building Frames.

This study examined the environment impacts of seven concrete and steel building frames representative of present day building technologies in Sweden. The study was split into four residential and three commercial buildings, the residential comprising of an insitu concrete frame, a precast concrete frame, a steel/concrete frame and a steel/steel frame. The commercial comprising of all but the later. The functional unit was defined as one average m^2 of floor area during the lifetime of the building, this included construction, use and demolition. The entire building was not defined, the study being more concerned with a representative segment on which the function unit was based (Jonsson, Bjorklund et al. 1998).

The aims of the study were:

- To Learn about the environmental impact of structural concrete and steel frames in buildings throughout the life cycle,
- To create a model for assessing and improving future frames, and
- To study the methodological problems that arise when performing LCA for such a complex structure as a building frame.

The conclusions of the study were as follows:

- The steel frames had a slightly higher environmental impact than the other frames, but the span between highest and lowest values was not significant enough to draw any conclusions about which frame construction had the lowest environmental impact.
- The building construction had about the same contribution as the maintenance and heat losses through external walls during service life. Whereas demolition and final disposal has considerably lower impact assuming that all demolition materials are used on site as fill and are not defined as waste.
- The impact of total theoretical energy use during service life largely exceeds the impacts from the other life cycle stages, when assuming a user time of 50 years.
- The relative importance of the environmental indicators was dependent upon the assessment method used.
- The risk of mistakes in the analysis increases with the degree of complexity of the functional unit. It also becomes more difficult to get consistency when applying chosen system boundaries.

Contrary to the first study, the Swedish study estimated that operational impacts over a theoretical 50 year lifetime would be far greater than the embodied impacts accrued over the same time period. The heating season is very different in Sweden to Australia which could account for some of this difference, however as more specific details were not provided it is difficult to compare these in greater depth.

As with the previous study the impact of the fast changing internal layers of the building over the life cycle have not been discussed and it is unclear whether they have been considered in the total lifetime embodied energy calculations. Again these could influence the ratio of embodied to operation energy. Also worth recording was the lack of significant difference between the impacts of the steel and concrete frames, indicating that for the same functional unit both have similar impacts.

5.3.7.3 LCA Study 3, by Brocllesby (Brocklesby, 1998).

The Environmental Impact of Building Frames

This Study investigated the environmental impacts of the choice of structural frame materials when used in a number of standard office buildings from a UK vantage point (Brocklesby, 1998). The results were calculated based on both a standard set of environmental impact data for construction materials and also with various parameters changed to highlight the sensitivity of the analysis to the data selected. The study then went on to suggest ways in which the environmental impact of structural frames may be minimised.

The aims of the study were then:

- To compare the environmental impacts of a number of steel and concrete office frames, and;
- Using a range of parameters more sensitive to local conditions, concrete substitutes and recycled steel, assess both the sensitivity of the initial results and examine plausible alternatives to the standard data.

Four pairs of structural frames were assessed, these had a reinforced concrete frame and floor and a steel frame and composite floor option. The parameters selected in the sensitivity study were mostly related to the specification of the concrete in the structural frame. Concrete, due to its cement content, has a relatively high carbon dioxide value but this can be greatly affected by using cement substitutes or selecting a lightweight concrete. The parameters used in the study to estimate the extreme cases were as follows:

- On site recycling and batching. This assessment assumes that the concrete mix designs remained the same for mixes using recycled aggregates.
- High and low values for aggregate and cement content were used to calculate the upper and lower bands for these environmental impacts.
- The use of cement replacement materials in concrete mixes
- The two factors of mix design and on site batching and recycling were combined to give an overall lowest value for concrete use.
- Values for new and recycled steel were used to give a higher and lower steel value for the frames.

For the majority of the structural frames investigated, a steel frame structure required a higher energy input than an equivalent concrete frame. When cement replacement materials were used, the difference becomes more pronounced, but when recycled steel is used the difference is reduced. However, the carbon dioxide requirements are similar for both material types. Where Ordinary Portland Cement (OPC) concrete is used the steel frame produces about 10% less CO_2. When cement replacement materials are used, the concrete frame might release 10% less than the equivalent steel frame. As cement production releases a very significant quantity of CO_2, great improvements can be made in a structures environmental performance by the reduction of this material.

This study highlighted a number of ways in which the environmental impact of structural frames may be minimised. Particularly focusing on using cement replacement materials to reduce the energy and CO_2 impacts from concrete, although this may increase transportation impacts. The report did not however, look at any of the other layers of the building and the impact of changing these over the lifecycle.

5.3.7.4 LCA Study 4, By A Amato (Amato 1996)

A Comparative Environmental Appraisal of Alternative Framing Systems for Office Buildings

This study was initiated by Oxford Brookes University, in partnership with the Steel Construction Institute, in response to claims made by various 'concrete interest groups' that the use of reinforced concrete construction is environmentally more benign than equivalent construction using steel[4].

Aims

The aims were as follows:

- To determine if there is any difference in the 'environmental performance' of steel and concrete framed office buildings.
- To determine if there is an operational energy benefit in the passive thermal performance of concrete compared to steel framed buildings.
- Investigate the relationship between operational and embodied energy.

Frames and Service Systems

The SCI study considered two office buildings, a four storey and a higher-specification, eight storey building. Five structural systems incorporating a range of service options from natural ventilation, through various mechanical systems to full air conditioning were modeled, see

[4] Henceforth it will be referred to as the SCI study.

Tables 5.3 and 5.4. The life-cycle energy inputs and CO_2 outputs were modeled for a notional 60-year building life including some refurbishment. Data for building quantities and initial embodied energy and CO_2 levels was supplied by David Langdon & Everest quantity surveyors. Office design and layout was selected after consultation with a steering group, brief details are given below, with a more detailed design specification in Appendix B.

Table 5-3 Variation of initial structural embodied energy and CO_2 with different structural systems
(Amato 1996)

Type of Structural system	Embodied energy (GJ/ m^2)	Embodied CO_2 (kg/ m^2)
A. Steel frame, slim floor beams with precast concrete slabs	2.6	251
B. Steel frame, composite beams and composite slabs	2.6	241
C. In-situ reinforced concrete frame and slabs	2.5	286
D. Steel frame, cellular beams with composite slabs	2.9	259
E. Concrete frame, precast concrete hollow core units	2.7	333

Table 5-4 Comparisons of services options over 60 years

Type of Service System	Operational energy (GJ/ m^2)	Operational CO_2 (kg/ m^2)
1. Heating and natural ventilation	12.7	724
2. Heating and mechanical supply and extraction	36.0	2239
3. As 2 above with extraction via a false floor	36.0	2235
4. As 3 above with enhanced heat transfer from the slab	36.2	2247

SCI Functional Unit

Functional unit is taken as one squared metre of gross floor area (GFA) of office. To get to this stage, the total area for each element is multiplied by the unit weight, the elements for each layer are then summed, and this total divided by the gross floor area (2600 m^2). This means that floors, wall elements, roof etc are all calculated on a m^2 of GFA basis, similar to a cost per m^2 calculation.

SCI Key Definitions and Methodological Boundaries

Within this study embodied energy is defined as:

> *The total primary embodied energy/ CO_2 consumed during the complete manufacturing process, from extraction of raw materials to the point of economic use, including all transport energy.*

Primary energy is the energy generated not that delivered to the distribution system and can be defined as:

> *The total calorific value of all the hydro-carbons extracted from reservoirs of stocks of fuels, plus the electricity imported and the electricity generated by nuclear, hydro, wind and tidal schemes.*

However as with all studies a number of further definitions are needed to clarify how embodied energy and CO_2 values have been calculated. In this study these are as follows:

- Feedstock Energy. Throughout this study feedstock energy has not been included in the embodied energy calculations, as the database used does not include these values.
- Partitioning. This considers the by-products or co-production from a material manufacturing industry. No allowance has been made for partitioning of construction materials within this database.
- Imports. Embodied energy values of imported materials have been calculated as far as data is available to reflect the actual energy used, in their production and transportation both in to and out of the UK.
- Timber and Sequestered CO_2. In some LCI's the CO_2 burden of timber (e. that generated during processing) has a deduction made equal to the quantity of CO_2 it fixes from the atmosphere. Where 'green' timber is used from a local plantation and there is minimal processing of sawn timber the embodied CO_2 burden will be relatively small. However apart from specific projects the majority of UK constructional timber is imported, kiln dried, treated with preservatives and transported long distances by road.
- Transport and Embodied Energy. The transport component of embodied energy is significant, especially for aggregates, sand and some natural stone, were the transport can be the largest energy input. Therefore the SCI study carried out further research to check the road transport components of the key materials compared.
- Recycling and Reuse of Construction Materials. In this study all recycled and reused materials have been assumed to have a zero embodied energy/ CO_2 value.
- Operational Energy/ CO_2. Operational energy is considered as the energy required to operate the building for its function and includes the following energy inputs:
  - Heating, cooling, ventilation and lighting.
  - Small power usage, i.e. computers and office equipment.
  - Other services, i.e. lifts, security systems, telecommunication systems.

The conclusions of the SCI study are as follows:

- There is no significant difference in the embodied energy/ CO_2 between steel and concrete framed office building. The concrete options are higher in terms of CO_2 and the steel in terms of embodied energy. This generally agrees with the Swedish study (LCA study 2).
- Transportation components are a major factor in calculating the embodied environmental burdens. This was the only study to undertake a transport sensitivity study and so these results are difficult to compare. Concrete materials generally tavel short distances, but as they are bulky require large transporters and a large number of trips. Metal products on the other hand can be stacked more efficiently however they may travel great distances, steel sections often being imported from Europe or further afield.
- Over the lifetime of a building, the operational (or in use) environmental burdens greatly exceed the embodied burdens- typically by a factor of 10. This contradicts the work by Trealor but is more in agreement with the Swedish study.
- The additional burdens associated with repairs and maintenance over the lifetime are significant. Further research is needed here to quantify these impacts.
- Natural ventilation systems can greatly reduce the lifetime operational burdens as compared with heating, ventilation and air conditioning (HVAC) systems.

5.4 Methodological Framework for New Research

In order to provide a consistent approach this study adopts the methodological framework of the previously discussed SCI study. This was selected for the following reasons;

- The database on which the study was based was made available and the support of the author given.
- This study was unique as it allowed identification and manipulation of the different layers to the building over the life cycle.

However, there were limitations to the SCI study, one of the main ones being the lack of sensitivity for the concrete data. For each type of concrete only one value was assumed while alternative recycled and reused steel values were offered. LCA study three, summarised above, concluded that the embodied values of concrete can vary considerably depending on location, batching and cement substitutes used. Whilst it is beyond the scope of this investigation to adopt such a concrete sensitive analysis, the range of values attributable to concrete are acknowledged. The SCI study also failed to:

- Provide a detailed breakdown of impacts into the different layers of the building.
- Examine the lifetime changes of these (separate) layers in more detail.
- Look at the increasing efficiency of mechanical plant and so reduced operational impacts.

- Examine different lifetime scenarios

Therefore, answering these questions will form the part of the aims of the next chapter.

5.5 Conclusions

This chapter has provided the context in which to address the core aim of Part III of the thesis which is to quantify were the greatest environmental impacts are over the lifecycle of an office building. It has identified a building type to be investigated, a methodology with which to do this and looked at a range of case studies were this methodology has been applied. In selecting office buildings and LCA, this study follows the general pattern adopted by the building industry.

The reviewed studies compared the impacts of steel and concrete office building frames. They concluded that there was no significant difference between the impacts of the steel and concrete frames. Steel frames generally being higher in embodied energy terms and concrete in carbon dioxide terms. Three of the studies compared the embodied impacts against the operational impacts over a notional lifetime, which varied from 40 to 60 years. However they disagreed when comparing the ratio of embodied to operational impacts over the specified lifetime. Two studies proposing that operational energy was up to ten times the embodied, whilst the third proposed that embodied accounted for 60% of the lifetime total energy.

The fourth study was sensitive to varying the impact of the concrete, through batching, on site mixing and cement substitutes. It concluded that it was possible to considerably lower the impact of a concrete frame through the careful selection of concrete variables. It also noted that using a recycled value for steel lowers its impact.

However, none of these studies were sensitive to the different time dependent layers of buildings, as they considered all layers combined as one or only considered the structural layer. Therefore this research aims to further the contribution to knowledge in this area by separating the time dependant layers and considering their total impact over the lifecycle.

It has also been noted that other methodologies exist, particularly the MIPS approach that might be of great value to building studies if more raw data was available. The service concept embedded in the MIPS approach offers an extra step in analysis, going beyond the product and to the service it provides, paving the way for de-materialisation and a more circular systems approach to the built environment.

6 OFFICE BUILDING LIFECYCLE INVESTIGATION

6.1 Introduction, Aims and Structure

In this second chapter of Part III a Life Cycle Assessment is conducted on office buildings to assess the environmental impacts over the lifecycle. This builds on the work developed throughout this thesis, using the methodology identified in the previous chapter to investigate buildings in their dynamic time dependent layers and look at the effects of Designing for Disassembly. As identified in the pervious chapter the core goal of Part III is to:

- **Determining where the greatest use of resources and major impacts occur throughout the building life cycle.**

This has been divided into the following aims, which continue from those of Chapter 5 and build on points raised at the end of that chapter which were focused around the shortcomings of the reviewed case studies.

- Identify the impacts of the different layers of the building, at initial point of use and over the lifetime.
- Compare the relative impacts of the different layers
- Examine the likely impacts for using building types which allow DfD
- Compare the embodied with the operation impacts over the lifecycle

The chapter opens with a description of the building type to be investigated, the parameters set and the embodied energy and carbon dioxide values adopted. It then continues with the actual investigation, starting with the impacts of the total buildings. Following this the buildings are separated into their time dependent layers starting with the first to be constructed and last to be removed- the foundations.

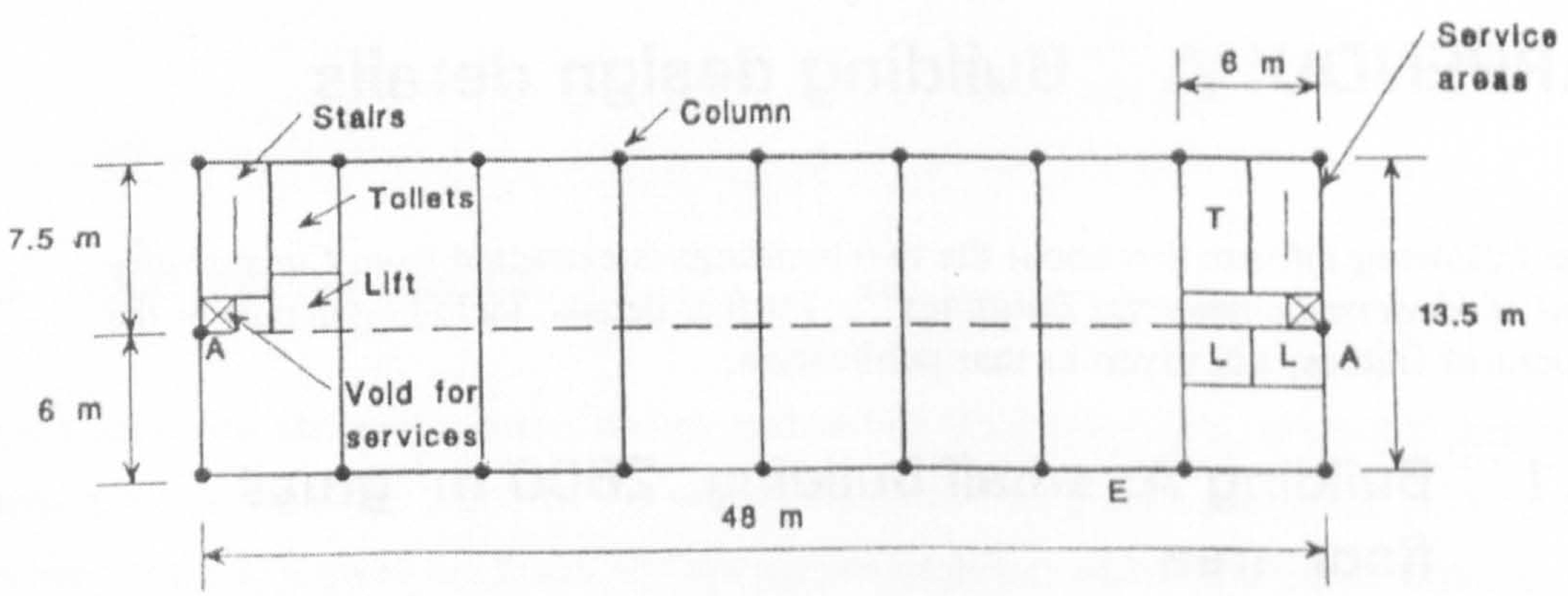
6.2 Case Study Parameters

Initially five standard frame and floor systems were investigated along with generic values for the other layers see Table 6.1. All these building systems were developed from a theoretical provincial city office building of four floors with a floor plan of 48 x 13.5 metres (648m^2), a live load of 5 KN/m2, and a one hour fire resistance (see Appendix B for detailed design specifications). The layout of the floor plate with internal column positions is given in Figure 6.1.

Table 6-1The Different Layers of the Building

Structural Layers	
Foundations	Reinforced concrete pad foundations
Frame options	
A	Steel frame, slim floor beams with precast concrete slabs
B	Steel frame, composite beams and composite slabs
C	In-situ reinforced concrete frame and slabs
D	Steel frame, cellular beams with composite slabs
E	Concrete frame, precast concrete hollow core units
Generic layers	
Roof	Steel frame, timber rafters, felt and tiles
Stairs	Reinforced concrete
Cladding	Facing Brick and block with UPVC windows
Finishes	Plaster, block and plasterboard
Raised floor	Steel plates with pedestals
Carpet	Wool polyester mix with underlay
False ceiling	Steel frame with mineral tiles
Services	Electric lighting and power and low temperature hot water heating, natural ventilation

Figure 6-1 Floor plate of building
(Amato 1996)



To provide uniformity throughout, the functional unit is taken (as in the SCI study) as one square metre of gross floor area (gross floor area is 4x648=2592m^2). Therefore for each element it is the total of that element for the entire building divided by the gross floor area.

The assessment indicates an input value (embodied energy), and an output/emission value (carbon dioxide), at the construction and also the subsequent changes during the use phase. This has been carried out within the framework of Life Cycle Assessment (LCA), being closer to a Life Cycle Inventory (LCI) than a full LCA. This is because no attempt is made to add relative weighting to the values or to translate them into indicators such as global warming or acid rain. Table 6.2 below shows the primary embodied energy and carbon dioxide values for the basic construction materials used in calculating the embodied impacts (for a complete list please see Appendix C).

Also included in the assessment is the mass value, this is the starting point for calculating the embodied energy and carbon dioxide values. Therefore providing the mass enables the future variation of; these values, the inclusion of other environmental indicators, or the use of alternative analysis systems such as the MIPS methodology described in chapter 5.

Table 6-2 Primary Embodied energy and CO2 values for basic construction materials (Amato 1996).

Material component	**Primary Embodied Energy GJ/t**	**Embodied CO2 kg/t**
In situ concrete substructure	0.84	119
In situ concrete superstructure	1.09	163
Reinforcement	26.8	2030
Precast concrete	1.36	203
Timber	13	1633
Chipboard	36	2560
Plywood	17	1465
Structural steel	26.8	2030
Sheet steel	34	2698
Facing Brick	11.7	878
Common Brick	5.8	490
Block	1.31	203
UPVC windows	120	12840

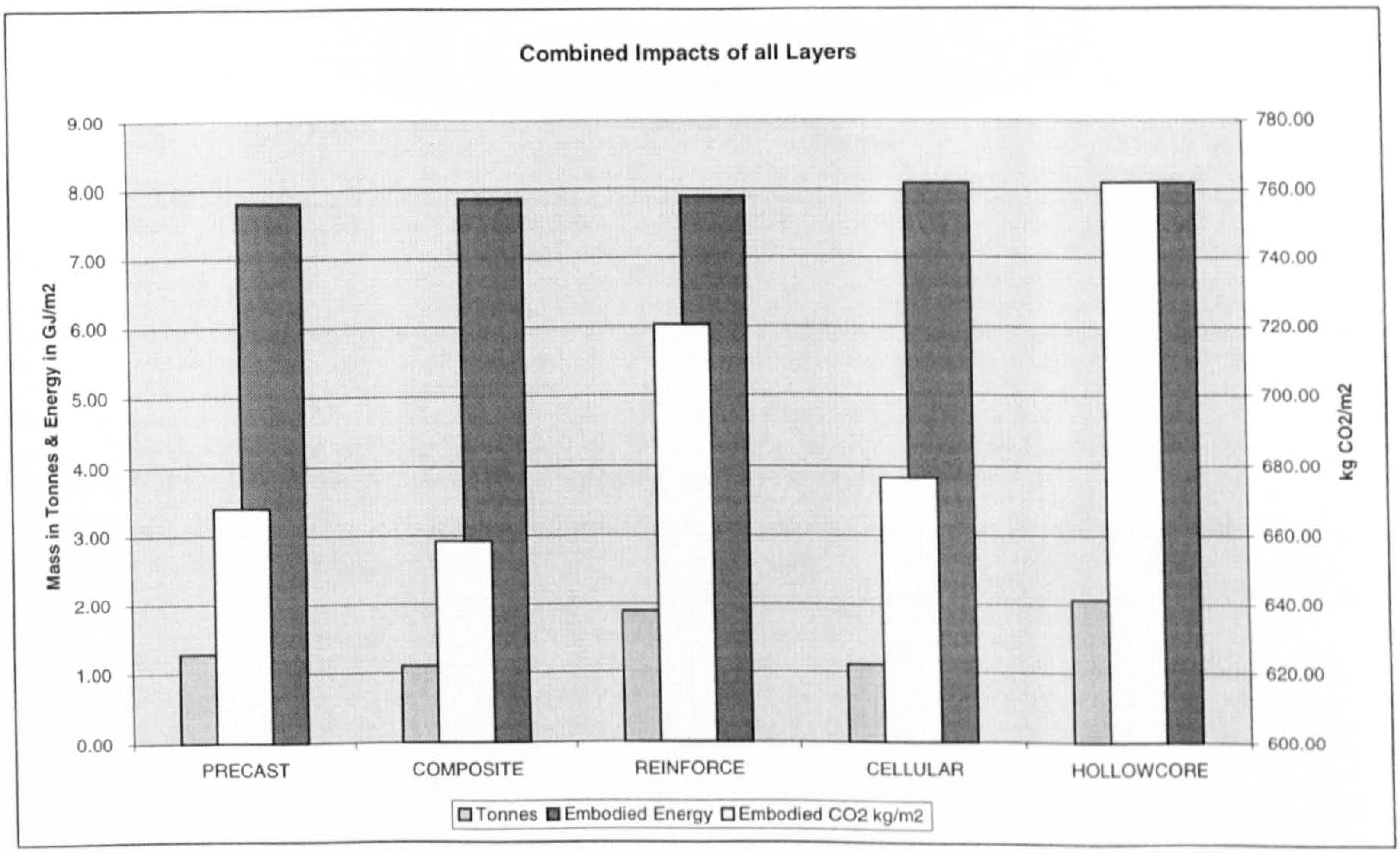
6.3 Total Building Impacts

Figure 6.2 below shows the mass, energy and carbon dioxide impacts, at point of use for all the building layers combined together. As with all the combined graphs presented in this chapter, the left-hand y-axis gives the mass and energy values in tonnes/m^2 and GJ/m^2 and the right hand y-axis the carbon dioxide values in kg CO_2/m^2. The graph indicates that, as found by the SCI study, the energy impacts of the five frames are very similar while the mass and CO_2 impacts vary according to the concrete content.

The composite floor office building has the lowest overall impact for the three categories assessed with the hollowcore the highest. Embodied energy ranging from 7.8 to 8.1 GJ/m^2, mass from 1.1 to 2.1 tonnes/m^2 and CO_2 from 658 to 762 kg CO_2/m^2 respectively.

For the composite floored building the percentage impact of each layer at point of use is shown below in Table 6.3. Figure 6.3 also presents the percentage impact of the various layers of the composite building. As would be expected the frame and floors make the biggest single contribution for all three values. When combined with the foundations and roof they account for 73% of the mass, 33% of the embodied energy and 39% of the CO_2. The brick and block cladding accounting for the next largest impact for any layer, with the embodied energy of the raised floor and carpet also being significant.

Figure 6-2 Total Combined Impacts



The cladding consists of an external leaf of facing brick, insulation, and an internal leaf of block, with UPVC windows, a very common cladding solution. Manufacturing facing brick is however, a very energy intensive process, as reflected in its high embodied energy and carbon dioxide figure (this is twice that of common brick, see Table 6.2). Using common brickwork or a more prefabricated external cladding system could lead to considerable savings in environmental impact. Whilst being highlighted here, this has not been explored in greater depth within this thesis and the major emphasis was on the frame and floors.

Figure 6-3 Percentage Embodied Energy Impact for Composite

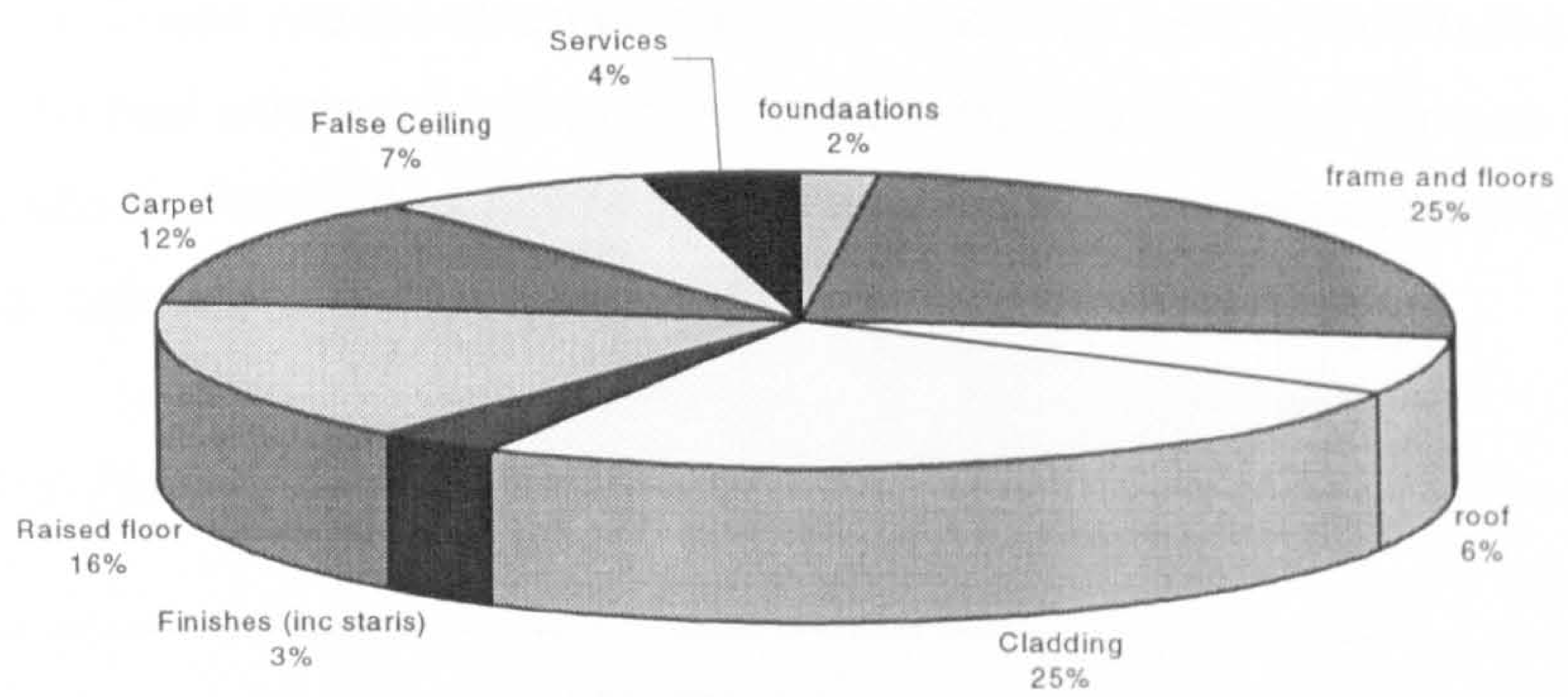


Table 6-3 Impact of each layer of Composite as percentage of total

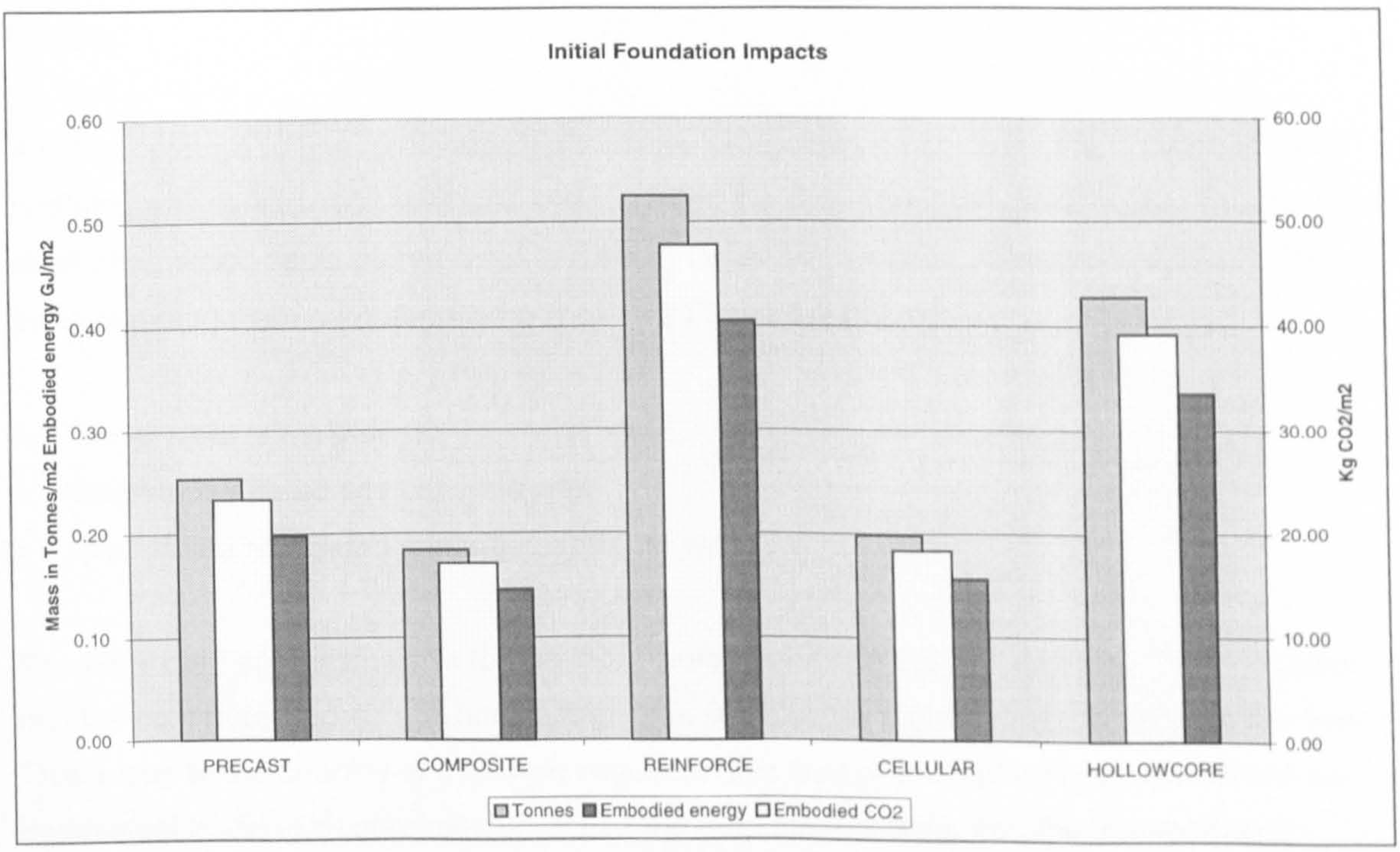
Composite Layer	Mass % of total	Embodied Energy % of total	Embodied CO_2 % of total	Ranking (1=high) mass	energy	CO_2
Foundations	17	2	3	3		
Frame and Floors	37	25	25	1	=1	1
Roof	19	6	11	2	5	4
Cladding	13	25	23	4	=1	2
Finishes (inc stairs)	8	3	4	5		
Raised Floor	4	16	14		2	3
Carpet	1	12	10		3	5
False ceiling	1	7	6		4	
Services	1	4	4			
Total	100	100	100			

6.4 Foundations

6.4.1 Description

For the five building examples considered the foundations have all been of steel reinforced concrete footings. These are the simplest and most common type of foundation construction. The volume of the pad varies according to the ground conditions and the mass of the superstructure above. For the five building types examined the foundations environmental impact varied as follows:

Figure 6-4 Initial Foundation Impacts



The three steel frame options have the least overall impact. At the start of the use phase the foundation embodied energy of the cellular frame was 0.16 GJ/m^2 and of the reinforced concrete framewas 0.41 GJ/m^2. Although twice that of the cellular this is still less than 5% of the total initial embodied energy. As the foundations are not changed their relative impact will be reduced by the end of the building's lifecycle.

6.4.2 Design for Disassembly Challenges

To fully implement a DfD strategy the whole building should be removed, however, concrete foundations are difficult to extract and are often left behind contaminating the site. Land contaminated by foundations of previous structures has become one of the main problems faced by groundwork contractors whatever type of substructure they are installing. In fact the term solid pollution is now used to describe old concrete foundations left in the ground on brown field sites (Wilson 2000). This has led to developers selecting green field sites where there is no danger of encountering abandoned foundations from previous structures (Gorgolewski 1997). Therefore although the percentage impact of the foundations over the building lifecycle is very small, the systems level environmental impact of the chosen foundation type can affect the long-term use of the site.

6.4.3 Possible Solutions

One option is to use lightweight buildings therefore minimising the foundations. The foundations for the lighter weight steel framed buildings in the above examples have less than half of the mass, embodied energy, and carbon dioxide impacts of the concrete based alternatives. However, designing with minimal foundations can restrict the future reuse potential of the building.

Another option is to use removable foundations, Gorgolewski examined the impacts of three retaining wall construction methods and identified the environmental advantages of using sheet steel piling which could be removed and either reused or recycled (Gorgolewski 1997). The three retaining walls compared were (see also Figure 6.5 below):

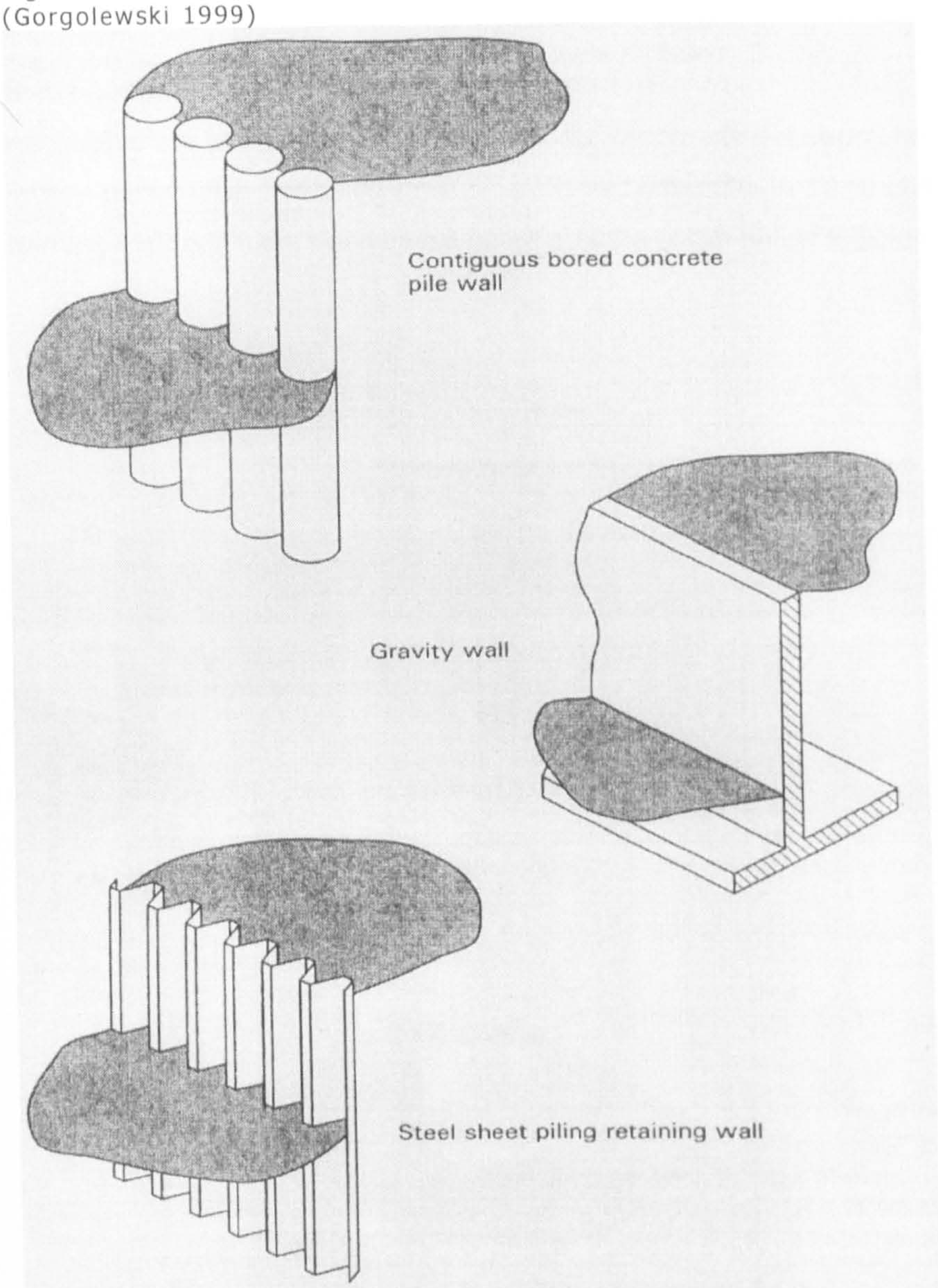
- Sheet steel piling wall
- Continuous bored pile concrete wall
- Cast in situ reinforced concrete cantilever wall

The embodied energy analysis for the three walls is given in Table 6.4 below. This indicates that the continuous bored pile construction has significantly higher impact than the other two. This is due to the quantity of materials required, (this type of foundation uses almost half as much steel in the form of reinforcement as the pure steel option), and the transportation necessary to bring these materials to site.

Table 6-4 Foundation Embodied Energy Analysis (Gorgolewski 1999), p31

Foundation	Embodied Energy (GJ/m length of wall)
Sheet Steel Piling Wall	26.5
Continuous bored concrete	37.7
In-situ reinforced concrete	25.9

Figure 6-5 Sheet, Continuous and Cast Foundations (Gorgolewski 1999)



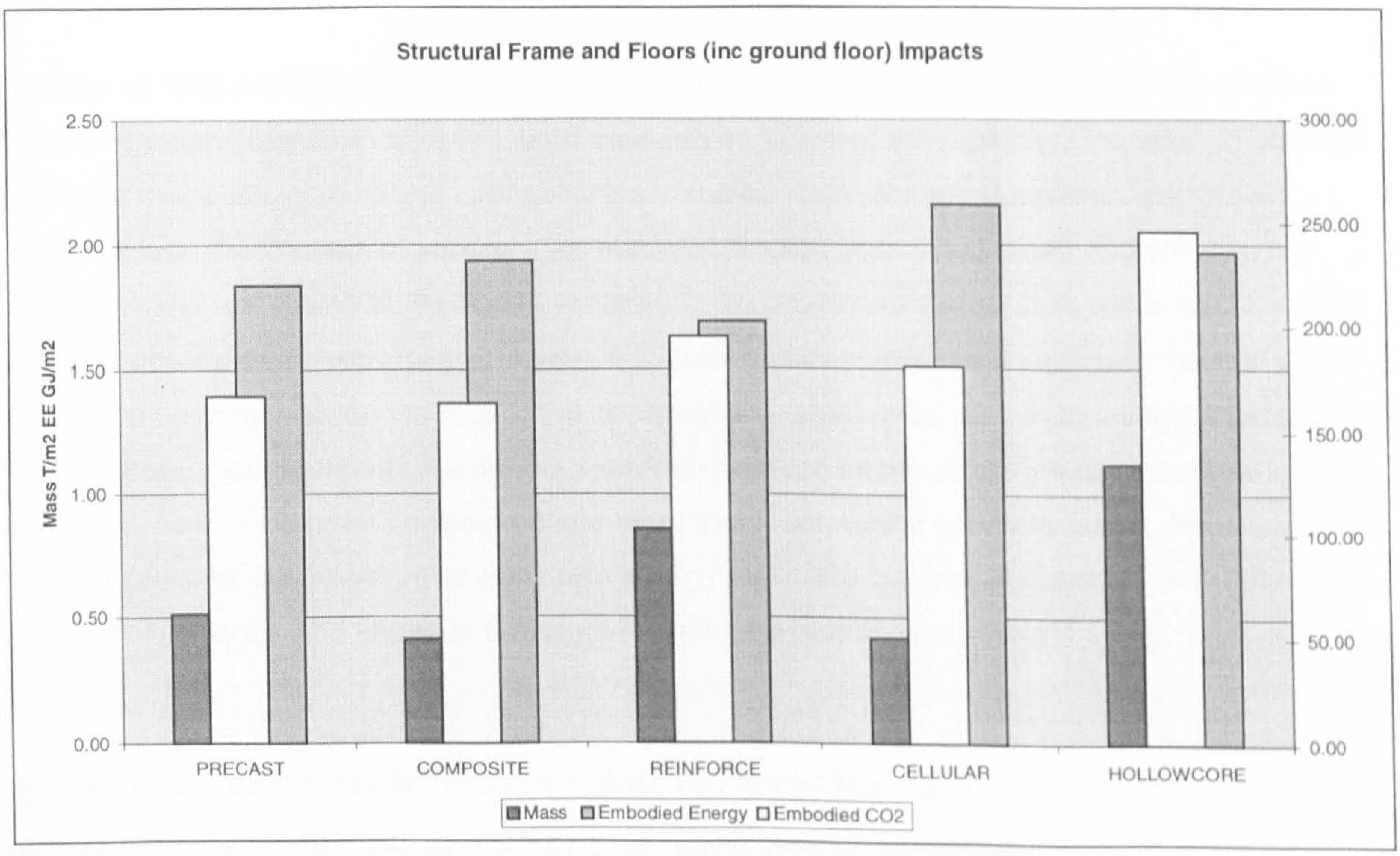
Steel piles can be extracted and a range of techniques using readily available equipment has been developed for this purpose. There is an established market for second hand piles if they are in sound condition. If not, they can be used as scrap steel and returned to the steel production process. However, a survey by Corus in 1998 indicated that only 3% of bearing piles are of steel construction (Wilson 2000). This was attributed to the noise and vibration problems of using a hydraulic hammer to drive steel bearing piles in urban areas. To overcome this Corus are currently investigating alternative methods of installing steel bearing piles. Concrete foundations have no such problems, but as indicated above a concrete pile has a much larger physical and ecological footprint than a steel pile of similar capacity.

6.5 Frame

6.5.1 Description

Although there are a multitude of methods for constructing a structural frame they all basically rely on using either hot rolled steel or reinforced concrete. In the analysis here five different framing methods have been investigated and the graph below indicates the relative impacts.

Figure 6-6 Initial Frame Impacts



The embodied energy values for the five frames varied from 1.7 GJ/m^2 for the reinforced frame to 2.2 GJ/m^2 for the cellular, indicating that the more steel intensive options have a higher embodied energy. These represent 22 to 27% of the initial total embodied energy.

However with CO_2 the relative impacts are reversed with the values ranging from 158 kg CO_2/m^2 for the composite to 246 kg CO_2/m^2 for the more massive hollowcore option due to cements high CO_2 burden, representing 25 to 34% of the total.

6.5.2 DfD Challenges & Possible Solutions: Concrete frames

It is well recognised that reinforced concrete frames cannot be disassembled and reused, the only option being crushing and possible recycling of resultant material into aggregate for new concrete. The steel reinforcement is generally separated and sent for recycling.

Whilst the disassembly and reuse potential of concrete frames is limited, Brocklesby indicated that by using cement and aggregate substitutes the initial embodied concrete frame impact can be significantly reduced (Brocklesby and Davison 1998). Ironically many of the cement substitutes are residues of the steel making operation, and such is their value that steel makers are often equally concerned about the quality of the residue as that of the steel produced.

Frames constructed from reinforced concrete are generally robust and, providing the systems level strategies have been adopted, lend themselves to future adaptability. Changing of building codes to make the local recycling of concrete into aggregate accepted standard procedure would reduce the impacts of concrete frames, which apart from the cement and steel reinforcement are mostly in the (local) excavation and transportation of bulk materials. There is also the possibility of reinforcing concrete with plastic fibre as oppose to steel. At the end of life this could be crushed with the rest of the concrete and considered as additional aggregate instead of as a contaminant. Replacing the steel may also increase the life of a concrete structure, as it is often the corrosion of the steel that leads to the concrete failing. Moisture attacks the steel if insufficient cover is provided or there is a fracture in the concrete. This then (oxidizes) corrodes and expands therefore blowing the concrete covering it.

6.5.3 DfD Challenges & Possible Solutions: Steel frames

Steel frames generally have slightly higher single lifetime embodied energy impacts. They do though have the potential to be disassembled and reused/recycled. The main issues surrounding the reuse of structural steel are:

- Fire Cladding
- Connections
- Standardisation
- Information

6.5.3.1 Fire Cladding

Most structural steel must be clad to increase its fire resistance. The fire rating of a building, given in hours, this is a function of its height, use, access and location.

There are two traditional approaches to increasing the fire resistance, a wet and dry method. In the wet method an intumescent paint is applied, or cementatous slurry is sprayed onto the steelwork. Both these methods make reuse difficult as it is difficult to identify the section sizes and all connections are covered. Also the covering must be removed through a mechanical or chemical process increasing the environmental impact of the reused steel.

The dry method involves encasing the steel with a plasterboard type material. These contain specific (silica) materials to increase fire resistance. This can more easily be removed allowing access to the steel sections.

A third method is to increase the section size of steel elements to provide standard fire resistance without additional cladding. In this approach steel members can be considered not in isolation but as part of a complete system. For example in the recently developed Slimdeck system by British Steel (now Corus) the asymmetric beams do not need additional cover to the bottom flange. This is due to the flange thickness being increased and also the fact that, as it is within the floor zone, the floor slab protects the web and top flange of the beam.

To negate the need for fire cladding for a whole building the section sizes would need to be increased by approximately 10% (Plank 2000).

For the three steel frame options examined, the embodied energy of the fire cladding ranges from 14% (Precast) to 30% (composite) of the total structural steel (frames and floors, see Table 6.5). In all three options increasing the section size of the structural steel by 10% and so eliminating the need for fire cladding reduces the overall frame embodied energy impact. This approach could also make the steel frame quicker to erect and deconstruct.

Table 6-5 Fire Cladding and Structural Frame variations

Frame	**Embodied Energy GJ/m2**			
	Fire Cladding	Structural Frame + Fire cladding	% fire cladding to frame	10% frame increase minus fire cladding
Precast	0.16	1.33	14	1.29
Composite	0.28	1.24	29	1.06
Cellular	0.31	1.48	27	1.28

6.5.3.2 *Connections*

To disassemble a steel frame, demolition contractors could unbolt at the connections. However, usually they cut the members where convenient, particularly if access is difficult or safety is an issue. The new hi-reach machines have hydraulic jaws that make cutting the steel members a straightforward operation.

A range of criteria have been identified which must be considered to enable connections to be reversed, these are (Angenent 1996):

- Reversibility. The connection can close and open several times without loss of performance.
- Standardisation. The connection can be ISO standardised world-wide.
- Tools/skills. Only standard tools and skills should be required.
- Fool Proofing. It should not be possible to make a false connection without this being obvious.
- Removability of elements. The connecting system should enable the removal of a single element, without having to remove several neighbouring elements.
- Compensation of form, tolerance and expansion. The connection should compensate for small deviations in form and dimensions and thermal expansion/contraction.
- Continuity. The connection should have virtually the same properties as the elements it connects.

In the second stage of this work, seventeen conventional (wet and dry) building connecting systems/materials were evaluated for the ability to meet the above criteria. From this analysis bolting emerged as the only existing technology that meets virtually all criteria. However bolting also has some disadvantages:

- Connections are only at predetermined locations but these locations are not standardized resulting in the inability to replace one member with another.
- A bolt is a point connection, while in buildings often line connections are needed, requiring lots of bolts (comparing bolted and welded joints).
- Access to bolted connections can often be restricted or dangerous.
- Bolted connections stand proud of the joint, are generally visible and may ruin the aesthetic of a building (again compared to welded connections)

However, like the other case studies reviewed in chapter 5, this research failed to identify the time dependent nature of a buildings layers. It assumed that all elements should be connected according to the same criteria. This is not necessarily the case as some elements are changed very infrequently, if at all, in the building lifetime where as others change very rapidly. For the long-term elements maybe sacrificial connections could be used. While these would be destroyed during disassembly they could enable the reuse of the element and a better initial connection solution. For example using a lime based mortar for connecting bricks or blocks in the skin. To disassemble the skin the mortar must be destroyed, it is a sacrificial connection.

However lime mortar is relatively easy to separate from the bricks (more so than cement based mortars) and the bricks may then be reused.

For the shorter-term elements such as the services; gas, water, central heating, electricity and telecommunications, manufacturers are developing 'plug and play' connections, which meet most of the criteria identified above (Angenent 1996). The modular jack used in telephone systems being a particularly good example. It is reversible, standardised, requires little skill and no tools can only be installed one way and is made of similar materials as the socket it fits into.

6.5.3.3 Standardisation

To optimally design steel framed buildings, designers select from a vast range of steel section sizes. Whilst this leads to the minimum quantity and mass of steel in the building the range of element sizes complicates their potential reuse. There is some talk within the industry to reduce the range of section sizes available from around the current 50 mark to something more like 12. In effect building from this reduced list of elements would increase the mass, and hence the impact of steel used in any individual building. However it could increase significantly the reuse of sections' which results in a considerably lower multi-life impact (Raven 2000).

6.5.3.4 Information

To be able to reuse steel there is a need to know prior to the instigation of a project the current reusable sections available or those that will be available from the demolition of existing buildings on the site. As identified in the demolition section, a database or catalogue of the location and size of all sections used would go some way to solving this issue.

Another method would be to adopt automatic identification (auto-ID) technologies to enable the rapid identification of components without recourse to keyboard entry. Ideally, the label would remain on the component throughout its service life. By linking the identification to a database, information on the component and any treatments, coatings or modifications could also be kept. Theoretically the history of the loading and resultant stresses and the 'past lives' of the component could also be stored. Finch, et al., has investigated the possibilities of using auto-ID systems such as; bar codes, smart cards, optical character recognition and radio frequencies (Finch, Flanagan et al. 1994). They conclude that auto-ID will inevitably become a key technology in the construction industry. After testing several systems, bar coding stands out as the most durable and cost effective solution to providing long term localised information of standard building components. For high value components which acquire complex performance histories an active tag system, similar to that already being used in the automotive industry could be adopted. This enables the updating of information recorded on the tag in real time without the need for physical intervention.

Whatever system is adopted, increasing the database of information and reducing the time to access it are likely to be key steps in raising the number of components and materials reused and recycled.

6.5.4 Future

Steel frames are almost internal scaffolding. As such they could be leased (from a developer or manufacturer) to the client for a specific lifetime or for the lifetime of the building. At the end this time the developer or manufacturer would regain ownership and either reuse insitu or deconstruct and reuse as part of a new build. Such a scenario would be heavily reliant on quality information being kept and the existence of the leasing agent at future date.

6.6 Floors

6.6.1 Standard Floors

As individual floors are not common to the whole of the building, as say the roof or the cladding, it is difficult to compare different floor constructions within the existing functional unit. Therefore for the floors a more direct comparison is made, with the functional unit being one squared metre of a 48x13.5m floor with the same layout and loading characteristics as used so far (as specified in Appendix B). The solid ground-bearing slab, as well as the four standard floor constructions listed below, was initially considered for this investigation.

Standard Floor Constructions:

- Precast. 200mm precast hollowcore units on steel asymmetric beams, see figure 6.7.
- Composite. Steel beams supporting steel decking with 120mm thick concrete slab (effective depth accounting for profiles 107mm), see Figure 6.8.
- Slimdeck. Asymmetric beams integrated into steel deep decking with 290mm concrete slab (effective depth accounting for profiles 145mm), see Figure 6.9.
- 200mm reinforced concrete flat slab and beam, see Figure 6.10.

As well as comparing the relative impacts, this investigation is aimed at identifying the potential for disassembly and reuse or recycling. Considering these floors, neither the composite, the Slimdeck nor reinforced floors can be disassembled. For structural integrity they all rely on the composite action between the steel and concrete, requiring the permanent bonding of these materials. However, whilst the possibility for reuse is limited, the crushing, separating and material recycling of these floor constructions is standard demolition procedure.

The precast floor panels on the other hand can be separated from the structural frame. As part of standard demolition practice they are often already lifted from the frame and crushed at ground level. Potentially they could instead be flat packed, transported from site, stored and reused elsewhere, provided a similar structural grid was adopted. In some instances a screed is poured over the top of the panels, making the job of separating the panels more onerous.

Figure 6-7 Detail of Precast Hollowcore Units

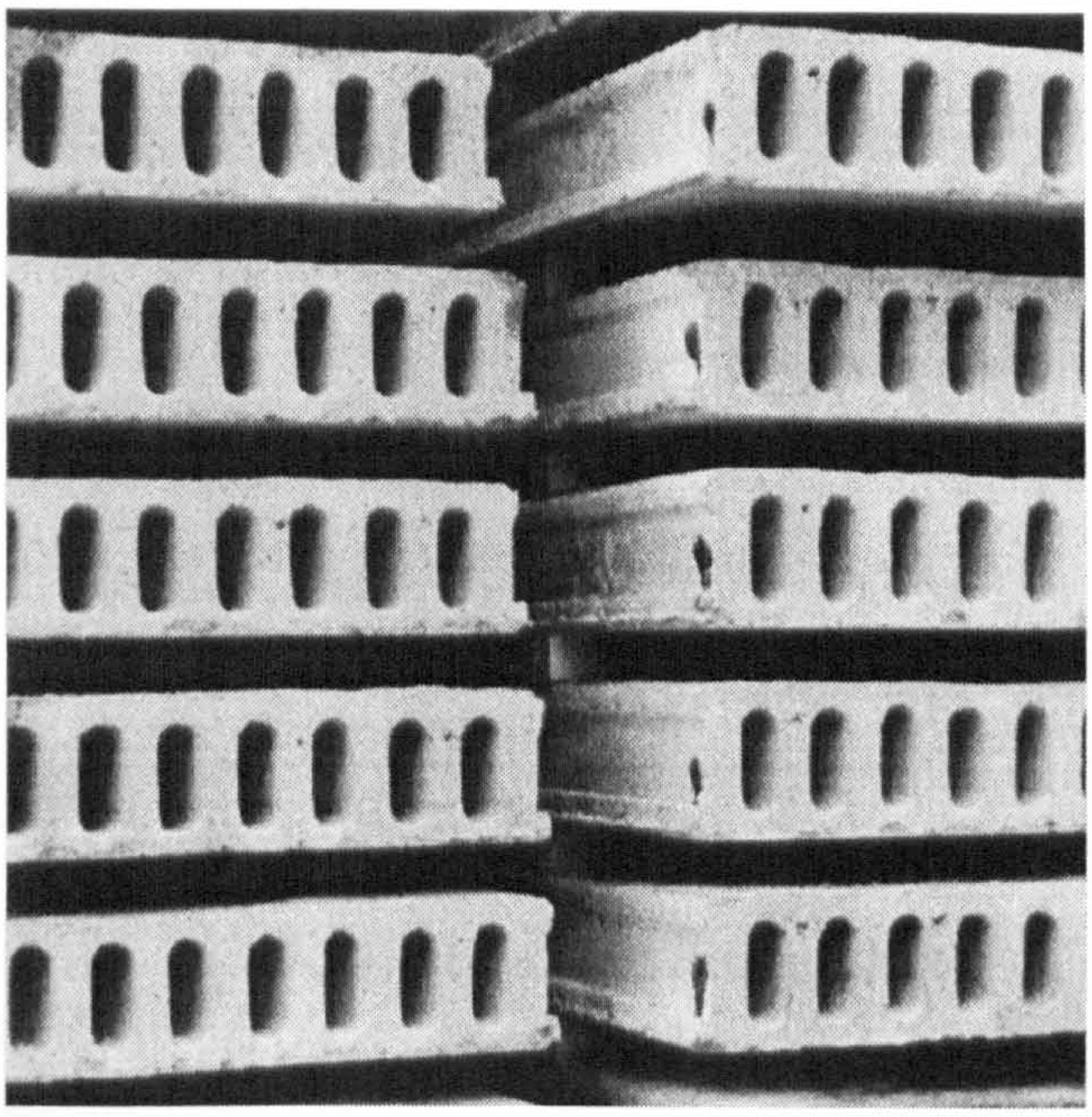


Figure 6-8 Detail of construction of Composite Slabs.
Note the supporting steel beam underneath the floor construction
(Trebilcock 1996)

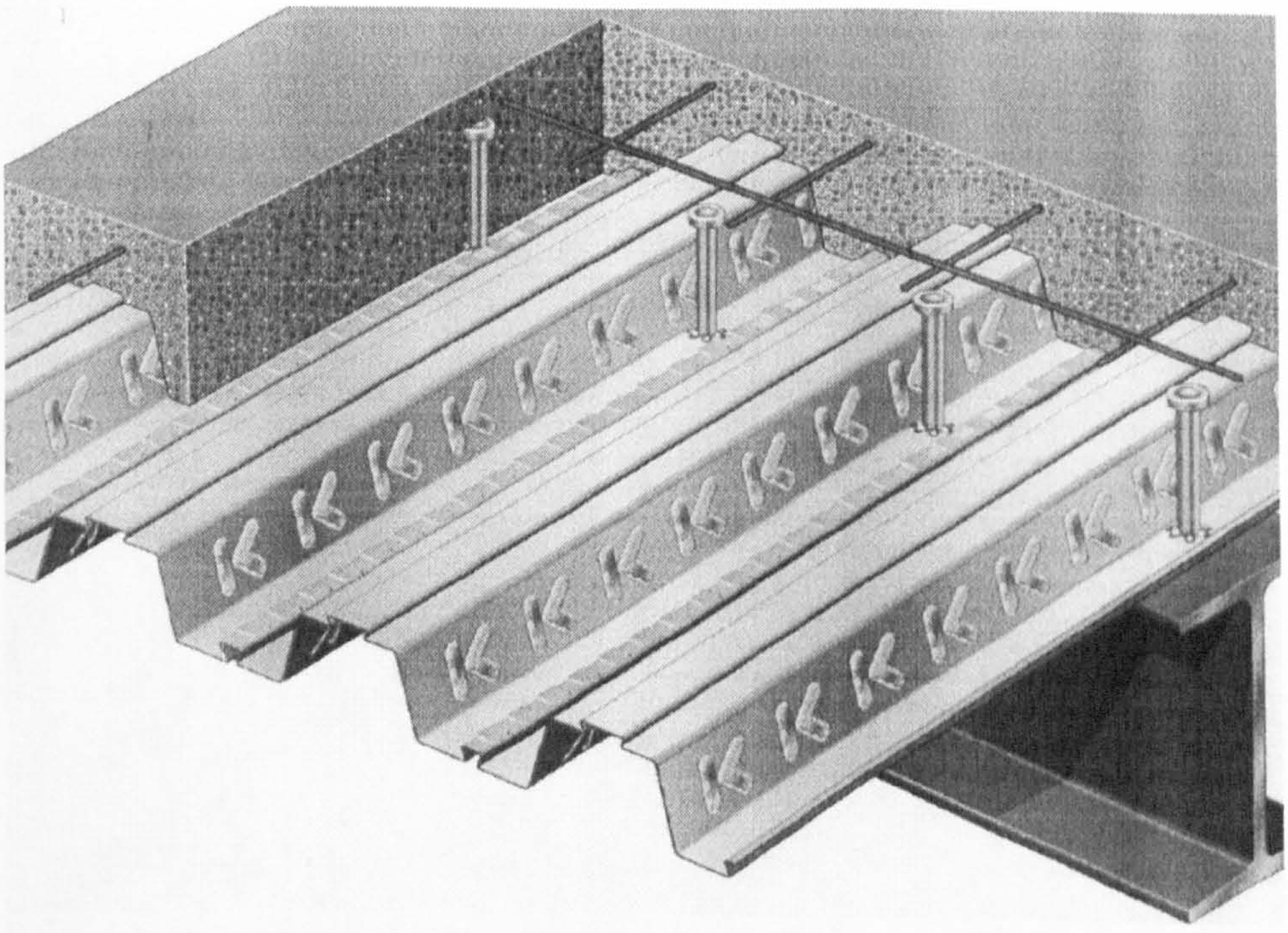


Figure 6-9 Detail of Slimdeck Construction
Note the supporting steel beam integrated into the floor slab (Trebilcock 1996)

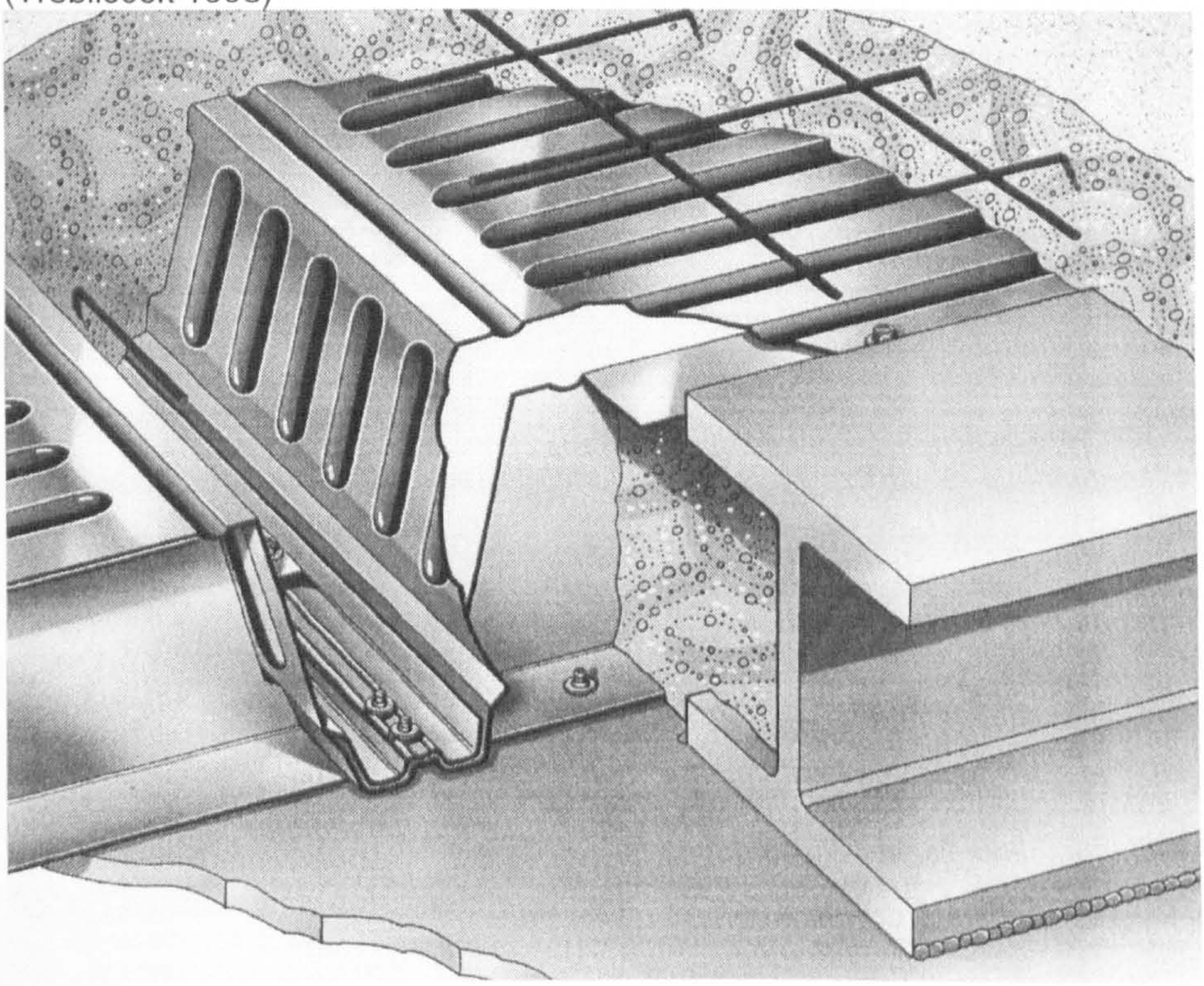
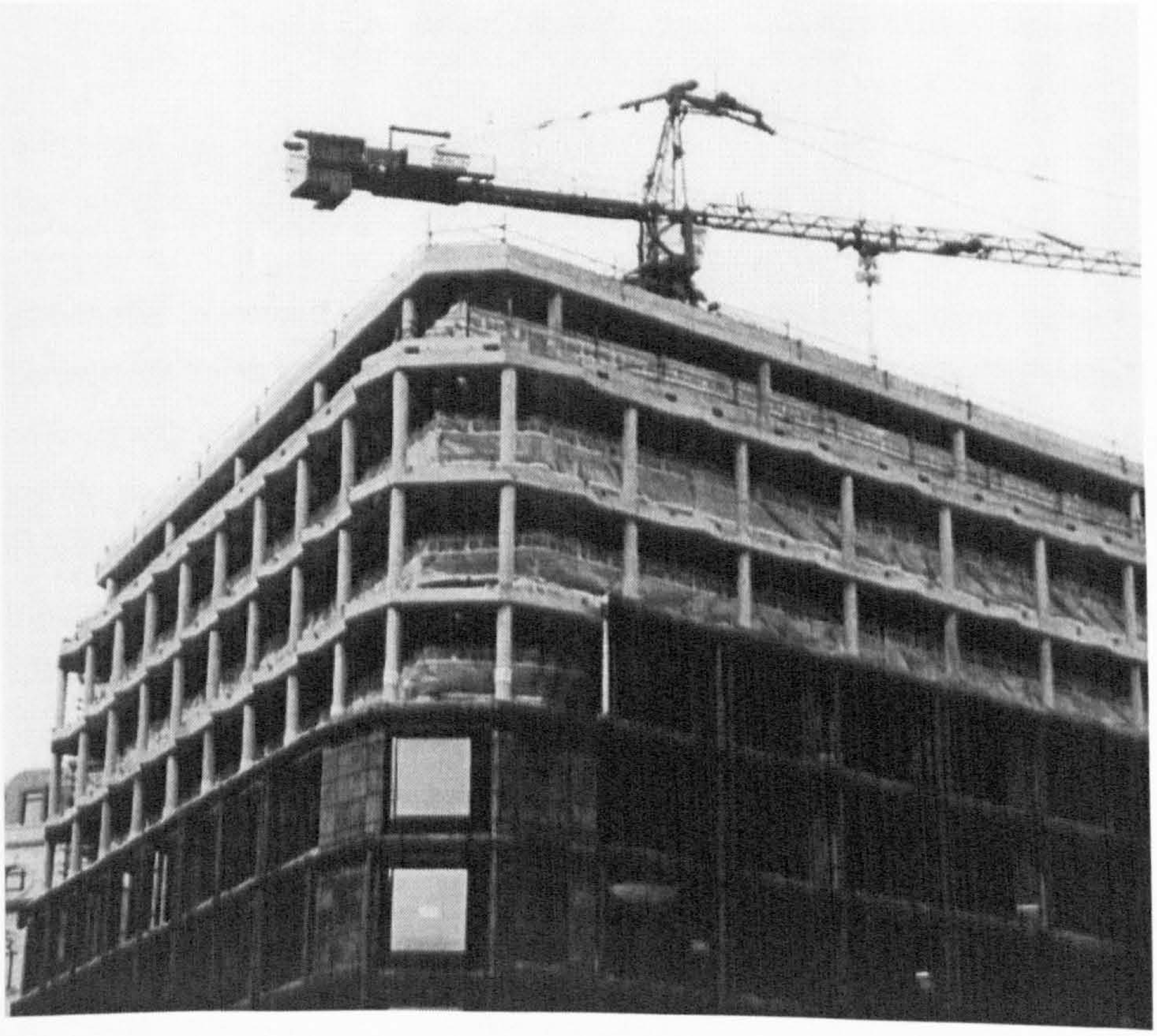


Figure 6-10 Concrete Floors and Frame under construction



However today with the extensive use of raised floors this is becoming less common with just the joints between the panels being filled with mortar. This is easily removed before disassembly.

6.6.2 Floors Designed for Disassembly

To widen this investigation four additional floors are also considered which are more suited to disassembly, these are:

6.6.2.1 Termodeck

A recent advance in precast floor units is the Termodeck floor (see figure 6.11). This uses the hollow-cores in the precast units to distribute conditioned air throughout the building. The increased (internal) surface area of concrete made available by this technique allows for more effective access to the thermal mass of the unit. However, the cores in standard precast panels are too small for this purpose. Therefore, for an equivalent span, a deeper precast section (with larger hollow-cores) must be used, see Table 6.6. As the precast sections get deeper, so the mass and hence energy and carbon dioxide impacts increase relative to a standard precast floor. Therefore in purely structural terms it is a less attractive environmental option.

Table 6-6 Section Properties for Precast and Termodeck for 7.5m span and 5 kN/m^2 Live Load

	Floor Depth (mm)	Core Height (mm)	Core Width (mm)	Fire Resistance (Hours)	Self Weight (kN/m^2)
Precast	200	150	150	2	3.07
Termodeck	260	175	175	2	3.97

Its benefits lie instead in its ability to provide a total flooring solution. Recent buildings with Termodeck floors have avoided using conventional (radiator) heating systems and suspended ceilings with all the heating and ventilation services being carried in the hollow-cores. In some instances raised floors have also been avoided, with the main electrical and communications services being carried in corridor channels and the final distribution completed in surface mounted trunking. Therefore Termodeck will be referred to later in this text when the whole floor zone is considered.

Termodeck floors can be used for spans of 5 to 18 metres and for live loads of up to 15 kN/m^2. As discussed above all precast flooring panels have the potential to be reused. For a Termodeck solution to be reused the same configuration of hollow-cores and manifolds connecting them would have to be adopted, or else these sealed and new cores cut.

Figure 6-11 Termodeck
(Tarmac-Termodeck)

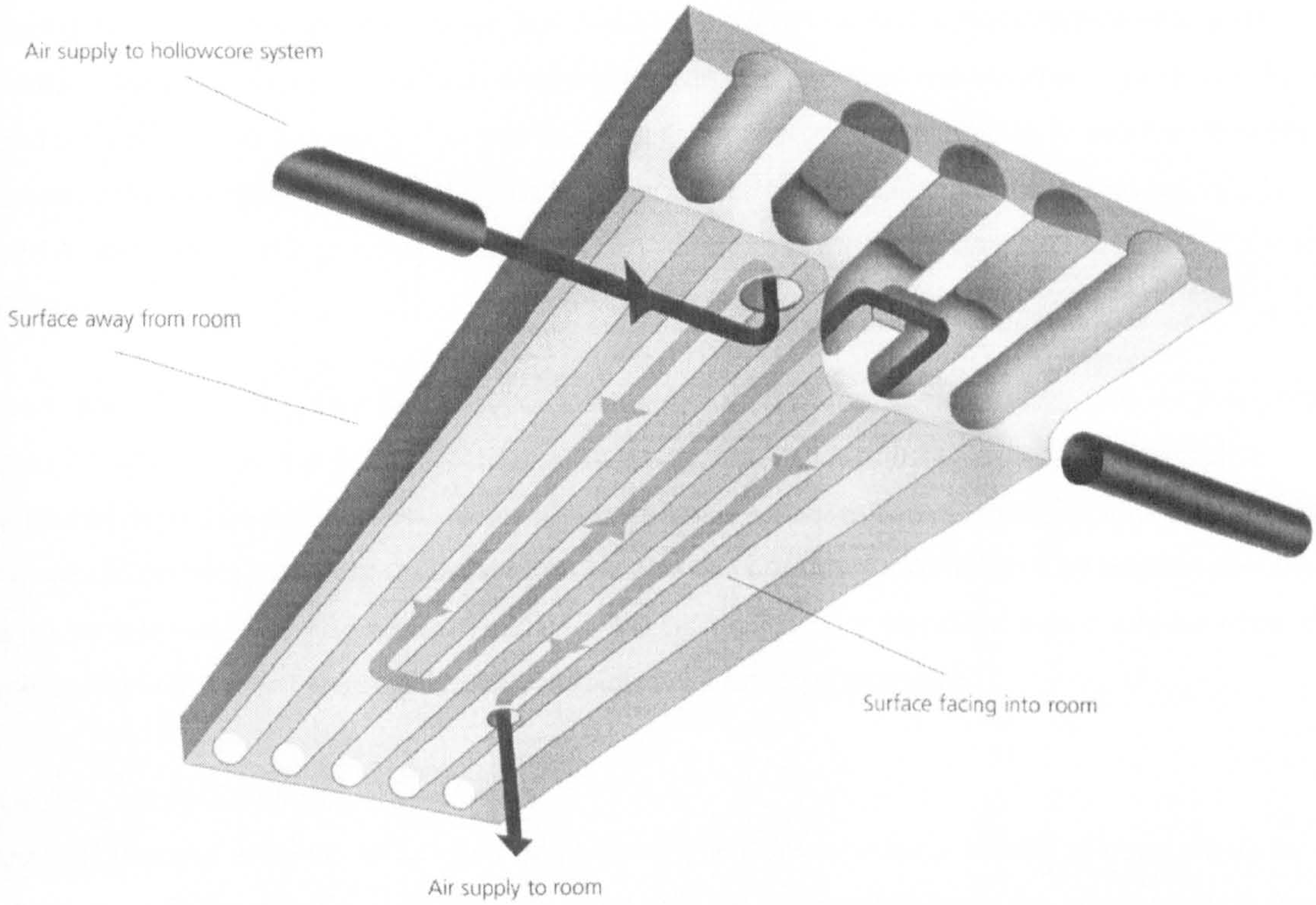
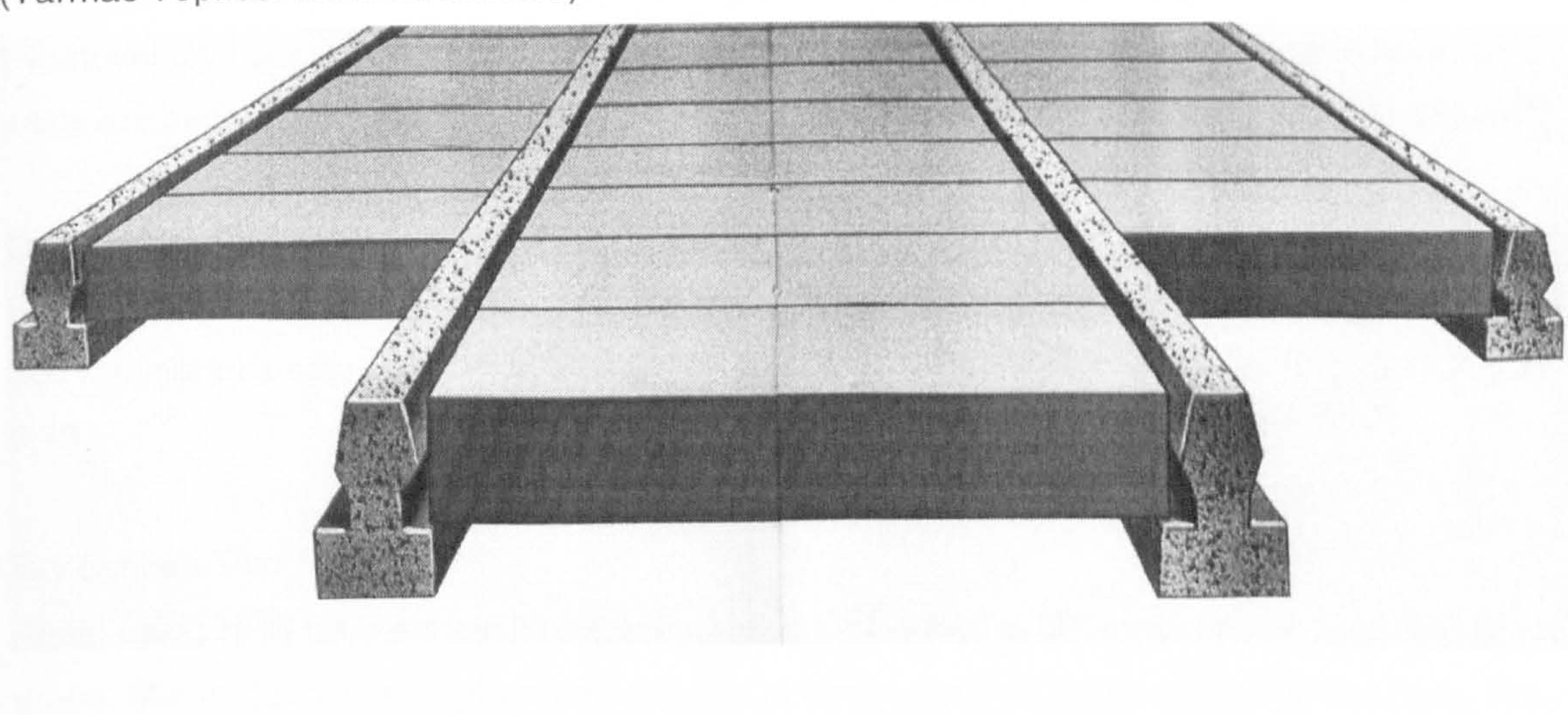


Figure 6-12 Beam and Block
(Tarmac Topfloor-Beam and Block)



6.6.2.2 Beam and Block

Another concrete system that involves few wet trades on site is beam and block construction (see figure 6.12). This system comprises prefabricated pre-stressed concrete beams with standard building blocks or purpose-made infill pots laid between the beams. This is mainly used for suspended ground and upper floors in domestic construction due to the fact that the beams and blocks can be moved by hand, without the need for lifting gear. It can equally be used commercially but as soon as a crane is on site other methods become more practical and efficient.

Beam and Block floors can be used commercially for spans of 4 to 8 metres and for live loads up to 7.5 kN/m^2. As this is mainly a dry system on site and requires no fixing between the elements, it can be dismantled. Although sometimes a self-levelling screed is laid over the floor that would require breaking up before removal of the concrete elements. The beams can be used on a similar or smaller structural grid, the blocks being a standard size could be reused for any frame with similar loading characteristics or for another purpose.

6.6.2.3 Steel solutions

Another framing solution, which has been gaining acceptance for a variety of uses since its introduction in the 1980's, is lightweight steel framing. It is mainly used for small-scale industrial and commercial units (buildings up to four stories), mezzanine floors, partitions, cladding, roofing and domestic house framing. Drawing on the domestic and mezzanine flooring systems two novel dry floor constructions using cold formed sections (CFS) are investigated here. CFS joists are capable of spanning up to 10 metres and can be used for live loads of up to $5kN/m^2$.

Dry System One

Hot rolled sections (HRS) for used for the main structural grid (see Figure 6.1) and CFS joists at 300 mm centres spanning 6m to these. On top of this is 38mm chipboard decking, See Figure 6.13.

Dry System Two

Again using HRS for the main structural grid and CFS joists at 300mm centres spanning 6m to these. 60mm deep steel profiled decking and a 12mm plywood finish makes up the floor, Figure 6.14)

In both of these systems additional fire cladding to the underside of the joists is required. Sound insulation can be improved by installing a quilt between the joists and also as a layer above the steel decking. One lightweight steel manufacturing company has suggested such a system in their literature, see Figure 6.15. However, on investigation it was discovered that the company had never tested such a system. Also in their present form neither CFS system has the capacity to store thermal energy as they have little mass, therefore relying on the heating and ventilation services to provide this entire requirement. In the future a modular floor layer could be introduced which performs this function, but as yet none exists.

Figure 6-13 Dry System One

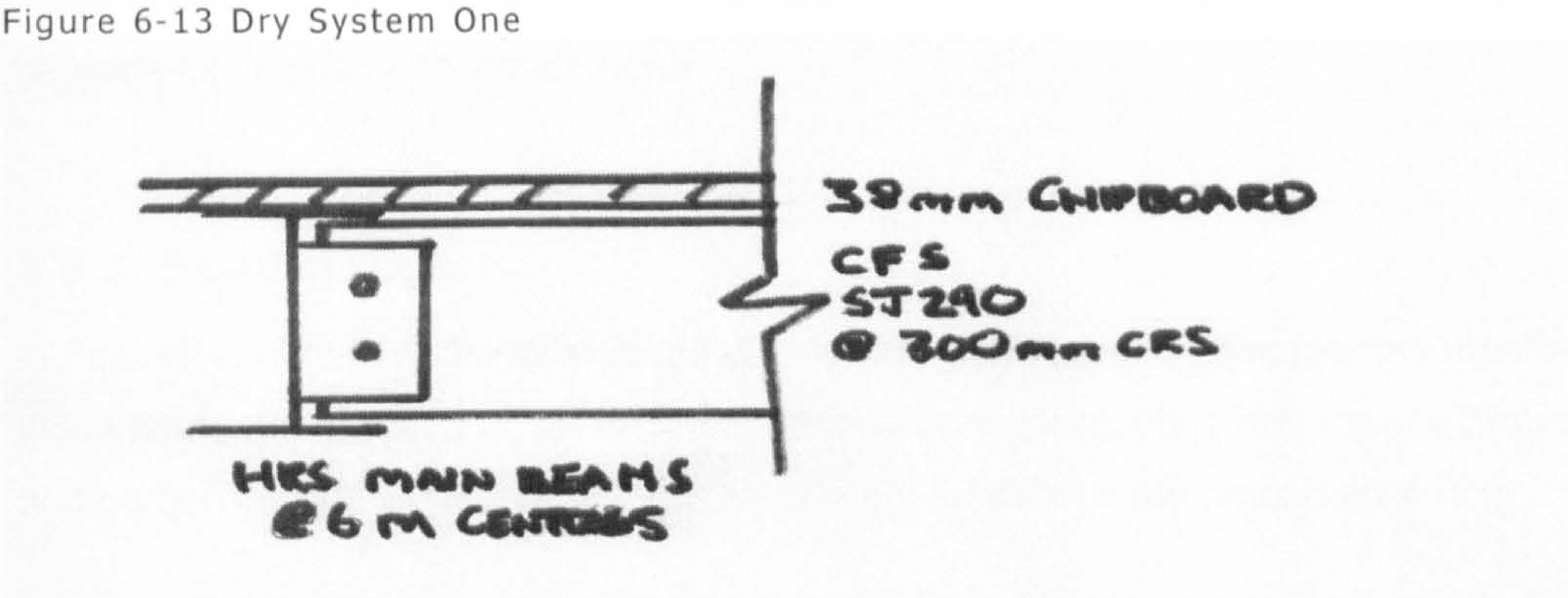


Figure 6-14 Dry System Two

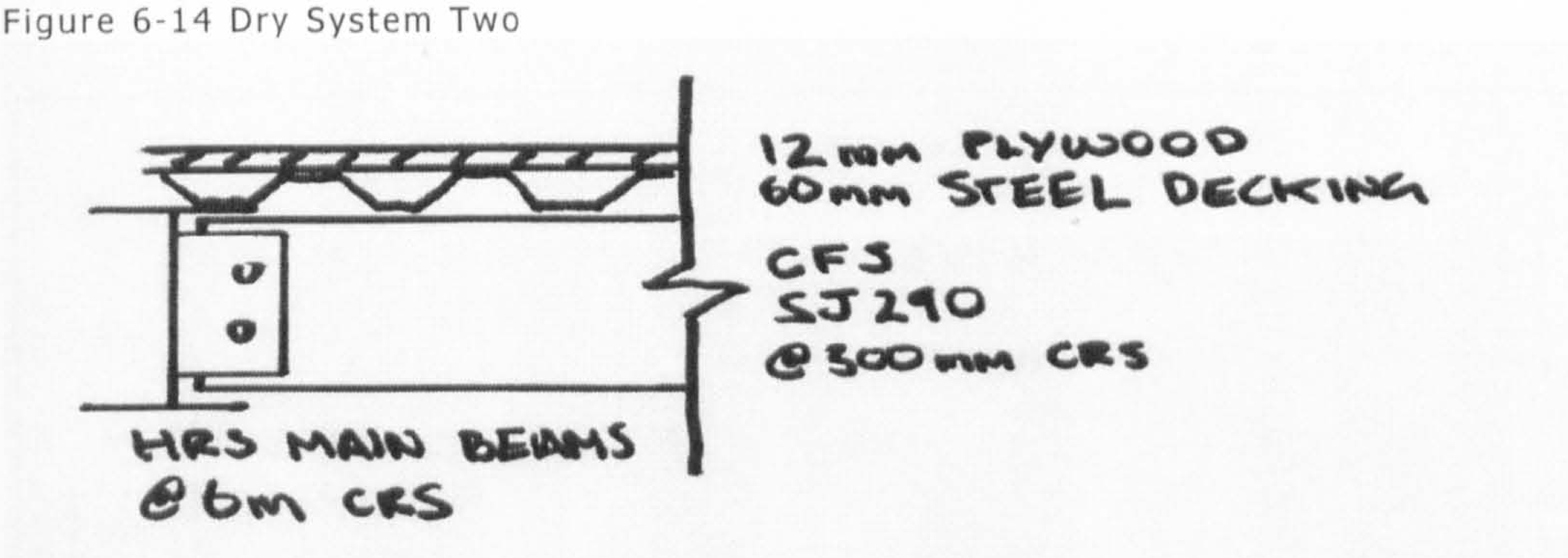
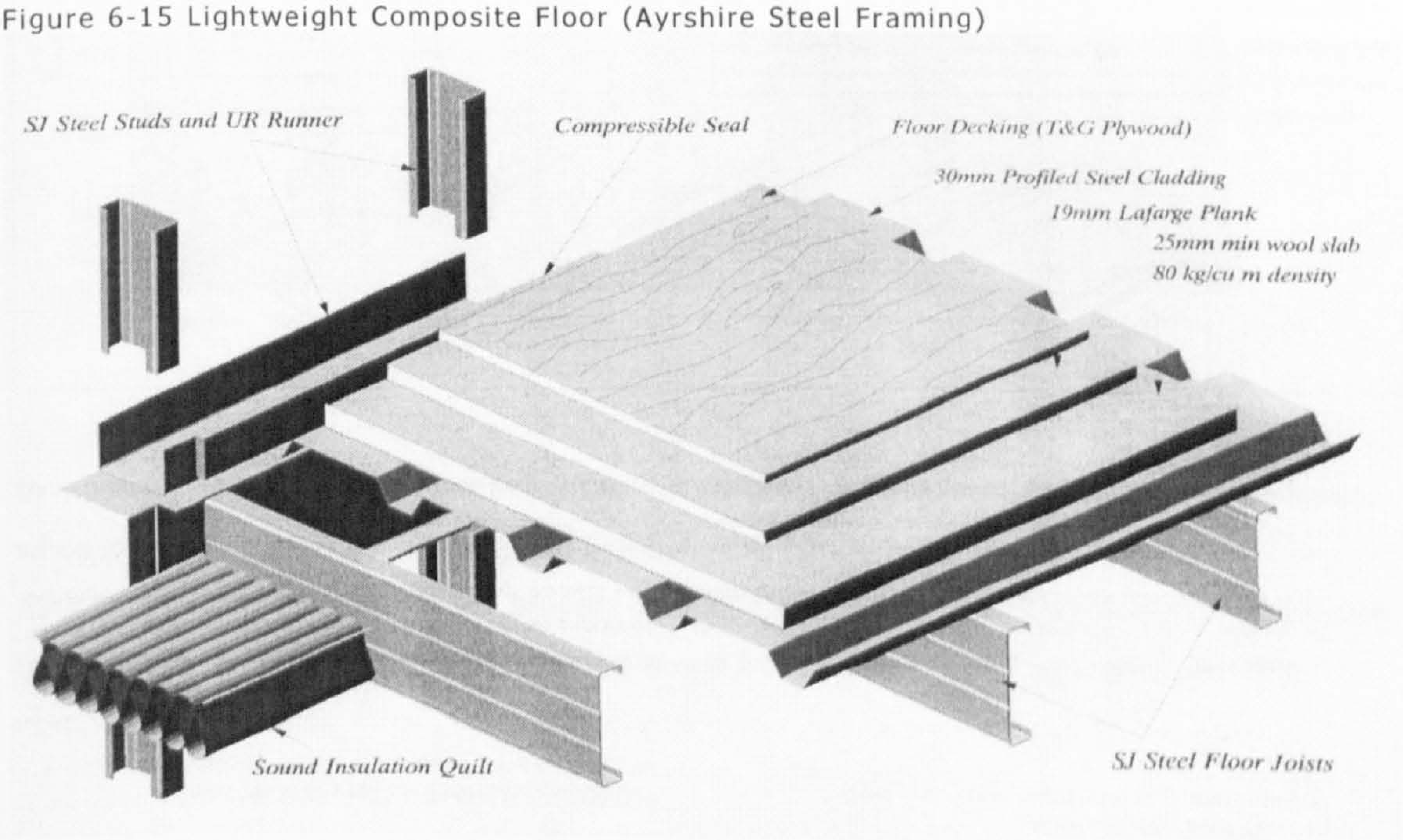


Figure 6-15 Lightweight Composite Floor (Ayrshire Steel Framing)

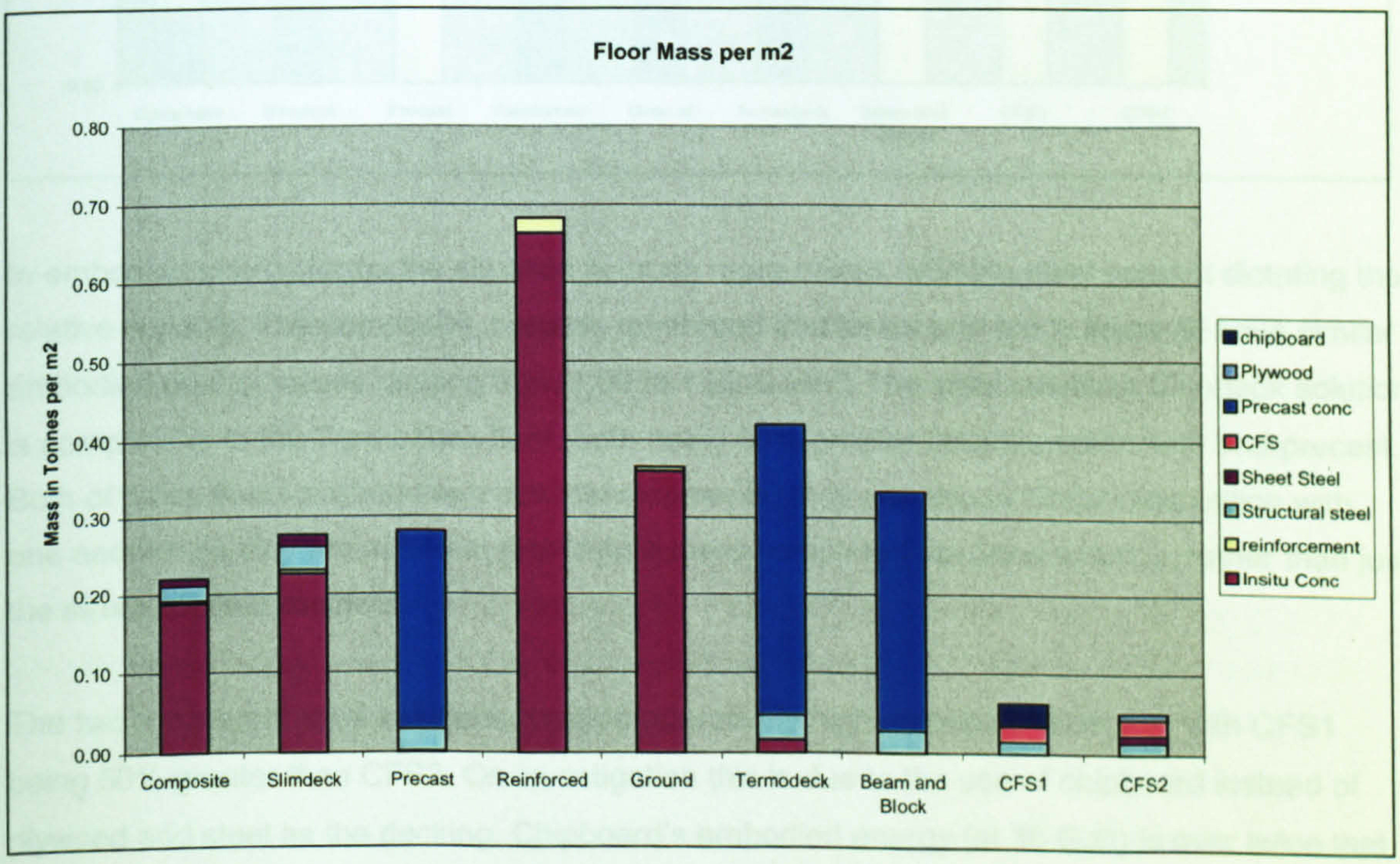


In both these systems the joists finish flush with the top of the main beams. Therefore the decking (steel and/or timber) can be in standard sheet sizes allowing a wide range of reuse. The CFS joists could be reused for similar or smaller structural grids. The decking will be mechanically fixed (screwed) to the joists causing some wear it is also unlikely that the screw holes in the joist, decking and plywood could be matched up in the future causing some further degradation in quality of the elements.

6.6.3 Relative Impacts

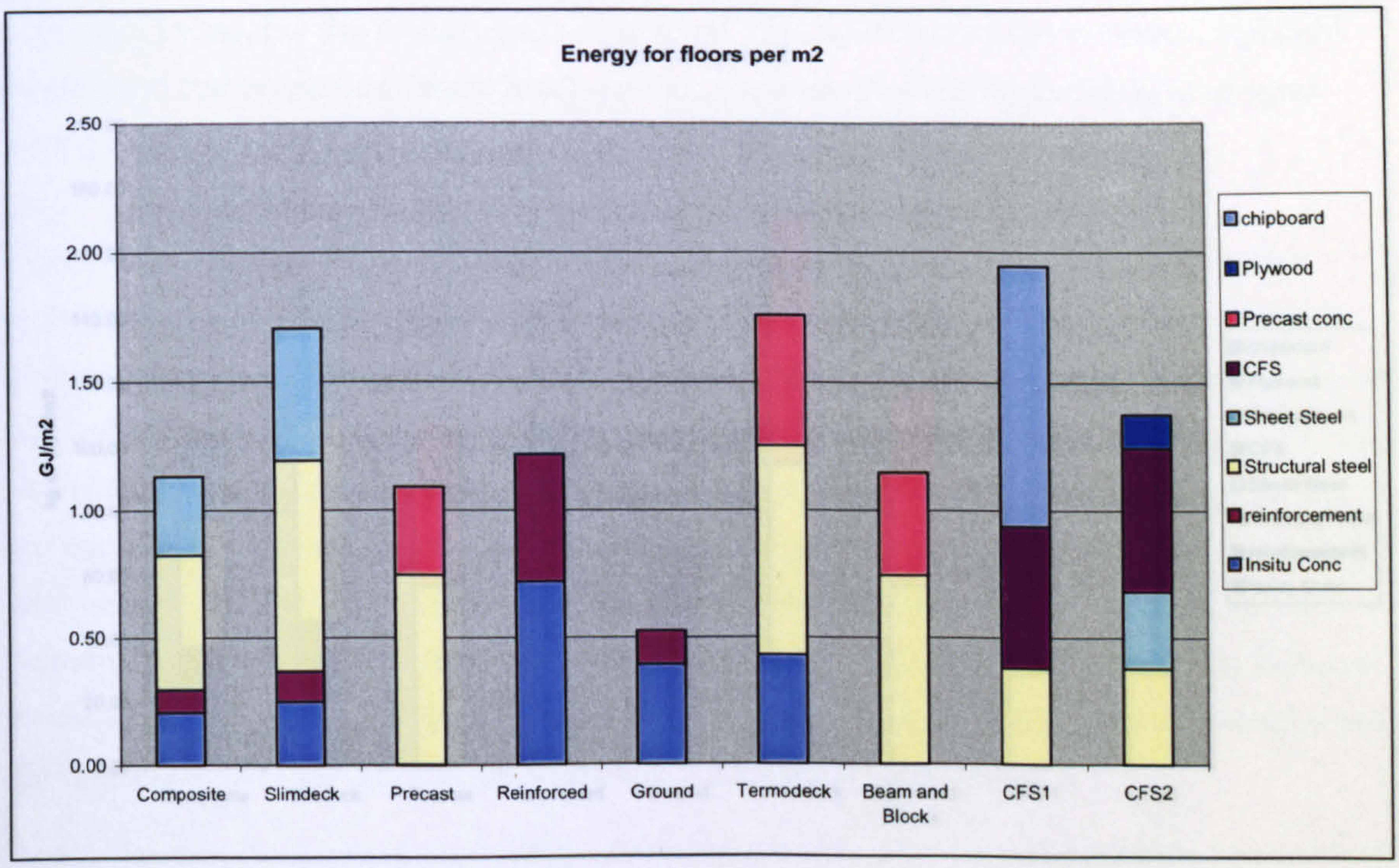
In Figures 6.16 to 6.18 the relative mass, embodied energy & carbon dioxide impacts for all these floors are shown. For all the floors the concrete content has the main bearing on the mass and carbon dioxide values while the steel content influences the embodied energy.

Figure 6-16 Mass of Floors



In mass terms, as would be expected the lightweight steel solutions have the lowest values, while the reinforced concrete floor the highest. The Termodeck floor, whilst inefficient in structural terms compared to the precast is 50% less massive than the reinforced. Excluding these three, the other floors all lie within a range from 0.22 to 0.37 Tonnes/m^2, with the composite the lowest.

Figure 6-17 Embodied Energy of Floors

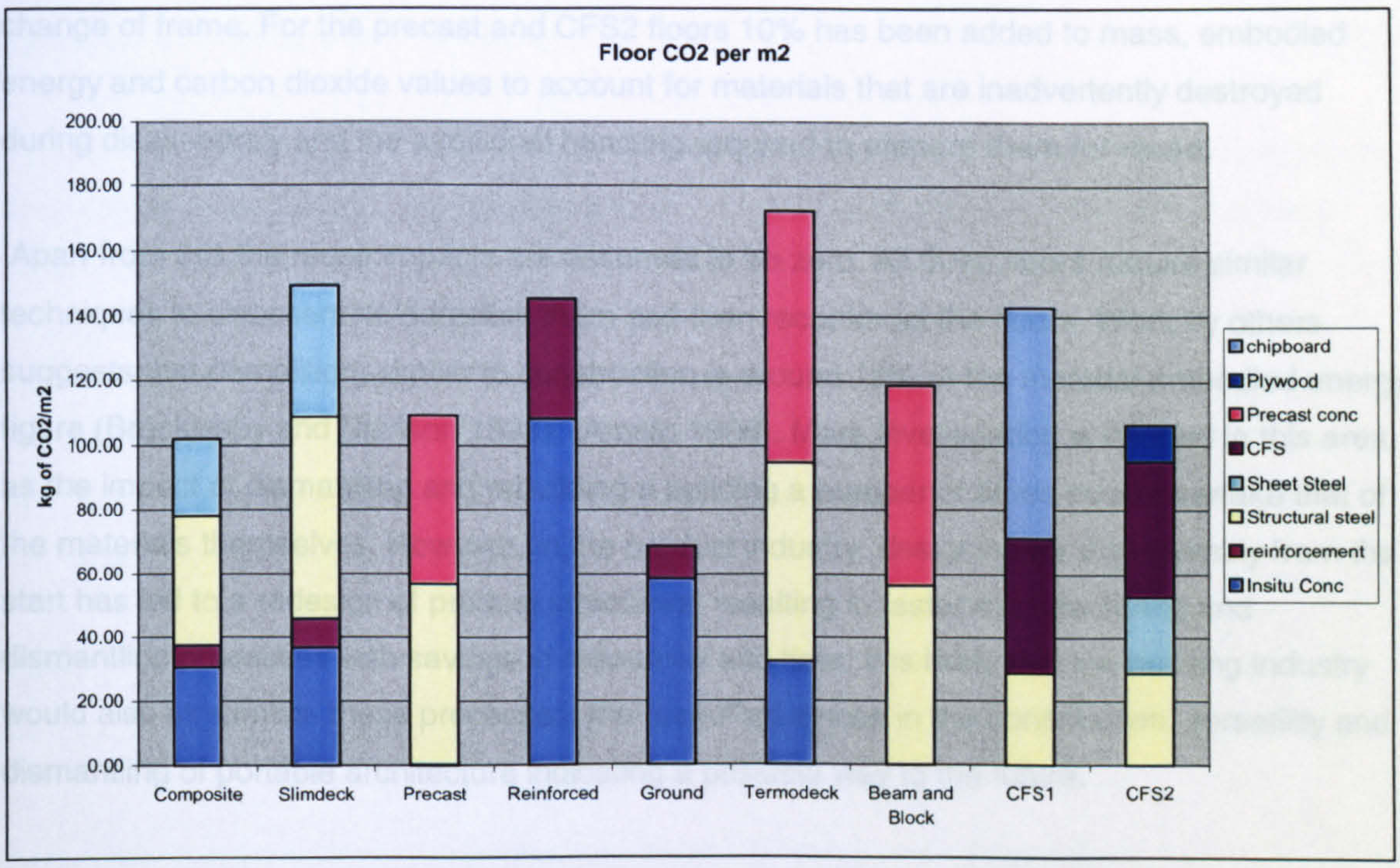


In embodied energy terms the situation is much more mixed, with the steel content dictating the relative impacts. The composite, precast, reinforced and beam and block floors all have similar embodied energy values ranging from 1.09 to 1.22 GJ/m^2. The steel intensive Slimdeck solution is comparable to the Termodeck floor, both being 50% greater than the composite and precast. Both of these floors are relatively new developments, they are also in direct competition with one another as they are aimed at providing a more complete floor zone solution, rather than just the structural floor element.

The two lightweight steel solutions have comparatively high embodied energies, with CFS1 being 50% greater than CFS2. On investigation this is due to the use of chipboard instead of plywood and steel as the decking. Chipboard's embodied energy (at 36 GJ/t) is over twice that of plywood (17 GJ/t) and 40% more than steel (26.8 GJ/t).

The CO_2 graph is similar to the embodied energy graph, with the concrete, and so cement intensive floors catching up with the steel intensive solutions. Again the standard composite and precast have low values, with CFS2 swapping places with the reinforced and joining these.

Figure 6-18 Carbon Dioxide Values for Floors



The one floor yet to be compared is the ground-bearing slab. This has the lowest energy and CO_2 values for any floor. However ground floor slabs cannot be disassembled and if left after demolition of the super-structure may be considered as ground contamination. This problem is exacerbated if polystyrene is used as permanent shuttering when pouring the slab, as is often the case today. Polystyrene cannot be separated from the concrete and makes its future recycling difficult. This floor was included to investigate the potential of replacing the ground floor slab with a suspended floor. However, when considering one lifetime only this does not look to be environmentally advantageous.

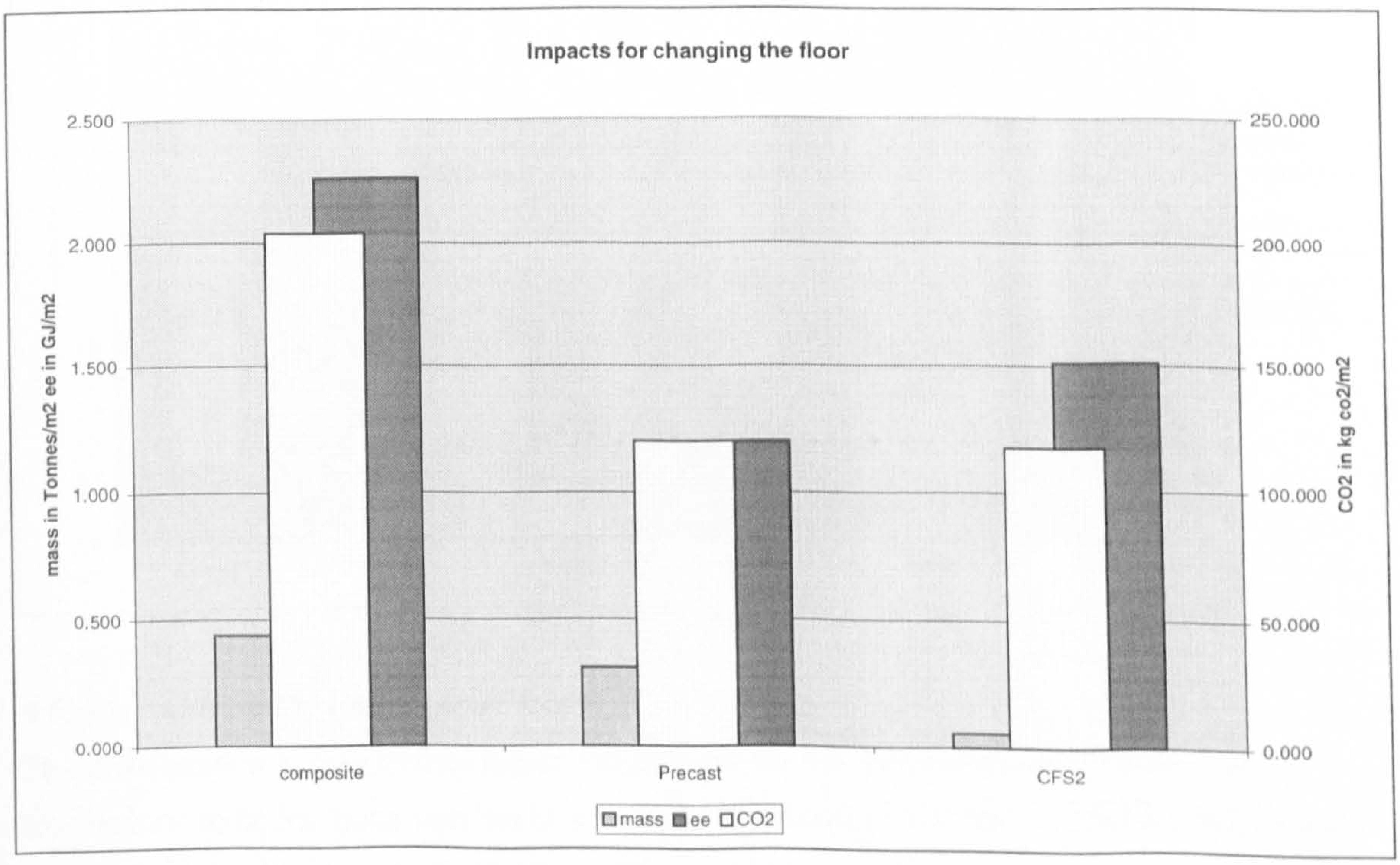
Of the eight suspended floors considered the composite, precast and CFS2 had the lowest overall impacts. The investigation is now extended to consider the disassembly and re-assembling of the structural floor. The composite, precast and CFS2 floors will be used here as they represent steel and concrete intensive solutions with varying degrees of disassembly and comparable single life impacts.

6.6.4 Changing the floors

As discussed above, the composite floor elements cannot be disassembled and in order to change the floor they must be replaced, including the main structural floor beams, which via shear studs are bonded to the slab. The steel will be recycled and the concrete crushed and used for low-grade uses but there is currently little potential for recycling it into new concrete. In the precast floor a small amount of insitu concrete must be broken out and replaced with each change of frame. For the precast and CFS2 floors 10% has been added to mass, embodied energy and carbon dioxide values to account for materials that are inadvertently destroyed during disassembly and the additional handling required to prepare them for reuse.

Apart from this the reuse impacts are assumed to be zero. All three floors require similar techniques to disassemble/demolish them and then reconstruct the floors. Work by others suggests that demolition, similar to construction is around 10% of the material embodied energy figure (Brocklesby and Davison 1998), (Amato 1996). More investigation is needed in this area, as the impact of dismantling and rebuilding a building a number of times could overtake that of the materials themselves. However, in the product industry, designing for disassembly from the start has led to a redesign of product structures, resulting in faster manufacturing and dismantling processes with savings in resources and time. It is likely that the building industry would also streamline these processes, the recent advances in the construction, versatility and dismantling of portable architecture indicating a possible way to the future.

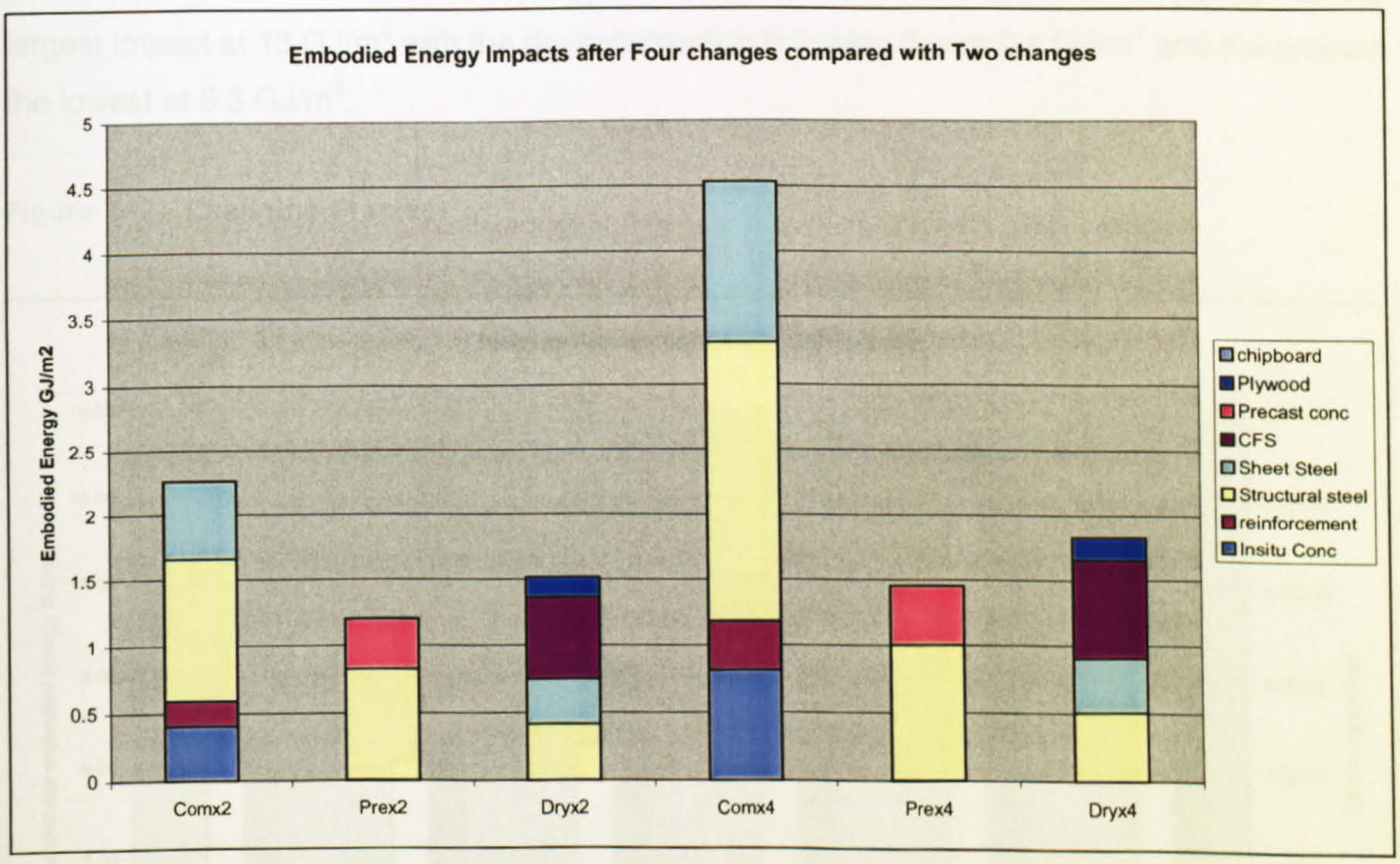
Figure 6-19 Replacing Floors



With just one change of the structural floor the composite floor, initially the least impacting now has the highest values for all three categories. For mass the in-situ concrete accounts for over 90% of the impact while for embodied energy and CO_2 the steel accounts for over 80% of the impact. As previously discussed this steel can be successfully separated and recycled. However, there is a considerable environmental advantage in reusing rather than recycling steel and if the composite floor could be redesigned to allow separation and reuse its impact would be reduced to near the precast value.

The precast and CFS2 floors have similar energy and CO_2 values to their original values as all their elements are reused. Subsequent frame changes would not alter these values greatly unless removing and reusing them damaged the elements more than the 10% allowed for. This is indicated in Figure 6.20 below, which shows the embodied energy impacts of the floor materials after four changes, compared to two changes. The composite having doubled in impact, were as the precast and dry floors have only increased by 20%. This suggests that if a floor is to be replaced, designing for disassembly would reduce the lifetime environmental impacts, even with greater initial values.

Figure 6-20 Embodied Energy Impacts after Four Floor Changes



6.6.4.1 Moving the Frame and Floors

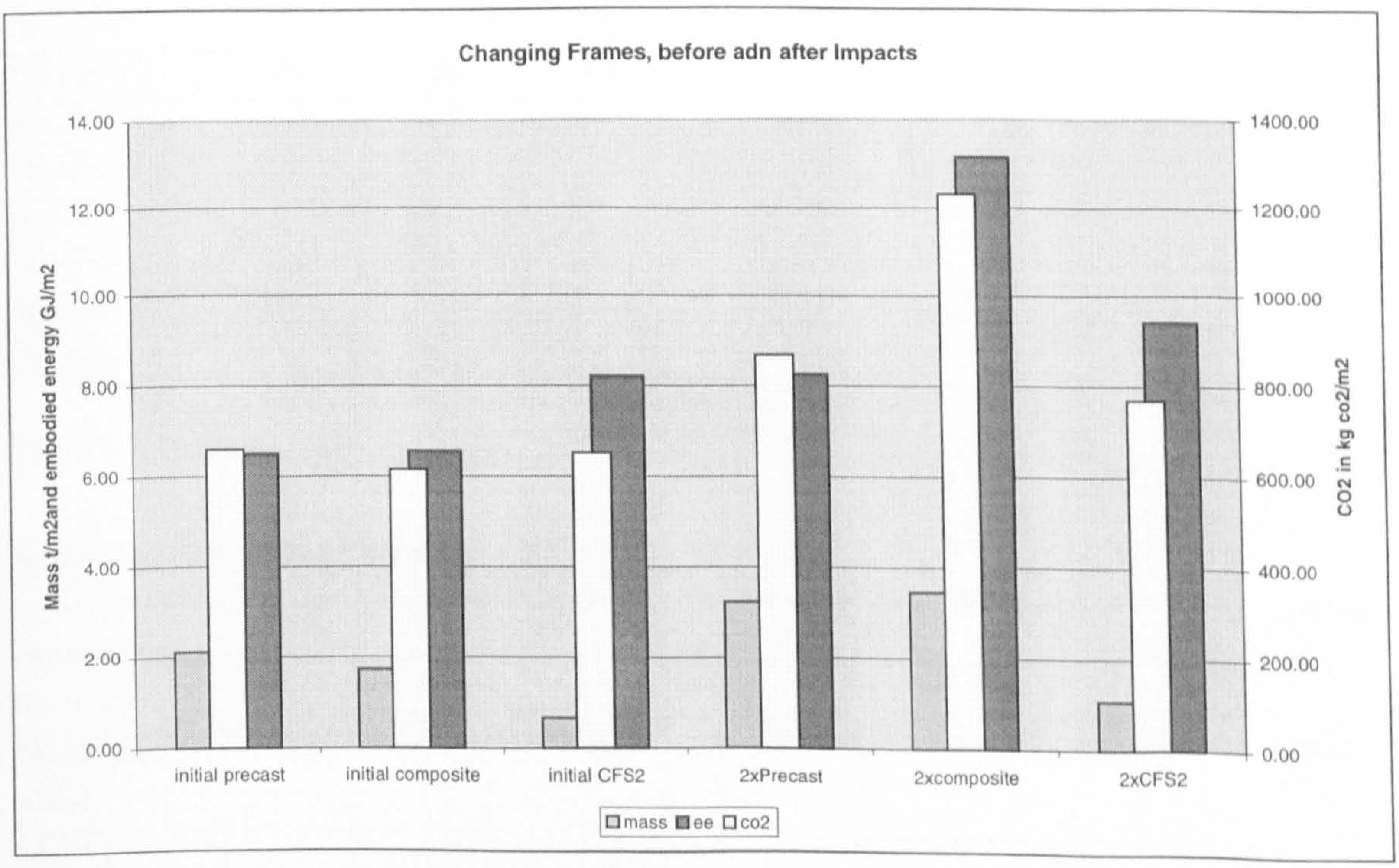
The investigation is now further expanded to consider the whole structural frame, from foundations to floors, based on the building type identified at the start of this chapter, ie with four usable floors and a plan of 48x13.5m. In this scenario the entire frame is disassembled or demolished and re-erected. The model assumes that new foundations must be laid for the three frames types. However it does not include excavation and disposal of earth or the impact of shuttering. The dry floor construction has a suspended ground floor of the same construction as its other floors whereas the precast and composite floored buildings have ground-bearing slabs. Local ground bearing slabs could be introduced in the dry floor construction for high point loads such as plant rooms. Foundations for the dry floor (CFS2) construction are assumed to be $100m^3$ compared to $120m^3$ for the composite and $160m^3$ for the precast frames.

6.6.4.2 Results Analysis

Comparing the graphs of Figure 6.21, the dry floor construction has the lowest mass both before and after the change of frame. This increases from 0.67 to 1.07 T/m^2 due mostly to the pad foundations. The composite and precast start at 1.72 and 2.13 T/m^2 and increase to 3.45 and 3.22 T/m^2 respectively. The fact that they remain so close (the composite just overtaking the precast) is again due to the foundations and ground floor slab, which account for 61% of the total precast, and 47% of the total composite mass.

In terms of embodied energy the initial values are much closer with the dry construction being 25% greater that the other two. The majority of its impact being due to the steel content which accounts for 86% of its embodied energy. After the frames are changed the composite has the largest impact at 13 GJ/m^2 with the dry construction following this at 9.4 GJ/m^2 and the precast the lowest at 8.3 GJ/m^2.

Figure 6-21 Changing Frames



Initially the carbon dioxide values are close, ranging from 616 kg of CO_2/ m^2 for the composite, through 654 kg of CO_2/ m^2 for the dry floor, to 661 kg of CO_2/ m^2 for the precast. After the frame change the composite value is much larger than the other two at 1232 CO_2/ m^2 compared to 867 CO_2/ m^2 for the precast and 767 CO_2/ m^2 for the dry construction. This is due to a combination of the replacement of steel and concrete in the building.

After just one frame change the composite initially of low impact becomes the largest for all three categories. The dry construction and precast are fairly close in impact value, neither standing out as being particularly better than the other.

Tables 6.7 to 6.9 below indicate in more detail the percentages of each of the main six materials used to initially construct and then reconstruct the frames, the maximum values being indicated in bold. For the precast, the foundations and ground floor account for most of the mass, while the structural frame accounts for the embodied energy and half of the carbon dioxide burden, the rest being shared between the ground and suspended floors. For the Composite nearly all the mass is in the floors, with the reinforcement and frame accounting for the embodied energy and the carbon dioxide being split between the elements. For the lightweight steel frame, the only concrete element are the foundations and these account for most of the mass, with the structural steel being responsible for the embodied energy and carbon dioxide values.

Table 6-7 Mass

Mass % of total			
	precast	composite	CFS2
Insitu conc.	**60**	**90**	**69**
Reinforcement	1	1	1
Structural steel	5	7	21
Sheet steel		2	5
Precast conc.	34		
Plywood			4

Table 6-8 Embodied energy

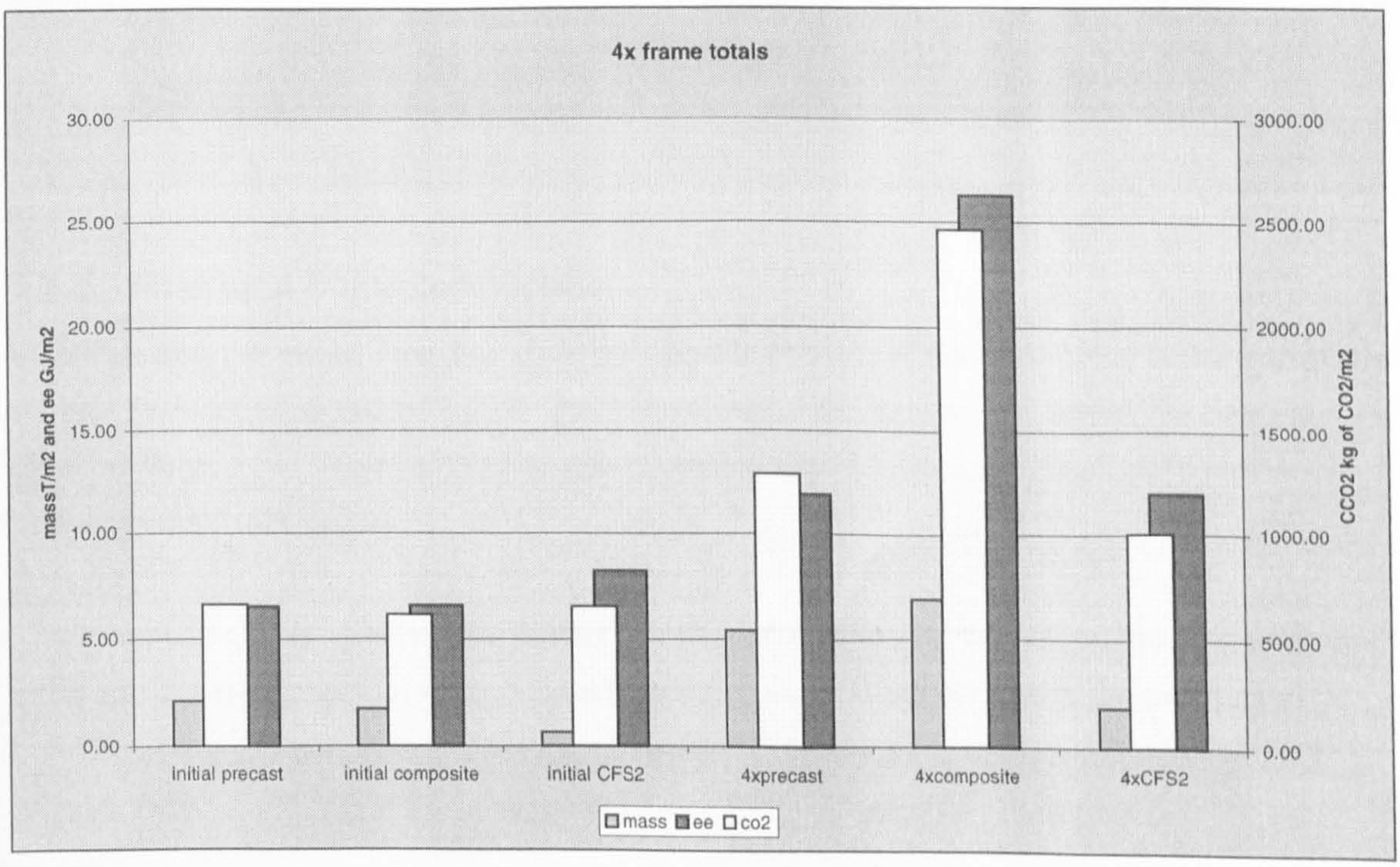
Embodied energy % of total			
	precast	composite	CFS2
Insitu conc.	22	24	7
Reinforcement	7	10	2
Structural steel	**52**	**48**	**66**
Sheet steel		18	18
Precast conc.	18		
Plywood			8

Table 6-9 Carbon Dioxide

Carbon Dioxide % of total			
	precast	composite	CFS2
Insitu conc.	30	38	11
Reinforcement	5	8	2
Structural steel	**38**	**39**	**61**
Sheet steel		16	17
Precast conc.	26		
plywood			8

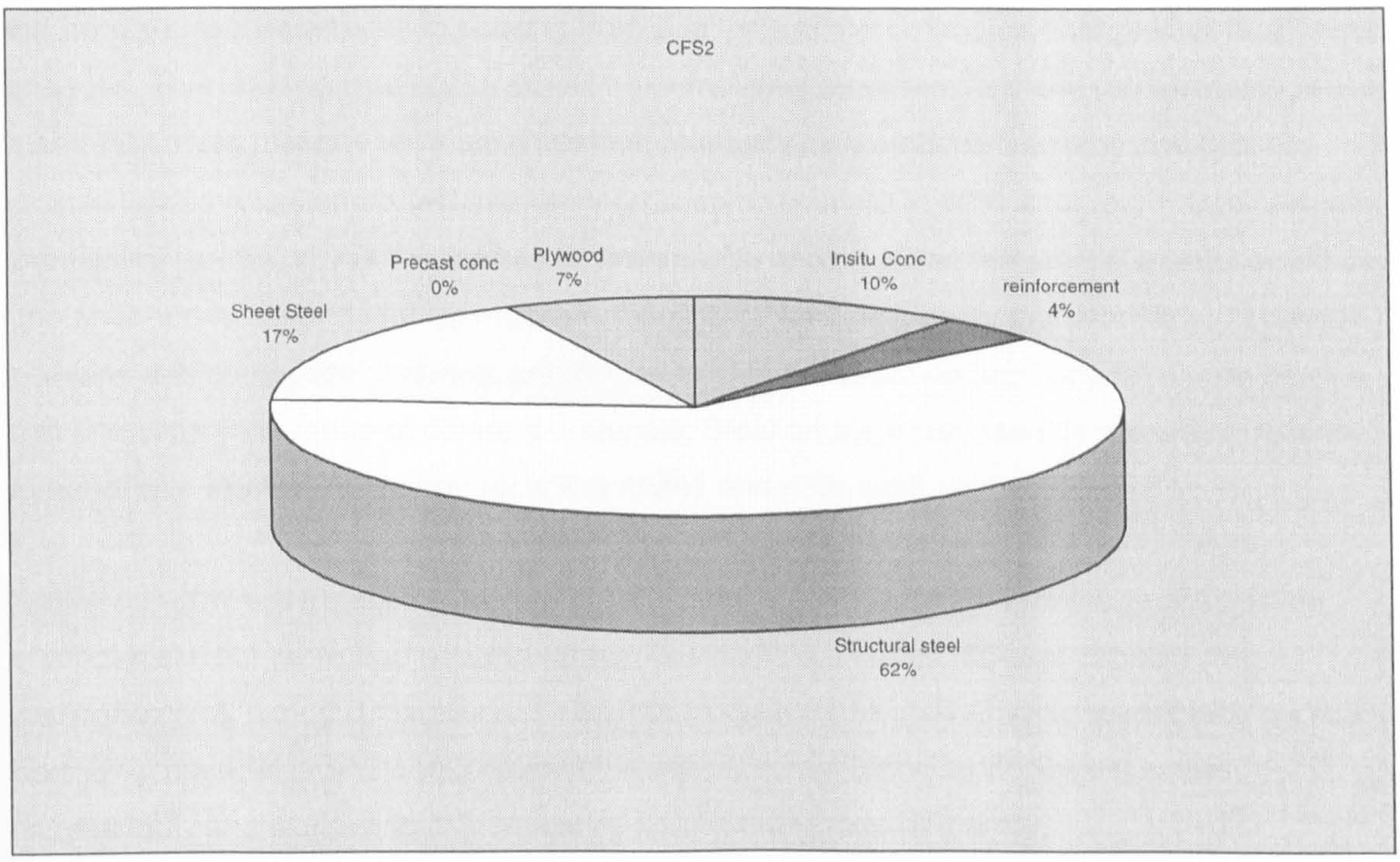
As with the floor investigation above, the analysis is now repeated assuming four complete changes of frames and floors. The total impacts after four changes compared to the initial impacts are shown in the figure below.

Figure 6-22 Embodied Energy after Four Frame Changes



The difference between the DfD frames and the none-DfD frames has been exaggerated, with the composite frame's impact now more than double the other two. The dry floor construction, due to its high levels of reusability now has the lowest values for all three impact categories. This suggests that while DfD initially may incur higher embodied impacts its long term impacts are likely to be less than a none DfD frame, provided its elements are incorporated into new buildings. Examining the detailed embodied energy impact after four frame changes, figure 6.23, indicates that the majority of the impact is still within the structural frame. When combined with the sheet steel in the floors this accounts for almost 80% of the embodied energy impact (down from 90% for the initial construction). Therefore encouraging the disassembly and reuse of steel elements could have a significant influence on the impact of future frames.

Figure 6-23 Details of Embodied Energy of Dry Frame after four changes



6.6.5 Structural frame conclusions

In this section the mass, energy and carbon dioxide impacts of different office building structural frames, from foundations through to floors have been investigated. Generally, the predominantly steel buildings have higher embodied energy values and the concrete buildings higher mass and carbon dioxide values.

The lowest single life values were for the composite building, this combined the properties of steel and concrete together to form an efficient structure. However due to the permanent bonding of steel to concrete in this type of structure the elements cannot be separate and reused. Destruction and material recycling being the only possible future option.

To address this a range of dry or prefabricated constructions, that could enable disassembly and re-erection, were also investigated. For a single lifetime these have a higher energy and carbon dioxide impact, but over subsequent lifetime their impact decreases relative to standard, composite constructions. For the DfD buildings the relative impact of elements which cannot be reused such as the foundations and ground bearing slabs increases with each cycle. In the three frame analysis above, the combined foundations, ground floor slab and reinforcement embodied energy impact for the precast construction increased from 20% to 40% after four frame changes.

This suggests that lightweight buildings with minimal foundations and a suspended ground floor would be advantageous, and one such building was included in the investigation. The impact of the none reusable elements increasing from 5 to 14% of the embodied energy after four frame changes. This building type could almost be completely disassembled and the elements reused, it had little mass, but due to its steel content, relatively high embodied energy and carbon dioxide values (steel embodied energy only dropping from 90 to 80% after four frame changes). Containing the majority of the frames environmental impact within the steel elements could be good method of assuring future reuse and recycling. As indicated by the demolition experts, complex and composite materials are difficult to identify, separate and recycle, as are frames that contain a wide range of different materials. Steel on the other hand, is an easy to identify material with existing reuse and recycling routes and reversible connections.

However, lightweight steel frames are not a prefect solution as they lack many of the other characteristics of more traditional buildings, having little: thermal storage capacity, fire resistance and, acoustic insulation. Therefore to improve its performance characteristics many additional material layers would need to be added, complicating its construction and disassembly and increasing its complexity and environmental impact.

6.6.6 Assumptions of the Three Frame Investigation

The investigation assumes that apart from 10% defects the reuse of elements has no environmental burden attached to it. It is unlikely that elements would be removed and reused in exactly the same position in the same building. More likely they would be transported, stored, transported again, reconfigured and reused in a different location on a different building. All these actions have an environmental burden attached to them, which could potentially increase the impact of reusing by another 10% of the embodied values. This investigation also attaches no environmental burden to the waste materials produced with each building change, for example removing and recycling (or landfilling) the ground floor slab and foundations.

There is also the issue of assigning an embodied energy value to a material that can have a number of lifetimes either being reused or recycled (metals, plastics, glass etc all have this potential). One questions whether you allocate all the impact to the first lifetime and assume subsequent lifetimes have zero impact or try and apportion the impact over a number of lifetimes. In attempting to address this situation the Steel Construction Institute (SCI) have identified three values for structural steel (Amato, Brimacombe et al. 1996). They argue that, if the first use carries the entire burden and subsequent uses none, most environmentally conscious designers will specify second hand or reused steel. Hence reducing the environmental impact of their scheme. However, to have second hand steel you must first have had new steel. As most steel is recycled many times all steel elements contain a proportion of new and scrap and it is impossible to tell how many times it might have been recycled. Therefore the SCI propose a 'multi-lifecycle value for steel as well as a primary value and a reused value.

The equation to estimate the multi-lifecycle value includes a number of variables, which influence its outcome, the main ones being: the number of lifecycle stages the material is likely to go through, and the value for reuse and the recycling yield. This can be regarded as a measure of the efficiency of the recycling process. For example a recycling yield of 50% means that only half of the quantity of material present in the preceding life cycle stage remains in the chain of utility and enters the next life cycle stage, the rest being lost to 'earth'. Consequently a range of multi-lifecycle values are produced, these are generally lower than primary use but higher than single value recycled which assumes that all the primary use takes all the burden.

In the case of reusing steel, the integrity of the element is retained, and the value includes an estimate for the average transportation and preparation of a reused element for inclusion in a new structure. Table 6.10 shows these values along with similar new and recycled values for other commonly recycled building materials.

Table 6-10 comparison of embodied energy of materials in primary and recycled forms (in GJ/t of delivered energy) (Amato, Brimacombe et al. 1996).

Material	**Primary**	**Recycled (single use)**	**Multi-lifecycle**	**Reused**
Aluminium	150-240	11-40	?	?
Steel	25-40	9-12	13-17	5-10
Glass	12-30	10	12	?
Copper	71-85	40-50	?	?
Precast Concrete	1.07	?	?	?
In situ Concrete	0.85	?	?	?

Choosing the multi-lifecycle value of steel lowers its environmental impact for any particular scenario. Concrete on the other hand generally has only one structural lifetime, afterwards being cascaded downwards to be used as fill. However, as stated earlier successful attempts have been made to crush concrete and use the resulting aggregate for new structural concrete (Collins 1994). Currently there are no embodied energy calculations to support this work but it is likely that using recycled aggregate from site combined with cement substitutes[5] will lower concrete's environmental impact in line with the steel multi-lifecycle value and so the two materials become comparable again.

As steel and concrete are ubiquitous in the construction industry and usually occur in buildings together it may be more beneficial, environmentally, structurally and economically, to push their combined performance characteristic to the limits rather than attempting to use them independently. The two materials have different structural, thermal and acoustic properties, which complement each other in a structural frame. Structural floors designed more along the lines of the Termodeck or the Slimdeck system are trying to address this by minimising the overall floor depth, allowing for services within the structural zone and providing better access to the thermal mass. However, this does not address DfD, the Slimdeck particularly cannot be separated and reused, the only option being destruction and material recycling. Potentially the Termodeck floor could be removed and reused, although using the ducts in a different plan configuration would be complicated and unlikely to succeed. However, whilst DfD at the whole floor (product) level might not be a practical option, floors (like the Slimdeck and Termodeck above) can be designed to maximize the recycling yield by following the material level DfD guidelines. These guidelines point to avoiding composites and suggest using simple materials with recognised recycling routes which are combined in none complex ways.

6.7 The Floor Zone

6.7.1 Description

Increasing demands are being made of the floor zone in modern office buildings, of which the structural floor is just one layer. Not only must it provide adequate structural integrity and fire resistance it must additionally often act as an acoustic and thermal buffer, using its mass to control daily fluctuations in temperate, and provide fresh air, power and adequate lighting to the occupants. All this must then be contained within an aesthetic skin and have the minimum depth and maximum possible span. These various functions of the floor mean that it is a complex system, constructed of many layers that require more detailed investigation.

Most, if not all, modern office buildings have a raised or access floor above the structural floor, this will be covered with carpet or more likely carpet tiles. Electrical and communications cables being routed through this zone. There are also a number of systems for ducting air through this zone.

[5] Cement substitutes include pulverised fuel ash (pfa) and ground granulated blast furnace slag (ggbs) and these, as shown by Brocklesby (see previous chapter), help to reduce the embodied energy and carbon dioxide impacts of concrete.

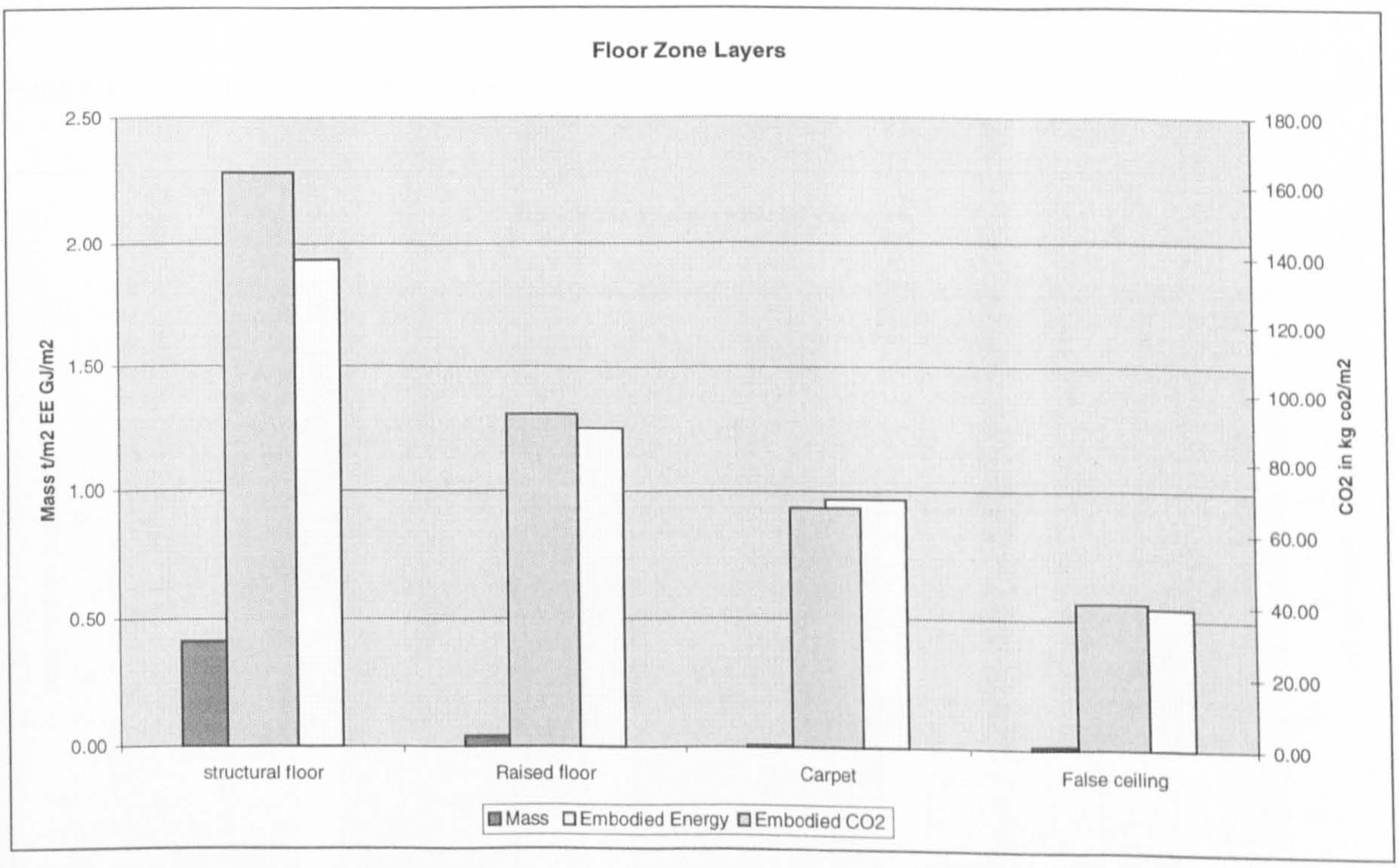
Below the structural floor a standard office would have a suspended ceiling. This would hide the cabling to the lighting system and also ventilation or air conditioning ducting. Alternatively if the thermal mass of the floor is to be utilised the sofit must be exposed either completely or through an open lattice suspended ceiling (Ogden 1997).

Standard office carpets are usually polymer based with a mix of wool and fibre and a rubber underlay. Raised floors consist of either flat steel plates or steel with chipboard core plates supported by steel pedestals. Suspended ceilings usually consist of a steel or aluminium grid with mineral fibre tiles. Alternative systems exist, such as perforated or lattice sheet steel panels.

6.7.2 Impact of Floor Zone Layers

All of these layers have environmental burdens, Figure 6.24 shows the initial mass, embodied energy and carbon dioxide values for these layers along with the composite structure per metre squared of gross floor area.

Figure 6-24 The Floor Zone



While all having low mass, the floor layers have relatively large energy and carbon dioxide values which is indicative of the high level of processing undertaken to turn basic materials into these products.

6.7.3 Impact Over Building Lifetime

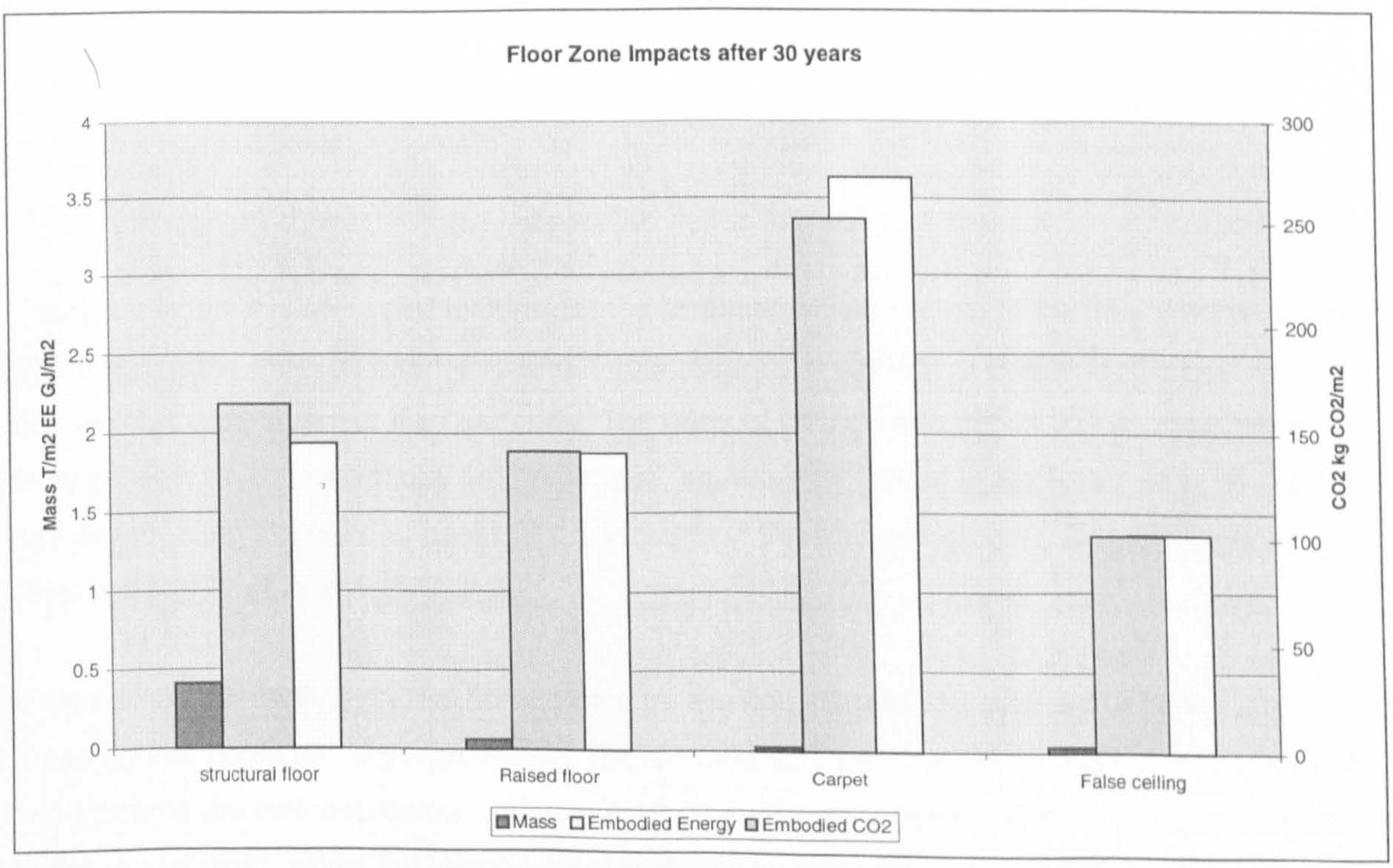
In a modern office the raised floor, carpet and false ceiling all have a shorter lifetime than the structural floor and over the course of even a thirty-year building lifetime these layers will undergo numerous changes. The current industry wide recognised lifetime for the main building layers is shown below.

Table 6-11 Lifespan of Building Layers (Trebilcock 1996)

Layer	Anticipated Life (in years)	Proportion of first cost
Site	Permanent	
Structure	30-100	15-25%
Skin	15-25	30-40%
Services	8-15	15-30%
Space plan	2-10	10-20%
Stuff	Always changing	

The changing services and space plan will effect the floor zone. Assuming carpet lifetime of 8 years, suspended ceiling of 10 and raised floor of 20 years, the accumulative embodied impacts of these layers over a 30 year lifetime is presented in Figure 6.25.

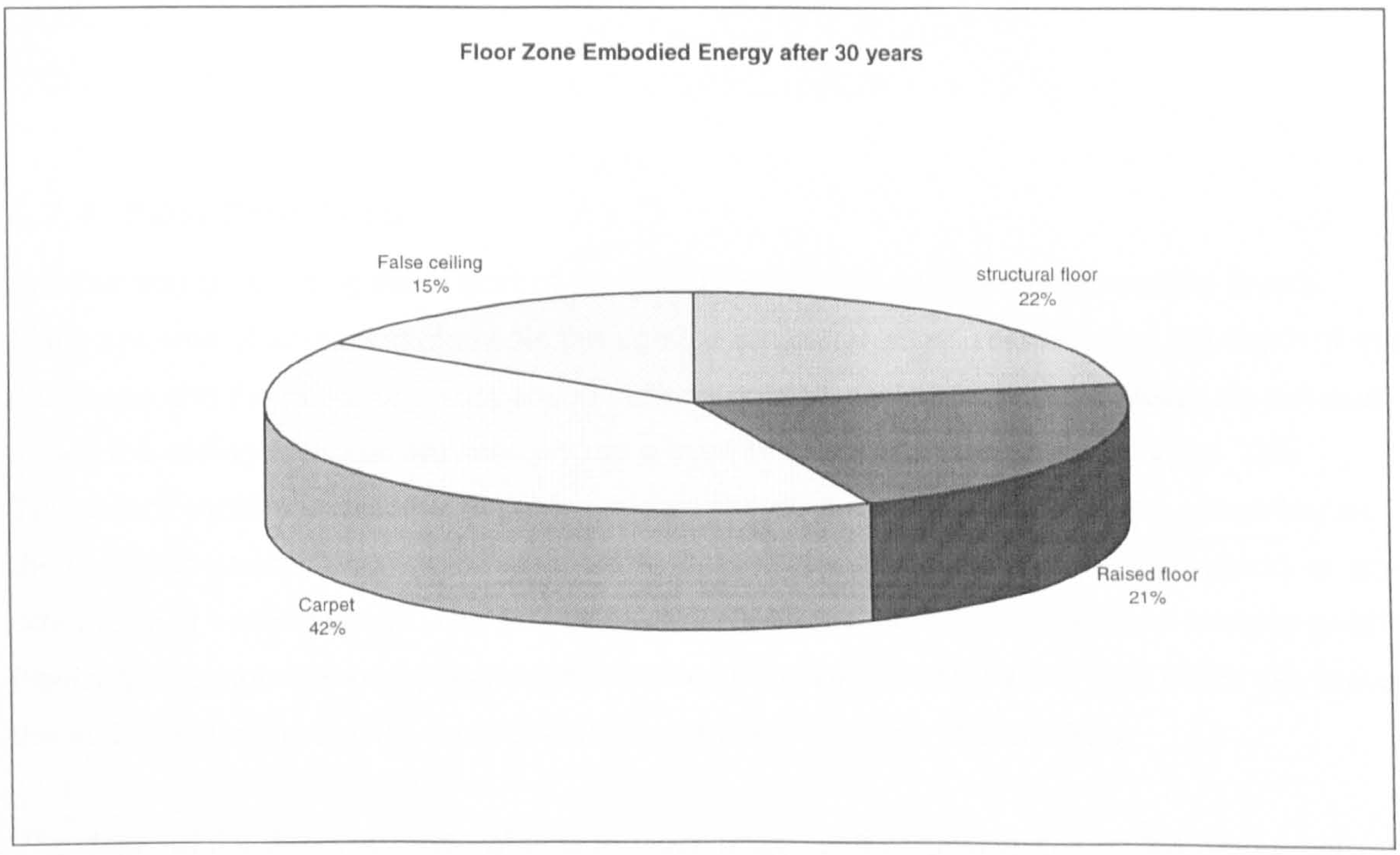
Figure 6-25 Floor Zone after 30 years



After 30 years the rapidly changing carpet becomes the main impact category. The embodied energy of this is 50% larger than that for the structure. The other two layers are also much closer to the impact of the structure.

Figure 6.26 below shows that when considering the floor zone as a whole, the structural layer accounts for only 22% of the total cumulative embodied energy over a 30 year lifetime, compared to 42% initially. If the building is going to be of continued use then the proportional impact of the structural layer will likely decrease further as the other layers continue to change.

Figure 6-26 Floor Zone Embodied Energy



Therefore whilst it is important to consider the disassembly and reuse of the floor elements the whole floor zone must be examined and a comprehensive strategy is needed for the other quicker changing layers of the floor zone. The rates of change adopted in this analysis were fairly conservative. The architectural press are, increasingly talking about faster rates of change, further enforcing the need to consider the impacts of the whole floor zone, (see for instance; (Stansall 1999), (Evans 1997)).

It was difficult to verify the initial impact data for the carpet and false ceiling and potentially these figures could be very high. Raised floors manufactures were contacted and the values of two systems are included below, in Table 6.12. The first-composite system impacts are similar to the model used, whilst the second-steel system's impacts are considerable lower, being approximately half that of the model used. This system uses steel only plates, were as the first uses a steel and chipboard composite plate. However, the steel only system uses a layer of adhesive over the entire floor area and while figures for this could not be found, adhesives are generally of high embodied energy impact and difficult to remove. Both manufacturers estimated a 15-20 year lifetime and neither had any take back or recycling systems in place. The composite system would be particularly difficult to recycle as the steel is bonded either side of the chipboard.

Table 6-12 Values for Raised Floors

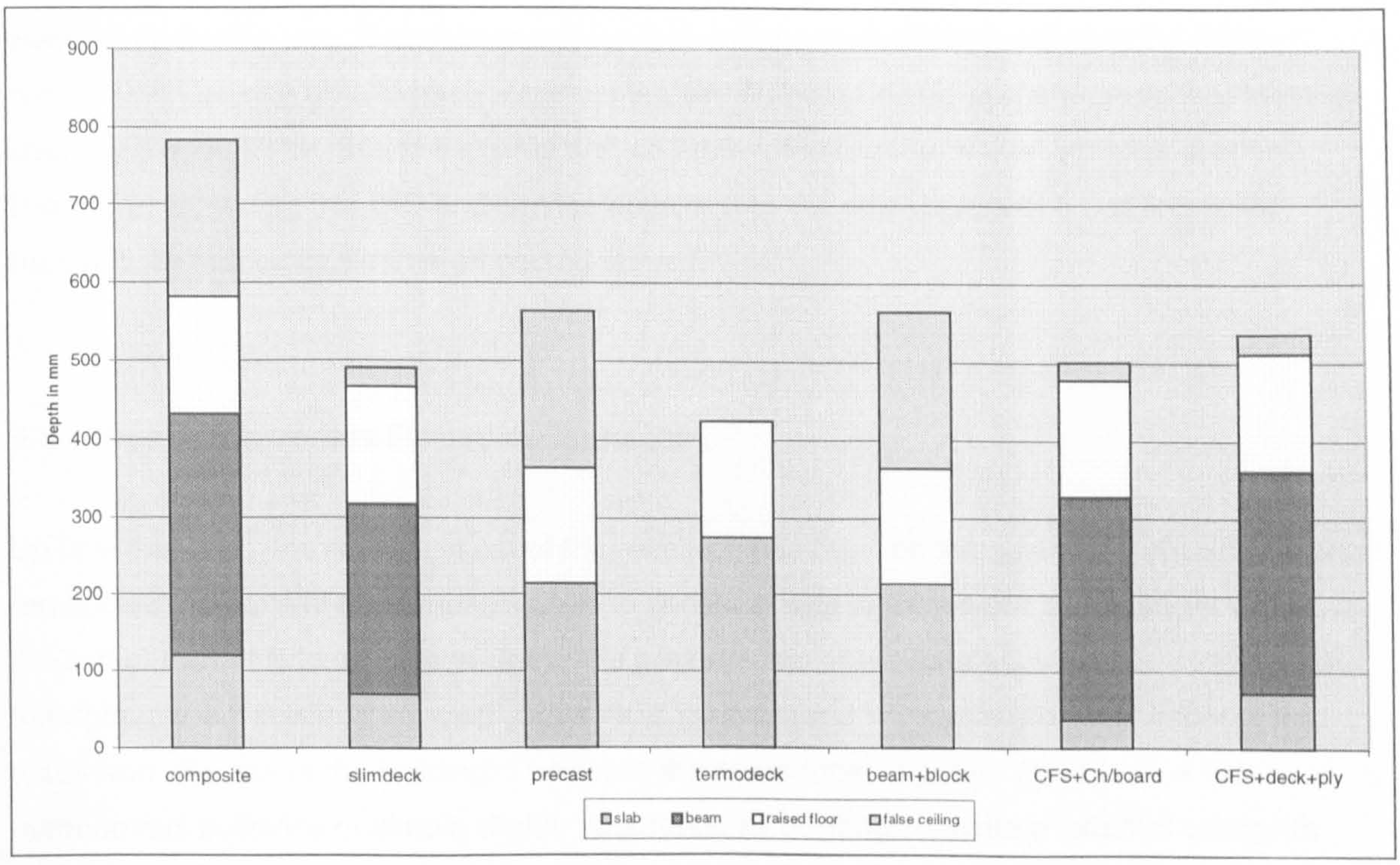
Raised Floor	Mass	Embodied Energy	Embodied CO2
	T/m2	GJ/m2	Kg CO2/m2
Model values	0.04	1.25	94
Composite	0.035	1.1	76
Steel	0.021	0.57	43

6.7.4 Floor Zone Depth

Another way of reducing the impact of the floor zone is to do away with some of the layers. Many systems offer ducting channels through the structural zone. This reduces the depth of the floor zone and the need for a suspended ceiling although aesthetically most clients do not want to see the ceiling mounted services and so a false or suspended ceiling is still used. The Termodeck system is possibly the only one that can do away with a false ceiling altogether as the floor is the heating/cooling circuit itself. It also negates the need for panel convectors or any other form of heating circuit. This leaves the floor plate clear of obstructions and enables greater flexibility in layout. However, even here the cores must be joined by a manifold which sits below the sofit and lighting circuits must be surface mounted or follow this manifold.

The depth of the floor zone also affects the total height of the building and so the amount of cladding required. Figure 6.27 below represents the floor zone depth for all the different constructions considered so far. The floors that can do without a suspended ceiling and also contain the floor beams within the depth of the slab are considerably narrower, the difference being up to 300mm. Over ten stories this becomes 3m and could enable either an additional floor to be included for the same building height or 10% to be saved from the cladding required. The Slimdeck and Termodeck floor systems have both been designed to reduce the floor depth, with the structural zones accommodating services, this is evident below, as they have the lowest depths for the different floors examined. Therefore while they are structurally more impacting than say the standard; composite or precast, they may reduce the building height, with an associated reduction in cladding impact or allow for more floors for the same height, increasing the density of occupation.

Figure 6-27 Total depth of Floor Zone



6.7.5 Dematerialization and the Service Concept Applied to Floor Zone

As already discussed when investigating the soft strip stage of demolition (section 4.3.8) a number of firms, particularly in the USA, are changing the way they do business and becoming providers of quality services, rather than sellers of products. One of the firms leading this change manufactures office carpets.

The company has replaced carpet with carpet tiles, and routinely checks and replaces the worn carpet tiles of all its customers. They then take back the worn carpet tiles and recycle them into new carpet tiles. This new service and continual recycling approach, has resulted in massive dematerialization, reducing by over 30 times the resources needed to provide carpets (Anderson, 1997).

Re-examining the impact of the various layers of the office building over the lifetime, and including a reduced impact by a factor of 30 for the carpet, would start to significantly change the balance of the embodied impacts. In the study undertaken, the carpet accounted for 40% of the floor zone embodied energy impact after 30 years. Assuming the other layers remain the same, the carpet would now be reduced to less than 2% of the total embodied impact.

What can be done with the carpet could potentially also be done with the other internal layers, such as the raised floor and suspended ceiling. However a reduction in impact by a factor of 30 is extreme, and most examples point to a dematerialization of between 4 and 10 (see for example Factor Four by Weizsacker and Lovins). Integral to the approach of all the firms involved with leasing or take back schemes is DfD. Without DfD (at system, product or material level) they wouldn't be able to separate and so remanufacture the 'waste' into new products. Therefore, extending this DfD and service approach to the other layers of a building could substantially reduce its lifetime-embodied impact.

6.8 Operation versus Embodied Impacts

Up until this point, the majority most of the research has been concerned with the environmental (embodied) impacts of the materials used to construct and refurbish our buildings. However, as the aim of Part III is to determine where the greatest use of resources and major impacts occur throughout the lifecycle, the investigation must be extended to include the other impacts that result from the use of the building. These are the operational impacts. Apart from a few autonomous buildings or simple shelter structures, all buildings consume external energy to provide adequate and comfortable working, living and, leisure conditions. As this chapter is concerned with office buildings, the operational impacts are then; those associated with providing thermal comfort (both heating and cooling), ventilation, general and task lighting, office power, water and sanitation, communications, security and any other tasks required of the modern office.

Therefore, in this final section of Part III, the embodied environmental impacts are compared with the operational impacts for an office building throughout its lifecycle. In undertaking this comparison it is noted that previous studies have assumed that most of the impacts lie in this operation or use phase of the building life cycle (Amato 1996). It is also noted that this paradigm is now being questioned due to both technical and organisational changes.

Firstly, considering the former, more energy efficient building services equipment and a better understanding of how to use natural and passive techniques has enabled building designers to reduce considerably the operational energy consumption. Energy efficient technology has been improving in fits and starts since the oil crisis of the 1970's. However, since the Rio Earth Summit of 1992, and the continuing series of climate conventions, these advances have become more regular and pronounced. Today most prestigious developments aim for high levels of energy efficiency and the majority of design practices sight this as a basic design parameter.

Existing buildings can also be retrofitted with energy efficient equipment during refurbishment. At its most basic level this consists of increasing the insulation levels, sealing against draughts and preventing excessive heat gain due to solar radiation. This involves changes to the external envelope and the services. For example, a number of case studies are reported were the improvements due to advanced glazing, cladding, and lighting systems were calculated to reduce the operational energy demand by over 60%, and figures like this are not unusual (DETR 1998), (Hawken, Lovins et al. 1999).

At the advanced level the growing acceptance of solar technology has led to a number of buildings being retrofitted with photo-voltaic panels. In the future these are likely to be combined with micro combined heat and power plants and hydrogen fuel cells. Together these would cover all the energy demands of the building and even export electricity in times of low building demand, turning it into a mini power station (Pearce 2000).

Glazing technology is also changing, it is now possible to 'tune' the glass to control solar radiation and thermal gain, and future windows may even be filled with water. In this system water is pumped through the cavity between double glazed panes. A chemical dissolved in the water absorbs infrared energy from sunlight but is transparent at visible wavelengths. Therefore, while heat is absorbed by the solution inside the windows, visible light passes straight through. Water from the windows circulates through a heat exchanger, allowing it to be stored or used elsewhere (Sample 2000). All these technologies are likely to reduce the operational energy consumption of a building at the expense of a more embodied energy intensive external envelope.

Secondly, organisational changes are also effecting the balance between the operational and embodied impacts. The growing trend to change the function of a building and the increasing churn rates of office buildings results in frequent changes to the internal and external layers. As shown above, the cumulative impact of just the changes to the floor zone can be significant. All the indications from industry are that the rate of change is only going to increase therefore further emphasising the importance of allowing the fluid change between the different layers and the ability to reuse or recycle the elements once removed.

6.8.1 Operational Energy Data

For office buildings in the UK, the DETR have produced a set of energy consumption benchmarks to guide designers in defining performance criteria, often termed the best practice figures, these are shown is Table 6.13 below.

Table 6-13 Energy Consumption Benchmarks
(DETR 1998)

Service Option	Performance Assessment	
	Low consumption (less than figure)	High consumption (greater than figure)
	Benchmarks in kWh/m^2/year	Benchmarks in kWh/m^2/year
Naturally ventilated cellular office	112	205
Naturally ventilated open plan	133	236
Air conditioned standard	225	404
Air conditioned prestige	348	568

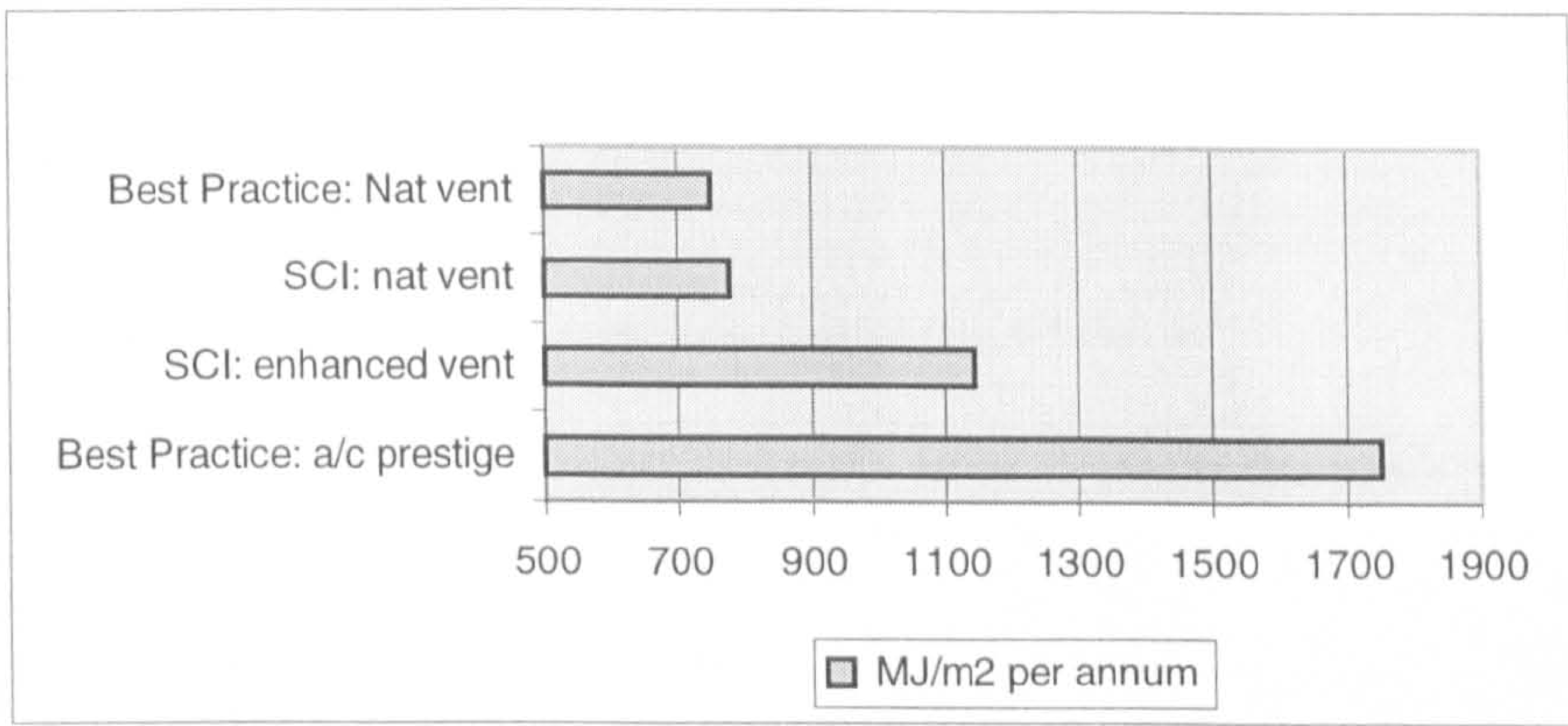
For the study conducted by SCI the annual energy figures where estimated for four different service scenarios from naturally ventilated though to fully air-conditioned. These are presented in Table 6.14 below, the values being given in MJ/m^2 per annum. The calculation was repeated for each of the different structural frame options investigated but resulted in very little change. This was because the only difference between the buildings was in the structural frame and floors, the rest of the layers being the same. The only influence the frame and floors could have on the operational energy consumption was in thermal storage capacity and as all involved at least 100mm of concrete this was very similar for all constructions.

Table 6-14 Annual operational energy consumption
(Amato 1996) p66

Service Option	Operational Energy MJ/ m^2/year
Heating & natural ventilation	776
Heating & mechanical supply & extract	1133
Heating & mechanical supply & extract via false floor (ff)	1141
Heating mech, supply extract via ff & enhanced heat transfer	1145

To compare the two sets of figures required some adjustment of the DETR best practice figures. This involved changing the units from kWh to MJ per m^2 and using the same working day length of 8 hours. These figures are presented if Figure 6.28 below.

Figure 6-28 Comparison of SCI and Best Practice operational energy values



The best practice naturally ventilated office has a slightly better performance than the SCI building (750 compared to 776 MJ/ m^2 per annum). While the SCI enhanced ventilation option is far lower than a full air-conditioned office.

6.8.2 Embodied Energy Changes over the Lifecycle

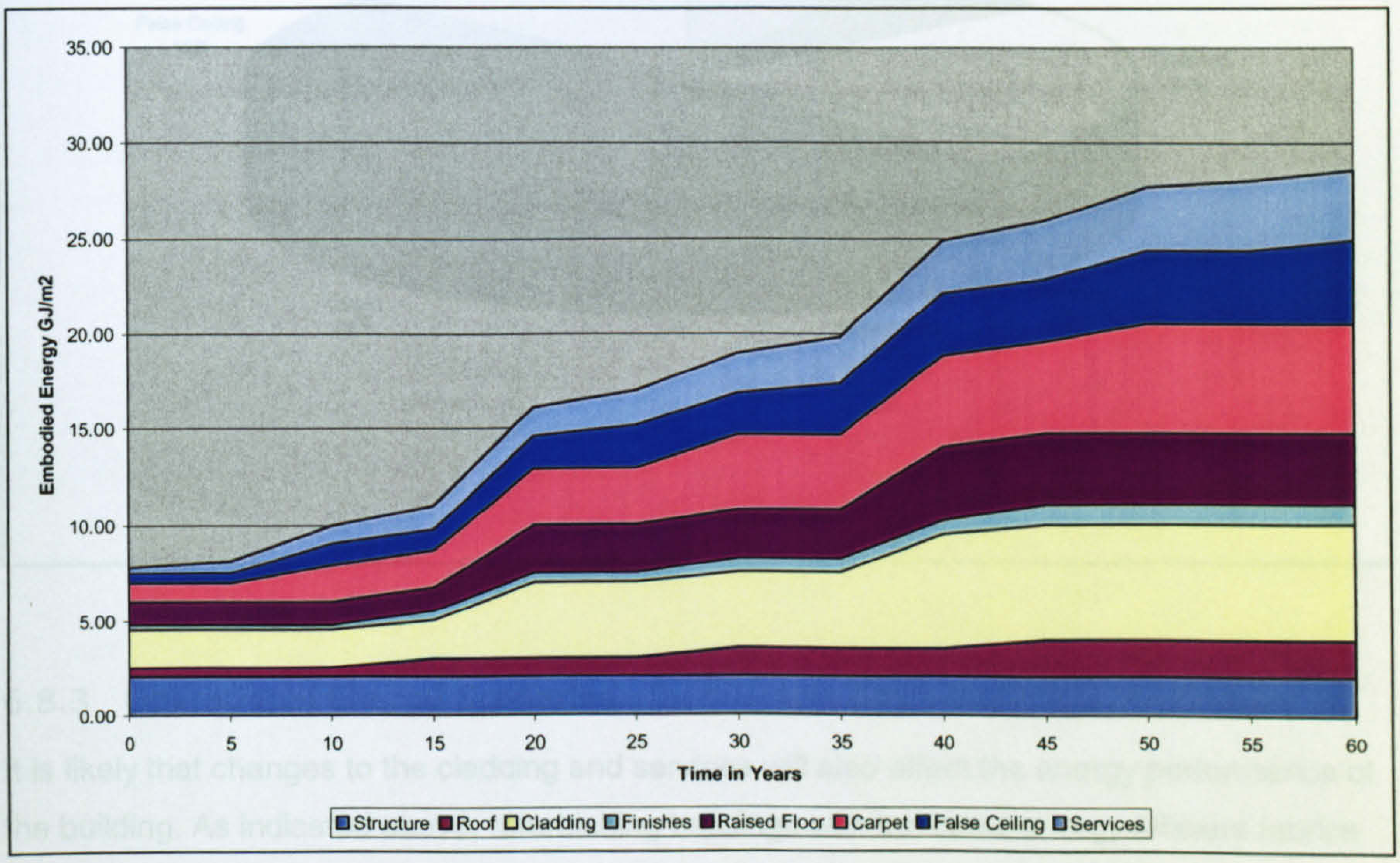
For this study, the two operational energy extremes of the SCI study will be compared to the embodied energy values over a 60-year lifetime. Also to be taken into account here are the regular increases in embodied energy due to changes in the building layers. Table 6.15 below indicates the frequency of these changes, in accordance with current recognised figures, see section 6.7.3 above.

Table 6-15 Life-span & Embodied Energy of Building Layers

Layer	Lifetime for this study (in years)	Embodied energy GJ/ m^2	Embodied energy after 60 years GJ/ m^2
Site	Permanent		
Structure (foundations, frame and floors)	60	2.08	2.08
Roof	15	0.49	1.97
Cladding (brick and block and windows)	20	1.99	5.97
Finishes	5	0.25	0.99
Raised Floor	20	1.25	3.75
Carpet	8	0.97	5.81
False Ceiling	10	0.55	4.36
Services	15	0.30	3.65
Totals		**7.88**	**28.59**

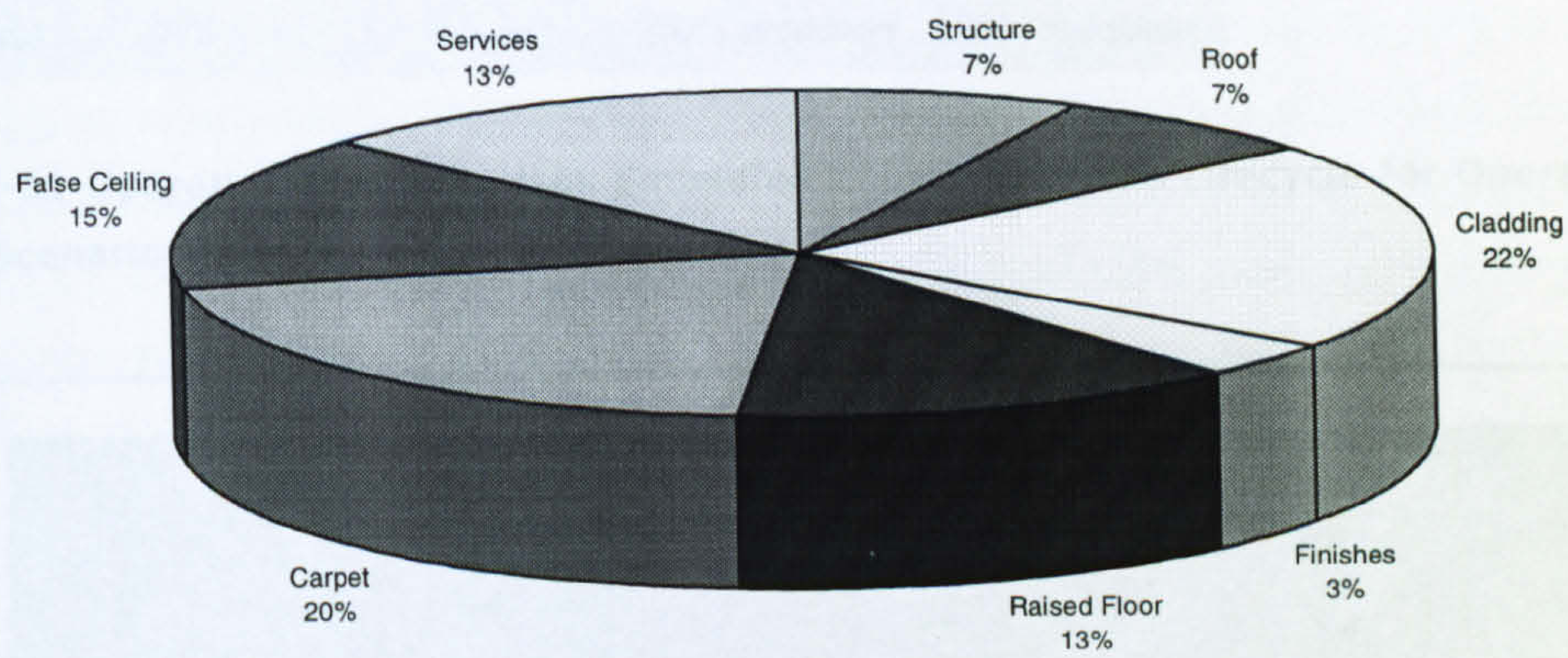
Figure 6.29 below presents the effect of these lifetime changes on the embodied energy over a 60year life span. At the end of sixty years the embodied energy of the building is 28.6 GJ/m^2, almost four times that at the beginning of 7.8 GJ/m^2. The major influencing layers being the external cladding at 6 GJ/m^2 followed by the carpet at 5.8 GJ/m^2, and the suspended ceiling at 4.4 GJ/m^2.

Figure 6-29 Embodied Energy over a 60 Year Lifecycle



In figure 6.30 below the percentage of the total embodied energy at the end of the 60 year lifetime are given. Initially the structure was the main layer with over 30% of the total embodied energy. Now at the end of the life (with no structural changes) this accounts for less than 10% of the total embodied energy. This again emphasizes the importance of considering the time-related impacts of all the layers of the building, not just the structural layers. The internal layers accounting for almost 50% at the end of 60 years.

Figure 6-30 Embodied Energy Percentages at end of 60 year Lifetime



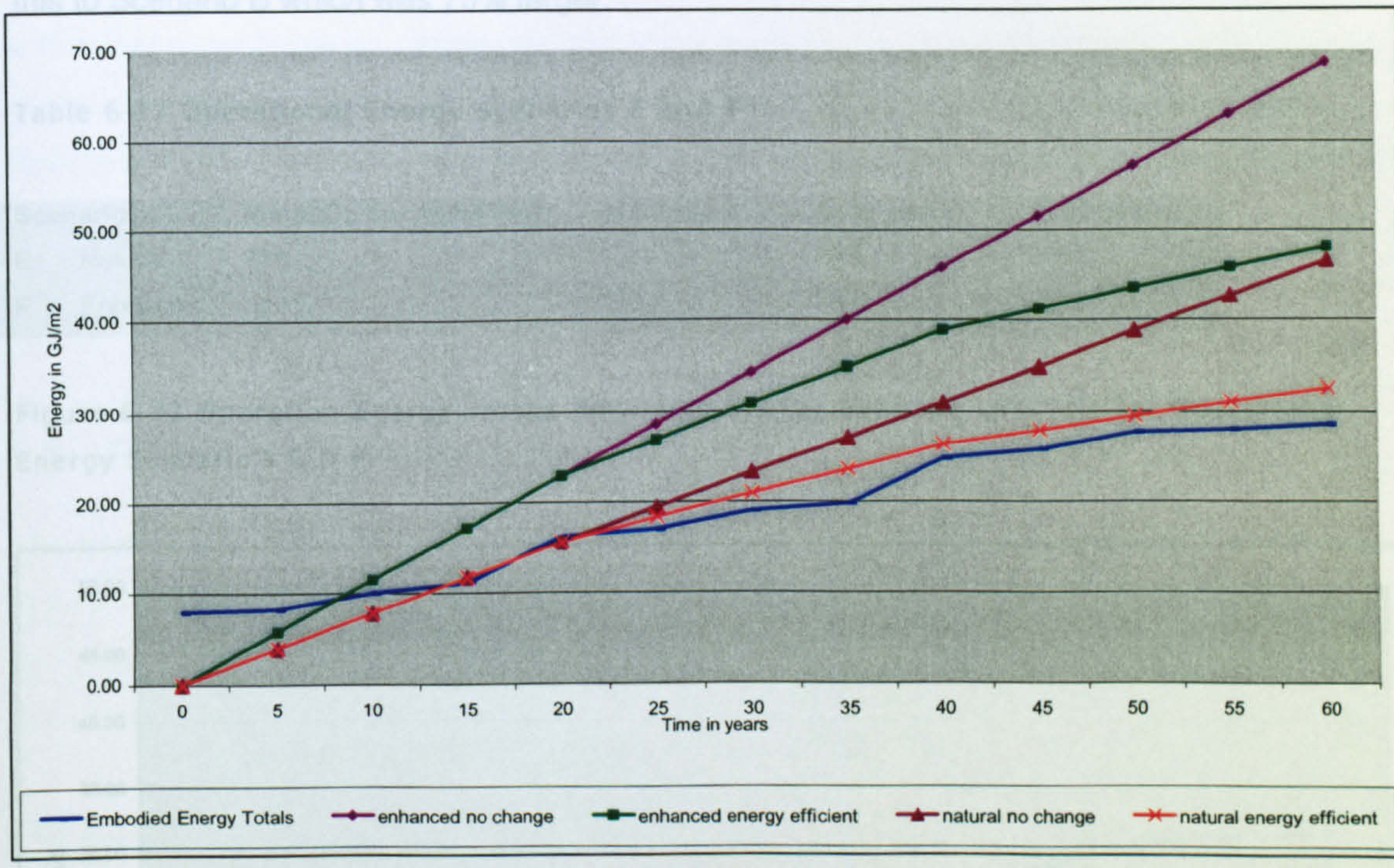
6.8.3 Operational Energy Scenarios

It is likely that changes to the cladding and services will also effect the energy performance of the building. As indicated above, refurbishing buildings with the latest energy efficient fabrics and technologies can reduce the operational energy by more than 60%. For the office case study examined here two different future operational energy scenarios are assumed. In the first, the operation energy stays constant for each refurbishment. This is unlikely, and therefore this would be the worst case scenario. For the second case, the operational energy will decrease with the energy efficient changes of cladding and services. Changing the cladding will result in increases in thermal insulation, daylight penetration and control of solar thermal gain and glare. Changing the services will result in more efficient mechanical heating and ventilation plant and artificial lighting. Therefore from 20 to 40 years a 30% increase in energy efficiency in assumed and from 40 to 60 years a 60% increase. These four scenarios are summarized in the table below.

Table 6-16 Operational Energy Scenarios

Scenario		Initial Op energy MJ/m2	At 20 years	At 40 years
A	Enhanced	1145	No change	No change
B	Enhanced	1145	30% reduction	60% reduction
C	Natural	776	No change	No Change
D	Natural	776	30% reduction	60% reduction

Figure 6-31 Operation Energy versus Embodied Energy over the Lifecycle for Operational Energy Scenario's A to D



6.8.4 Comparisons of Scenarios over the Lifecycle

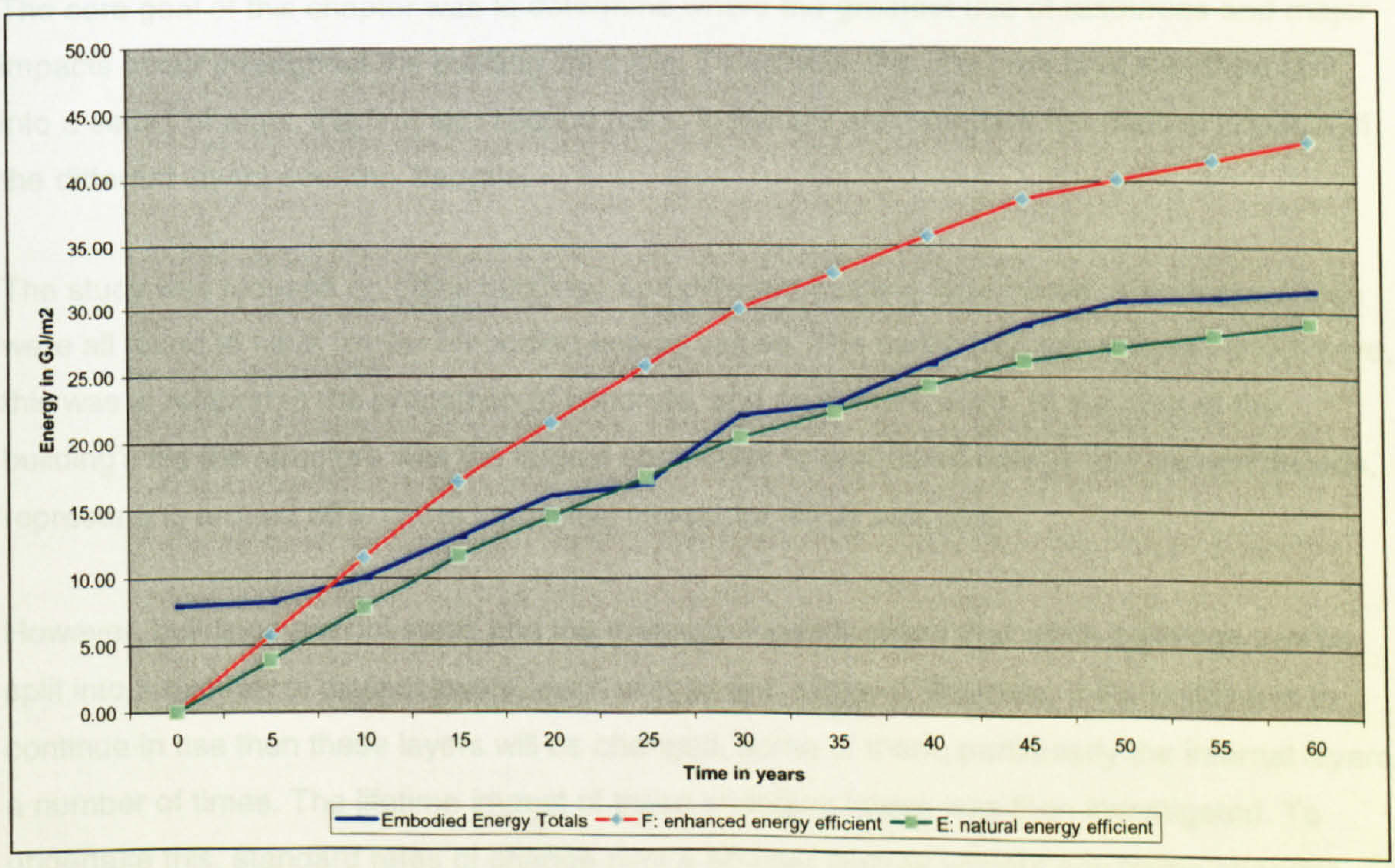
In Figure 6.31 above, the embodied energy is compared with the four operational energy scenarios as given above. This indicates that the operational energy curve crosses the embodied energy curve at 7 years for the scenarios A & B, and at 12 years for scenarios C & D. Scenario A, the highest operational energy case, is over twice the embodied energy at 69 GJ/m^2, compared to 28 GJ/m^2. However Scenario D, the most energy efficient case energy at 33 GJ/m^2 is only 18% higher than the embodied energy. Therefore indicating that for an energy efficient building the operational and embodied energies are comparable. As discussed earlier, energy efficient buildings often try to use the thermal mass of the building to iron out fluctuations in diurnal temperature, more advanced glazing techniques to improve day lighting, and prevent solar glare and gain, and passive stacks and solar chimneys to control ventilation. Generally adopting such deigns would increase the initial embodied energy of a scheme while reducing the operation energy used over the lifetime. This further supports the case that operational and embodied energies are comparable over the lifetime.

A further scenario is now explored, in which the change of the cladding layer is brought into line with the services, every 15 years, and the operational energy decreases by 25% at each of these 15 year refurbishment's (see Table 6.18). The lifetime impacts would look like Figure 6.32 below. The embodied energy now follows the naturally ventilated office operational energy (scenario E). The enhanced ventilation office scenario is still 40% larger (scenario F), compare this to Scenario B which was 75% larger.

Table 6-17 Operational Energy Scenarios E and F

Scenario		Initial Op energy MJ/m2	At 15 years	At 30 years	At 45 years
E	Natural	776	25%	25%	25%
F	Enhanced	1145	25%	25%	25%

Figure 6-32 Operation Energy versus Embodied Energy over the Lifecycle for Operational Energy Scenario's E & F



6.8.5 Operational Energy Conclusions

In this section the lifetime comparisons of operational and embodied energy were drawn. Whilst operational energy is generally greater than embodied energy this research indicates that it is not by the margin previously assumed. Most existing research has not included the impact of the changing layers when calculating the lifetime embodied energy. This can increase significantly the embodied energy impact while at the same time reducing the operational impacts through improving the natural conditions of the building and the energy efficiency of the services. To allow for variations in future services a range of future energy scenarios were investigated. In the most energy consuming case examined, operational energy was twice the embodied, conversely in the most energy efficient scenario the two figures were almost equal.

Predicting future operational energy scenarios is always going to be contentious, as is predicting the number of changes the building layers will go through during the lifetime. Therefore it could be argued that this research is highly speculative. However, the current trend is to adopt more passive building designs which leads to higher initial embodied energies but operational savings, and also to change the function of a building fairly rapidly, leading to lifetime embodied impact increases. Therefore this research is in line with the general direction of architecture and building services engineering.

6.9 Chapter conclusions

The core goal of this chapter was to determine where the greatest use of resources and major impacts occur throughout the building life cycle. To achieve this, the core goal was then split into a series of aims, the first and second being to identify and compare the relative impacts of the different layers over the lifecycle.

The study was focused on office buildings and different building types were considered, these were all found to have similar embodied energy values. The carbon dioxide values varied more, this was in relation to the proportion of concrete, and so cement used. At the start of the building's life the structure was the largest contributor to embodied energy and carbon dioxide, representing around 30% of the total initial impact for either category.

However, buildings are not static and the research then identified that office buildings can be split into a number of distinct layers, each with its own range of lifetimes. If the building is to continue in use then these layers will be changed, some of them, particularly the internal layers, a number of times. The lifetime impact of these changing layers was then investigated. To undertake this, standard rates of change over a 60-year lifetime without any frame changes were assumed. The investigation focused particularly on the floor zone layers, both at the ceiling and the floor. In modern offices; power, lighting, heating, ventilation, thermal storage and sound absorption are all controlled via by these layers. The inadequate provision of one of these functions could lead to reduced performance or even early building obsolescence, therefore these layers are replaced regularly, incurring embodied impacts with each change.

The layers study indicated that the cladding has the largest contribution to embodied energy impact accounting for 22% of the total, followed by the carpet 20% and the false ceiling at 18%, while the structure (which hasn't changed) only accounts for 7%, compared to 30% initially. The impact of the cladding was particularly high due to facing bricks being used, these have an embodied energy twice that of common bricks.

The combined internal layers have the largest single contribution to the embodied impacts of the office building at almost 50%. Currently there is little detailed quantitative work on the frequency, extent, and impact of these internal changes. The refurbishment of offices often being carried out by specialist contractors and to date little analysis of their activities has been conducted.

An alternative future for these internal layers was also discussed. This is based on the service concept and can lead to dramatic dematerializations of the products involved. An example of the impact of office carpet being reduced by 30 times being given, although this is the extreme, a factor of 4 to 10 being more realistic for most products. If this approach was adopted for all of the internal layers (and even extended to the cladding and structure) then the embodied impacts of a building could be significantly reduced. For such an approach to be practical the layers of the building would have to be accessible according to their hierarchy of use, and in order to remove them DfD would need to be included from the start.

This then brings the research onto the third aim of the chapter, which was to examine the implications of designing for disassembly. As the different layers were examined, so was their suitability to DfD assessed. Three frame and floor systems were investigated in detail, one allowing no disassembly (composite), one using a combination of standard precast concrete and steel elements, and one using a lightweight steel solution. Over a single lifetime the composite was the least impacting, however over subsequent lifetimes this frames impact became considerably larger than the others. For the precast frame the foundations and ground-bearing slab represented a proportionally increasing impact with each frame change as it could not be disassembled and so had to be demolished and replaced. The lightweight steel solution was possibly the best in terms of DfD. Apart from foundations it was a completely dry construction with bolted or screwed connections allowing disassembly. Initially it had a high embodied impact, due to its high steel content. However after two frame changes it was comparable to the precast and after four changes its impact was the lowest, and the gap between it and the precast continuing to increase with each subsequent frame change. This was again mainly due to the low proportion of insitu concrete and the high proportion of reusable steel elements. Also its low mass and standard elements would enable efficient storage and transportation to site of future reuse. However its long-term suitability is currently limited as additional fire protection, acoustic and thermal layers would be needed to give it a similar performance to the precast or composite floors.

The final aim was to compare the embodied impacts with the operational impacts over the lifecycle. This indicated that embodied impacts are more significant than previously assumed, particularly for office buildings that are kept in use through maintenance, refurbishment and replacement of the various layers. For future energy efficient scenarios the embodied impacts match the operational impacts over the lifecycle. Therefore, this research indicates that the operational and embodied impacts should be considered with equal merit when designing to reduce the use of resources and major impacts throughout the building life cycle.

7 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

This final chapter presents the conclusions of this research, based on a synthesis of the findings of the earlier chapters. It draws together the exploratory and experimental research, as presented in Chapters 4 to 6, with the literature, which was reviewed and developed through Chapters 2 and 3. As such it presents the contributions to knowledge achieved through this thesis. The research was conducted in order to assess the hypothesis, set out in Chapter one, which stated that:; Appropriate disassembly strategies can extend the functional lifetime of buildings, their elements and materials, and thereby reduce their lifetime environmental impacts. From the range of approaches and strategies established throughout the thesis this hypothesis has been validated. In addition, a number of recommendations for further research are made.

7.1 Buildings and Sustainability

The research presented within this thesis is concerned with improvements in the sustainability of the built environment. This is in response to the substantial and increasing body of evidence, which suggests that the current global patterns of production and consumption are not sustainable and that in order to affect environmental improvement, major changes are necessary.

The built environment from its construction, through its use and to its final demolition is responsible for approximately 50% of all the resources and energy used and 50% of all the waste produced. Therefore, if the sustainability of human activity is to be improved the built environment must be at the heart of this change.

7.2 Linear to Circular

Fundamental to a sustainable approach is thinking in a more lifecycle systems manner. What once were considered as wastes are seen as a future resource, and the lifetime of the building is seen as a dynamic flux of time dependent layers that adapt to the needs of the tenant and change with improvements in technology.

In searching for a systems methodology the development of natural systems has been highlighted. These start as simple linear input-output flows, but it is not long before feedback and maintenance rather than growth begins to replace this linear flow. Eventually natural systems get to a mature stage of circular flow, with resources moving round complex, web-like, systems with little waste. This, however, is not a stable condition, equilibrium is not reached, and minor changes and major fluxes are always altering the dynamic in the flow of resources through the system. These natural systems are characterized by three modes of order:

- Pattern Order,
- Structural Order, and
- Functional Order.

The pattern describes the organization of the system, the structure, the composition of living and non-living elements, and the function, the flow of resources through the system to maintain its order. Without these flows, equilibrium will be reached, and the system will cease to operate.

7.3 Building Patterns

The research then moved forward to look at human systems and the built environment. In contrast to natural systems, human industrial systems are usually linear, polluting, inflexible, and require the constant input of new resources and removal of wastes to maintain them. However, advancing human systems to mimic the 'mature' strategies of natural systems could enable a more circular arrangement of resource use, resulting in more resilience and adaptability, and potentially reducing our environmental impact. Drawing the built environment into the debate and applying the principles of natural systems to buildings within the three level system concept results in the following general design strategies:

Pattern Order	**Spatial layout, planned use and relation to existing local environment** • Encourage diversity, co-operation and resilience • Optimise and maintain rather than maximising growth • Run on information and feedback • Link across scales • Think over long time frames
Structural Order	**Physical embodiment of the pattern, i.e. the material structure** • Create materials cycles • Improve material and energy efficiency • Utilise renewable resources at replenishable rates • Use locally occurring resources
Functional Order	**Flow of energy and resources, the buildings services** • Gather and use energy efficiently • Reduce pollution by avoiding toxic substances and dissipative materials

This basic analogy can be applied across the whole spectrum of the built environment. By relating to buildings in this way, their relationship with the ecosphere, and the flow of resources through them can be more readily perceived. As such, pattern, structural, and functional order form the basic layer and first component of the analytical framework of this thesis.

7.4 Design for Disassembly

Within the construction sector, the majority of existing research has focused on the construction and operation stage. The research presented in this thesis has extended this by considering the demolition stage. Most decisions about a material's fate happen at the design stage, long before the material becomes waste. Therefore, it is important to integrate dismantling information into the design process. The advent of the Design for Disassembly (DfD) concept enables a more proactive 'designing out of waste' approach to be taken.

Spurred on by a new European law, the product design industry is leading the way in applying DfD. The new law states that by 2006 all manufacturers of electrical and electronic equipment will have to take back and recycle up to 90% of their products, once their owners have discarded them. Legislation concerning construction and demolition waste (C&DW) is also being increased, and following the lead of the product industry the DfD concept has been applied to buildings.

Generally the product industry has adopted a two tiered approach to DfD, and this has been expanded in this research to account for the physical scale, and variable time dependent layers of buildings. So DfD then becomes a three level approach (this can be overlaid on the pattern, system and functional modes of order, described earlier):

1. **Systems level**: Adaptable buildings that can change to suit changing requirements;
2. **Product level**: The products (or layers) of the building are designed to allow upgrading, repair and replacement. The replaced products can then enter the replenishing loop; and,
3. **Material Level**: When a product has been stripped back to its constituent materials these can undergo recycling.

Through a series of in-depth exploratory interviews with demolition experts, this approach has been expanded to cover a detailed range of strategies that must be considered when designing for disassembly. These strategies, which provide a significant contribution to knowledge, are given at the end of Chapter 4 and the main findings are discussed below.

7.4.1 Detailed Strategies

Perception

Demolition is, in fact, the start not the end of most building projects, particularly on inner city or brown-field sites. As such it needs to be fully integrated with the future works program, not, as it often seems, perceived as an obstacle to be quickly overcome before building can commence.

Time & Money

Time is inextricably linked to money, both in terms of that allowed for the demolition contract as a whole and as the deciding factor as to any material's fate. No time to dismantle re-useable materials simply means no materials for re-use. Due to developer pressure the main emphasis is now on demolishing as quickly as is safely possible. As such, demolition contracts have gone from six months to six weeks duration. If more time was available recycling might increase, but the bottom line is economic: labour is expensive and new products are now cheap.

Information

The emphasis here being on the quality not quantity of information available to the demolition contractor. This should include:

- As-built drawing records;
- Records of all changes to the building during its lifetime;
- Asset registers showing the elements, materials and their recycling potential;
- Identification of potentially hazardous materials;
- Details of prefabricated elements plus fixing and carrying points; and even
- Labeling of materials.

CDM regulations are starting to improve this situation. We live in a society that is increasingly geared towards and driven by information and this is also relevant to the building profession. Quality information can speed up both the pre-tender and main demolition contract, and allow pre-determination of waste and recycling routes.

Building in Layers

Demolition is the reverse of construction, starting from inside out. Making the high value and frequently changed internal layers easy to take apart/replace, or even leased from a service provider would ensure that the length of material life can be maximized. The cladding can also be designed for deconstruction within a longer time frame. The main structural frame and floors should be designed to be robust enough to withstand all the internal/external changes but be of simple construction to minimize deconstruction time and maximize recycling potential.

Avoid hazardous and complex composite materials

Dissimilar materials bonded together are difficult to separate. For example, polystyrene used for insulation and as permanent shuttering renders the attached concrete impossible to recycle.

Use simple structural grids

Modern buildings tend towards long spans and complicated and often hidden support structures. Demolishing these will prove very difficult.

Demolition Space

Space should be allowed on any site for the future erection of tower cranes and the location of hi-reach excavators. Also, internal atria or lift wells provide ideal locations for the removal of demolished material.

Prefabrication

Prefabrication has advantages for internal units and cladding panels, though likelihood of reuse is slender. Ease of construction/dismantling and of transport to recycling facility are plus points. They must be substantial enough to allow deconstruction.

Soft Strip

Demolition contractors come into contact with a building either at the end of its life, or at a time when a partial demolition is required to change the function and/or increase the life of the building. However, these are not the only times when a building may change. Commercial and retail buildings are altered on a frequent basis, this work usually being conducted by teams of shop fitters, not demolition contractors. The layers that are replaced include the internal configuration of partitions, doors, false and suspended ceilings, raised floors and services, in other words the soft strip elements. As internal refurbishment may involve a number of firms or a different firm every time it was difficult to find out much information about the soft strip.

Most of the materials in this layer have been highly processed into specific composite elements with resultant high-embodied impacts relative to the more basic-structural elements of the construction. Also, as most buildings will undergo a number of internal fit-outs through their lifetimes, for fashion to functional reasons it is the layer with possibly the largest overall environmental impact.

Once defined, the question is then how you integrate these strategies into the already crowed design and construction process?

The DETR in its recent sustainability publication 'Building a Better Quality of Life' (DETR 2000) highlighted the importance of considering the end of life within its Ten Themes for Action for the construction industry. Four of these themes are directly related to this thesis, these are; Theme One 'Reuse existing built assets', Theme Two 'design for minimum waste', Theme Three 'Aim for lean construction', and Theme Six 'do not pollute'. Therefore the precedent is set for including DfD strategies.

The BRE has produced BREEAM, which is an analysis tool that enables the design team to measure the effects of a building upon the environment. BREEAM covers issues ranging from global atmospheric pollution through to the comfort and health of occupants. Assessment credits are awarded for each area and these combine to form the final rating of the building. Already BREEAM covers recycling and reuse of materials, ecological value of the site and hazardous materials. Credits are given for using crushed demolition material as fill and in foundation concrete. Also for specifying materials which contain at least 50% by volume of 'waste' or 'by product' material, and for allowing separate storage space on site for recyclable materials. Avoiding hazardous such as lead, asbestos and urea formalderhyde improves the BREEAM rating as does using brown-field sites. Therefore as BREEAM already considers some of the issues of end of life, it would be relatively easy to extend and adjust the BREEAM assessment criteria to include the strategies highlighted in the DfD work.

The design process itself has recently been under scrutiny and many opportunities for improvement and change were identified by 'Rethinking Construction', the report of the Construction Task Force, chaired by Sir John Egan (DETR 1998).

The intellectual underpinning of Rethinking Construction is the philosophy of Lean Thinking and Lean Production. A Lean Production process is organised so that at every stage decisions are made with the needs of the customer paramount, instead of being organised according to perceived production constraints and the needs of the producers. The 'customer' here being defined, not by a simplistic version of the market, but, understood to include the users, the passers-by and those 'customers' not yet born.

This broadens the responsibility of the design team to the whole of society, today and in the future, which is essentially at the core of sustainability. The potential relationship between lean construction and sustainability suggested by such an inclusive idea of the customer is further reinforced by other aspects of the lean philosophy - the elimination of waste, the responsiveness of the process (feedback), and the economies that result from it (saving money, resources and the environment). With their overview of the entire project architects are best placed to integrate the principles and strategies of sustainability into the construction process.

Lean Production was first shown to be effective in car manufacturing and as discussed earlier in this thesis (Chapter 3) the car industry has also synthesised Design for Disassembly strategies into its manufacturing process. Therefore the building industry can again learn from the product industries and rethink the fundamentals of its delivery processes to consider the whole lifecycle of our buildings.

In the current RIBA plan of work, decommissioning, dismantling and disposal are the last two life cycle stages. Whilst the rest of life cycle stages are starting to feedback into one another or run concurrently (particularly for Design and Build or Management Procurement contracts) the last two stages are left alone, isolated from the rest of the building process. Thinking in lifecycles requires the linking of these end-of-life stages to the pre-design and design stages, therefore, future problems and waste can be highlighted and designed out of the building. This in essence leads to the inclusion of the DfD strategies highlighted above and detailed at the end of Chapter 4 of this thesis.

7.5 Office Buildings over the Lifecycle

Following the detailed focus on one lifecycle stage, Part III expanded the research to consider the full lifecycle impacts of office buildings, examining both the embodied and operational impacts. The core goal of Part III was to determine where the greatest use of resources and major impacts occurs throughout the building life cycle.

First the embodied impacts of the different layers of the building were investigated. Through the literature reviewed, and the demolition interviews conducted, this research has indicated that buildings are constructed, refurbished, and demolished in these layers and therefore Part III highlighted the differences in the impacts of them.

As would be expected, the structure was the largest contributor to embodied energy and carbon dioxide at the start of the building's life, representing around 30% of the total initial impact for either category.

However, the research was concerned with the dynamic flux of the building layers over time and so the lifetime impact of these changing layers was then investigated. This involved assuming standard rates of change over a 60-year lifetime. The investigation focused particularly on the floor zone, which in the modern office consists of a number of layers all vital for the performance of the building. With the embodied energy and carbon dioxide data provided, the study indicated that the cladding makes the largest contribution to embodied energy accounting for 22% of the total. The carpet closely followed this accounting for 20% of the embodied energy, and the false-ceiling at 18%, while the structure only accounts for 7%, compared to 30% initially. The impact of the cladding was particularly high due to facing bricks being used, these have an embodied energy twice that of common bricks.

Part III also looked at the difficulties in disassembling standard foundations and frames, and in detail at the impacts of a number of frame and floor assemblies that were designed to facilitate different degrees of disassembly. Over a single lifetime the composite assemblies had the least impact. However, if the frame or floor is to be disassembled and reassembled then the impact of the composite almost doubles. None of the elements can be separated and reused, material recycling being the only option. Ensuring that no contaminants are contained with the frame or floor structure (such as toxic materials or bonded insulation and formwork) would maximize the steel and concrete recycling yield.

If a frame or floor is likely to be changed a number of times then using precast concrete and prefabricated (and lightweight) steel elements will minimise the multi-lifecycle impacts. These assemblies generally have a larger initial impact than the standard constructions but their elemental construction enables reuse. Over subsequent lifetimes the impact of the layers that cannot be disassembled, such as foundations, increases relative to the other layers.

The final aim of Part III was to compare the embodied impacts with the operational impacts over the lifecycle. This indicated that embodied impacts are more significant than previously assumed, particularly for office buildings that are kept in use through maintenance, refurbishment and replacement of the various layers. For future energy efficient scenarios the embodied impacts may match the operational impacts over the lifecycle. Therefore, this research indicates that the operational and embodied impacts such be considered with equal merit when designing to reduce the use of resources and major impacts throughout the building lifecycle.

7.6 Dematerialization and the Service Concept

As described earlier in the research, offices in the future are likely to undergo numerous changes. To enable the partitions, services, utilities and furniture to be relocated with minimum disruption and maximum reuse (so avoiding disposal and replacement costs) designing for disassembly could become a key criteria. These internal, short lifetime layers, are on the whole products in their own right and should all be designed to allow upgrading, repair and replacement. The replaced products can then enter the reuse or materials recycling loop. Already furniture, carpet, equipment, partitions and lifts are being designed along these principles and a number of leading firms are leasing instead of selling these products, resulting in massive dematerialization. Extending the DfD and service approach to the other layers of a building could substantially reduce its lifetime-embodied impact.

7.7 Recommendations for Further Research

This work has attempted to go some way in defining buildings within a systems concept, exploring strategies that will enable disassembly and investigating the impacts of buildings over their lifetimes. The themes and strategies collated and defined during this research should not be seen as exhaustive but rather as an attempt the extent and enrich the current debate. There is considerable scope for further work on the issues raised and recommendations for further research are set out below. Due the multi-disciplinary nature of this thesis these cover a broad range of building related areas.

7.7.1 Quantitative Research

- **Soft Strip**. A useful and interesting future study could focus in more detail on the soft strip, including the layers of the floor zone. Such a study would record the quantities, and types of elements and materials involved, the frequency of changes, and the embodied impacts of this layer over a buildings lifecycle. As many of these soft strip elements exist in recognised product form they potentially could be designed for disassembly and the research might investigate the strategies required to achieve this.
- **Cladding**. A detailed quantitative analysis of different cladding solutions is also required. As the cladding can have a great influence on the solar gain, day-lighting and thermal comfort of the internal space, this study would also need to cover in detail operational impacts influenced by the various cladding options. For example, the wet-window glazing option, discussed earlier, could significantly reduce the heating and cooling demands of the office services, but installing such a system would lead to a large increase in the embodied impacts of the cladding. Similarly, covering the building in photo-voltaic's could make the operational energy neutral but increase the embodied impacts.

7.7.2 DfD Research

- **Connections**. Further work is needed to develop reversible connection systems for all the different building elements, currently bolted connections are the only true reversible joints. The product industry is leading the way here with 'plug and play', 'snap to fix' 'sacrificial' and temperature sensitive connection systems. The building work needs to recognise the time dependent nature of the various elements to be connected and so therefore, design the connections accordingly. The short and long lifetime elements do not all need to be connected to the same criteria.

- **Information.** To enable successful disassembly and reuse or recycling more information about the building elements and the changes to these over time is required. Systems need to be devised to store and update information on elements and materials and this could potentially link to their suppliers and possible future customers.
- **Foundations.** Thought must also be given to the none-DfD layers such as foundations, and novel solutions devised which minimise their multi-life impacts. The Japanese pavilion at Expo 2000 used concrete blocks and sand contained within a boarded scaffold frame for its foundations, these were completely removed after the event.

7.7.3 Further Methodology Research

- **Extend LCA work.** For the office investigation, Lifecycle Analysis (LCA) was used, as this is the major tool currently adopted by building analysts. However, the investigation was not a full LCA as further stages are required and these are best achieved using other software tools that were not available for this research. In these stages the energy and carbon dioxide figures are related to environmental indicators such as ozone depletion, global warming and acid rain. A further stage in this research might be to continue the investigation and define the impacts of the building layers in terms of these global indicators.
- **Use other methodologies.** It was also noted that other methodologies exist, particularly the Material Intensity per Service Unit (MIPS) approach that might be of great value to building studies if more raw data were available. The service concept embedded in the MIPS approach offers an extra step in analysis, going beyond the product and to the service it provides, paving the way for de-materialization and a more circular systems approach to the built environment.

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Appendix A

List of Demolition Interviewee's

	NAME	COMPANY	POSITION & DETAILS
1	Wayne Bagnel	Bagnel Group	Director, Involved with revision of British Standard on Demolition
2	Jim Connell	Connell Brothers	Partner, Demolition contractor of the Year
3	John McGregor	NFDC	Secretary of Institution
4	David Turner	Detech Environmental	Director, Vice President NFDC
5	Howard Button	Buttons	Director, Past President NFDC, vice president of IDE, Vice president of European Demolition Association
6	Jerard Sloyan	Sloyan Demolition	Partner, Involved with office demolition in Liverpool
7	Michael Graham	McGee's	Procurement Manager with one of London's busiest firms
8	John Law	Law Associates	Director, President of IDE
9	Mathew Kingsley	Scott Wilson Kirkpatrick	Demolition Consultants
10	Claire Woolveridge	CIRIA	Manager, Demolition expert
11	Clodagh McGrath	BRE	Researcher, Demolition expert
12	Sandra Gomez	BSRIA	Researcher, Demolition expert
13	Peter Robinson	Tarmac	Manager, Waste recycling and virgin aggregate supplier
14	Susan Wain	Environment Agency	Manager, Building waste officer

Appendix B

Office Design Specification

The building is typical of a speculative office building in either an edge of town or in a regional city in the UK, with a gross floor area of $2600m^2$. It is of modest specification and has the following features:

- It is 13.5m wide, 48m long and four storeys high, the width being appropriate for natural ventilation and maximum daylight penetration.
- Usable floor space consists of: Ground (solid slab), first, second and third (suspended floors) these four make up the office space. The fourth floor (suspended floor, as 1^{st} to 3^{rd}) supports the roof structure and the ceiling services of the floor below as well as main plant room.
- The building is not air conditioned or provided with comfort cooling but has perimeter heating.
- Servicing is from zones at the ends of the building. Escape stairways and lifts are also provided at these points. The building cannot be sub-divided without alternative means of fire escape.
- The fire resistance is 1 hour and the building is not sprinkler protected.
- The cladding is traditional brick/block with rectangular individual windows occupying 25% of the façade area. The cladding is supported at each floor level by a steel angle with additional vertical wind posts at approximately 3m spacing. Its weight is taken as 8 kN/m, acting as a horizontal line load.
- The floor to ceiling height is 2.7m and a raised floor of 150mm depth is specified.
- The foundations are assumed to be pad footings on sand and the ground floor is not suspended (ie it is ground bearing).
- The top floor is designed for the same loads as the other floors. An additional roof structure comprising steel portals, purlins and tiles is provided. The roof area is not suitable for occupancy and is discounted in the gross floor area.
- The foundation material is considered to be sand with a safe bearing pressure of 200 kNm^2. Hence, the minimum bearing area of the pad footings can be easily determined, knowing the column loads. The depth and width of the footings and the amount of reinforcement required is scheduled for each column size.
- Floor finishes: Raised access flooring-150mm deep, medium duty 600 x 600mm with loose lay carpet tile finish. Vinyl flooring to ancillary areas. Ceramic tiles to toilet floors and epoxy paint tp plant rooms floors.
- Suspended Ceiling: 500 x 500mm suspended ceiling with concealed grid. The ceiling grid is 1500mm square to match the structural grid.
- Toilets: Proprietary cubicles, modular duct panels and vanity units.

- Internal doors: Veneered solid core within a hardwood frame with stainless steel fitments.
- Internal walls: core walls are medium dense concrete block. Other walls are demountable lightweight steel/plasterboard partitions.
- Internal wall finishes: Wall finishes are plaster/plasterboard with emulsion paint finish.
- Windows: Openable aluminium polyester powder coated double glazed. 2100mm high with a sill level of 600mm above raised floor level.
- Cladding: Facing brick external leaf and block internal leaf.

Structural Design Criteria

- Designed for Imposed load of 3.5 kN/m^2 plus 1 kN/m^2 for partitions and 0.7 kN/m^2 for ceiling, services and raised floor.
- Deflection limits for steel options are taken as defined in BS 5950: Part 1. Total deflections of all options are limited to a maximum of span/200 or 60 mm in the long span options.
- The planning grid adopted is 1.5m and therefore column spacing and beam spans are generally based on multiple of this dimension, i.e. 6, 7.5 and 13.5 m.

APPENDIX C

Embodied Energy and Carbon Dioxide Data

Please see Table C1 on next page.

UK figures for embodied energy and embodied CO2 for construction materials													
First line	Primary energy GJ/tonne			Second line	kgCO2/GJ			Data from N Howard, BRE, Nov.1996					
Excvtn. & Disposal	In-situ conc Substruct.	In-situ conc Superstruct.	Common Bricks	Facing Bricks	Mortar	Hardcore	DPM / DPC	Reinf't.	Blocks	Glass Rein. Fibre	Precast Concrete		
0.095555556	0.84	1.31	5.78	11.71	0.84	0.277	120	26.8	1.36	35	1.36		
73.8	142	155	85	75	146	57	69	76	154	72	154		
Timber	Chipboard	Plywood	Mandolite	Vicuclad	Structural Steel	Sheet Steel	Stainless Steel	Roofing Felt	Roof Insulation	Wall Insulation	General Insulation		
13.04	36.29	17.02	64	70	26.8	34.2	18.84	77	35.2	35.2	35.2		
126	71	86	69	69	76	78.88888889	65	69	74	74	74		
Asphalt	Stone Chippings	Natural Slate	Crushed Slate	Concrete Tiles	Paving	Lead	Resin	Plaster	Plaster-board	GRG	Paint		
5	0.3	0.1609	0.1609	1.36	1.36	134	200	1.37	2.68	0	50		
73	73	73	73	154	154	72	69	68	67	0	66		
PVC	Softwood	Hardwood	Wood Stain / Varnish	Glass	Aluminium (in windows)	Steel (in windows)	UPVC (in windows)	Rubber Seals	Mastic Sealant	Concrete Screed	Nylon (In Carpet)		
120	13.04	15.88	50	14.68	240	34.2	120	150	200	1.55	190		
69	126	135	66	77	70	78.88888889	69	69	69	161	70		
Polyester (In Carpet)	Bitumen (In Carpet)	Wool (In Carpet)	Rubber Underlay	Vinyl Tiles	Clay Tiles	Terrazzo Tiles	Marble	Mineral Fibre Tiles	Ceramic Fittings	UPVC Pipework	Copper Pipework		
190	50	3	140	120	12	1.55	2	40	20	110	110		
70	70	72	70	69	75	154	73	74	75	65	66		
Steel Pipework	St. Steel Pipework	Cast iron Pipework	Plastic	PVC Wire Insulation	Copper Wire	Zinc	Brass	Steel Wire	Lifts and Escalator	Natural Stone	Reconst'd Stone	Sheet Aluminium	GRP Panel
35	18.84	35	150	110	110	87.1	104.88	36	36	0.4	1.5	200	100
78.88888889	65	75.74626866	69	69	66	72	66	80.02631579	80	73	161	70	69

Appendix D

List of publications

The research, particularly the DfD work was very topical and resulted in a lot of interest from both academics and practitioners. I spoke at a number of conferences, including 'Passive and Low Energy Architecture 2000' in Cambridge and 'Deconstruction Closing the Loop' at the BRE. A summary of the DfD work was published on the Internet, generating huge interest from around the world and resulting in the creation of a web site, containing a full paper on disassembly.

Conference papers

HAPM 99: A Recipe for Greenhousing, London, March 1999. Paper entitled, 'Building in Layers.'

Eco2 99: Product design for the 21C, Cardiff, May 1999. Paper entitled, 'Buildings as meta-products'.

Deconstruction closing the loop, BRE, Watford, May 2000. Paper entitled, 'Design for Dismantling'. And again at:

Institution of Demolition Engineers, Seminar 2000 '*Recycling and the Environment*' May 00

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