CLOSED LOOP MATERIAL CYCLE CONSTRUCTION

DEFINING AND ASSESSING CLOSED LOOP MATERIAL CYCLE CONSTRUCTION AS A COMPONENT OF A COMPREHENSIVE APPROACH TO SUSTAINABLE MATERIAL DESIGN IN THE CONTEXT OF SUSTAINABLE BUILDING

THESIS SUBMITTED FOR THE AWARD OF DOCTOR OF PHILOSOPHY

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MAY 2009

CARDIFF UNIVERSITY, SCHOOL OF ARCHITECTURE

DECLARATIONS

This work has not previously been accepted in substance for any degree and is not concurrently submitted in candidature for any degree.

Signed P. Sassi Date - 8 May 2009

STATEMENT 1

This thesis is being submitted in partial fulfillment of the requirements for the degree of PhD (Doctor of Philosophy).

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STATEMENT 2

This thesis is the result of my own independent work and investigation, except where otherwise stated. Other sources are acknowledged by explicit references.

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ABSTRACT

This thesis sets out to identify and define a set of criteria by which building materials and elements can be assessed in terms of forming part of closed loop material cycle, and from which legally binding targets can be developed to support good practice in relation to sustainable material design in the built environment.

An initial investigation into the research context of sustainability applied to the built environment and the means of implementing good practice in the building industry is followed by a review of selected sustainable material design philosophies. Based on a synthesis of these philosophies and how they can be applied to building practice, the dissertation proposes a concept for a comprehensive approach to sustainable material design that incorporates a requirement for close loop material cycle construction. The characteristics of closed loop material cycles and their relevance to the building industry are considered, and a set of criteria for closed loop material cycle construction is formulated, drawing on existing research and guidance on natural recovery and design for deconstruction and recycling.

The criteria are applied in a pilot assessment of selected materials, building elements and three whole house designs, which suggests that closed loop material cycle construction is technically feasible. The assessment results are used to suggest possible practical good practice targets for closed loop material cycle construction content that are achievable for mainstream housing construction and that can bring significant benefits in terms of improving the sustainability of construction developments.

The dissertation concludes with a critical reflection on the conceptual development and practical application of the closed loop material cycle criteria and proposes an agenda for further research in this field.

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ACKNOWLEDGEMENTS

I would like to acknowledge the contribution of all the individuals I approached throughout this study who have generously shared their ideas, knowledge and time. It is sometimes the apparently unrelated comments that are only possible when a discussion expands beyond what was envisaged that prompt new directions, and help sustain the interest through what has been a long process.

I would particularly like to thank Dr. Knight for enabling me to complete this journey.

ABBREVIATIONS

BS	British Standard
BRE	Building Research Establishment
C&D	construction and demolition ()
CFC	Chlorofluorocarbons
CLC	Closed loop cycle
CLMC	Closed loop material cycle
CSH	Code for Sustainable Homes
DPH	Dwellings per hectare
EN	European Norm
EPC	Energy Performance Certificate
EPS	Expanded polystyrene
EU	European Union
LCA	Life cycle analysis
MCS	Multiple Chemical Sensitivity
PAS	Publicly Available Specification
PBC	Polychlorobiphenyl
PE	Polyethylene
POPs	Persistent synthetic organic pollutants
PVC	Polyvinyl chloride
RIBA	Royal Institute of British Architects
UK	United Kingdom
US	United States of America
VOC	Volatile organic compound

DEFINITIONS

For the purposes of this research the following definitions have been adopted.

Building component – a homogeneous or composite building element that performs a specific function (e.g. window, gutter), may be manufactured off site (e.g. gutter) or prefabricated (e.g. window, wall panel) and tends to be considered, designed and detailed as an entity.

Building element – any part of a building that forms a recognisable entity. It could be of any size and could be composite (made with more than one material) or homogenous in terms of constituent parts. E.g. brick, window, roof, wall.

Building material – a homogeneous substance that forms part of a building element. E.g. fired (or unfired) clay, metal, glass

Building specification – document setting out parameters for the construction of a building. It includes material and workmanship clauses and can include other construction process related requirements.

Deconstruction - a process of carefully taking apart components of a building, possibly with some damage, with the intention of either reusing some of the components after refurbishment or reconditioning, or recycling the materials. It may be undertaken during refurbishment, when adapting a building for new use, or at the end of its life (Addis and Schouten, 2004, p.8)

Demolition - A term for both the name of the industry and a process of intentional destruction. (Hurley et al., 2001, p. piv).

Design for deconstruction - the phrase widely used in the construction and other industries to refer to the process of designing buildings to facilitate their deconstruction or disassembly. The same idea is sometimes conveyed as "design for disassembly", and both are widely abbreviated as DfD. (Addis and Schouten, 2004, p.8)

Design for environment – An engineering perspective in which environmentally related characteristics of a product, process or facility design are optimized. (British Standard Institution, 2006a, p.22)

Disassembly - A process of taking apart components without damaging them, but not necessarily to reuse them (Hurley et al., 2001, p. piv).

Downcycle - reuse a product, component or material for a purpose with lower performance requirements than it originally provided (Addis and Schouten, 2004, p.8)

Eco-efficiency – A business strategy to produce goods with lower use of materials and energy to realize economic benefits of environmental improvements. (British Standard Institution, 2006a, p.22)

Industrial ecology – An approach to the design of industrial products and processes that evaluates such activities through the dual perspectives of product competitiveness and environmental interactions (British Standard Institution, 2006a, p.22)

Industrial metabolism – A concept to emulate flows of material and energy in industrial activities from a biological systems perspective. (British Standard Institution, 2006a, p.22)

Industrial symbiosis – A relationship within which at least two willing industrial facilities exchange materials, energy, or information in a mutually beneficial manner. (British Standard Institution, 2006a, p.22)

Life cycle - consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal (British Standard Institution, 2006, p.2.).

Life cycle assessment – A concept and a methodology to evaluate the environmental effects of a product or activity holistically, by analyzing the entire life cycle of a particular material, process, product, technology, service or activity. The life cycle assessment consists of three complementary components: (1) goal and scope definition, (2) inventory analysis, and (3) impact analysis, together with an integrative procedure known as improvement analysis. (British Standard Institution, 2006a, p.22)

Material design – a plan, purpose or intention in relation to the use of materials. (This definition adopts a definition of 'design' i.e. 'a plan, purpose or intention' (Oxford University Press, 1991, p.315) with the focus on planning as intention to take into account the boarder issues associated with material options in buildings i.e. not only material selection but also e.g. value engineering).

Material flow analysis – An analysis of flow of materials within and across the boundaries of a particular geographical region. (British Standard Institution, 2006a, p.22)

Material life: design life - period of use intended by the designer (e.g. as stated by designer to the client to support specification decisions). It may well be the same as the required service life specified by the client or as the predicted service life stated by the manufacturer. (British Standard Institution, 1992, p.2, p.8).

Material life: durability - ability of a building and its parts to perform its required function over a period of time and under the influence of agents (British Standard Institution, 1992, p.1)

Material life: durability limit - point at which loss of performance leads to the end of the service life (British Standard Institution, 1992, p.1)

Material life: economic life – the time span in which there is a certain need for the product. (Nienhuis, Woesthuis, Frantzen, 2003, p. 323).

Material life: predicted service life - service life predicted from recorded performance or accelerated tests (e.g. as stated by the manufacturer or in a European Technical Approval) (British Standard Institution, 1992, p.2)

Material life: service life - actual period of time during which no excessive expenditure is required on operation, maintenance or repair of a component or construction (as recorded in use) (British Standard Institution, 1992, p.1)

Pollution Prevention – The design or operation of a process or item of equipment so as to minimize environmental impacts. (British Standard Institution, 2006a, p.22)

Primary material – a material whose production has involved extraction from natural reserves (Coventry and Guthrie, 1998, p.7).

Recondition - the process of restoring a building element or piece of equipment to a condition that allows it to be reused (Addis and Schouten, 2004, p.8)

Recycle - collect and separate useable materials from waste, and process them to produce marketable products (Addis and Schouten, 2004, p.8)

Refurbishment - Improving building performance through partial or complete replacement and/or upgrade of components and services. (Hurley et al., 2001, p. piv).

Remanufacture – The remanufacture of a discarded product replacing worn parts but retaining structural components that retain their integrity. (used to upgrade computers, copiers etc) (Ayres and Ayres, 1996)

Retrofit - Change of use or purpose after construction from which a building was designed (the term retrofit is rarely used in UK, predominantly a US term). (Hurley et al., 2001, p. piv).

Reuse put objects back into use, either for their original purpose or a different purpose without major prior reprocessing to change their physical characteristics, in order that they do not enter the waste stream. While it does not include reprocessing, it might involve some reconditioning (Addis and Schouten, 2004, p.9)

Upcycling – is a term sometimes used to define recycling with a non-diminishing use outcome and is typically used when the term recycling is taken to include reprocessing to a material with reduced performance requirements (i.e. downcycled). This term is not used in this dissertation. To differentiate between [1] recycling a material into a product with equivalent performance and [2] recycling a materials into a product with inferior performance requirements, the terms [1] recycling and [2] downcycling will be used.

Waste - The common usage of the word "waste" is often imprecise and almost a synonym for "unwanted material". The technical definition of waste is something that "the producer or holder discards or intends to or is required to discard" (Waste Management Licensing Regulations 1994). (Addis and Schouten, 2004, p.9)

Waste arisings – The total quantities of waste generated from any technique, process or activity within a given time period (Coventry and Guthrie, 1998, p.7)

Weighting - Weighting is the process of converting indicator results of different impact categories by using numerical factors based on value-choices. It may include aggregation of the weighted indicator results (British Standard Institution, 2006a, p.22).

1 INTRODUCTION, AIMS, OBJECTIVES AND METHODOLOGY

This introduction provides a brief contextual and personal justification for the choice of research topic. It then sets out the aims and objectives of this thesis, states the methodology adopted and outlines the structure of the dissertation.

1.1 OUTLINE OF RESEARCH CONTEXT AND JUSTIFICATION FOR RESEARCH FOCUS

Since beginning this study there has been a marked change in the public perception and acceptance of the term and principles of sustainability. Sustainability has become an established concept in western society and it is now generally accepted that the sustainability of planet earth in terms of its ability to support human life and the quality of life experienced today has been in the past and continues to be affected today by human activities. It is also generally accepted that change is necessary and urgent (Stern, 2007). To ensure a sustainable future that can continue to provide a healthy existence for humans and also, in line with certain environmental philosophies, for other inhabitants of this planet and the planet as a whole, human activities have to be scrutinised and altered as necessary.

From the early formal beginnings of the environmental movement last century our understanding of how human activities impact on the environment has increased and this deeper understanding has elicited increased concerns regarding both human well-being and the protection of the environment (Goudie, 2000). Within the built environment industry, building solutions have evolved in parallel with the changing understanding by addressing the problems perceived at the time. The single focus on energy efficiency of the 1970s has broadened to include concerns for the provision of healthy environments, water-saving developments, material resource-saving construction, pedestrian- and cycle-friendly and planted urban environments and much more. This increasingly comprehensive concept of sustainability demands a more holistic approach to design and development to address the wide-ranging and also interlinked issues. Furthermore, it is almost certain that our understanding of sustainability and consequently the approaches necessary to address issues related to sustainability it will continue to change. Therefore, any endeavour to improve the sustainability of the built environment has to attempt to pre-empt issues that are likely to develop in the future. In this dynamic context it is therefore necessary to adopt a both comprehensive and farsighted approach in order to fully address sustainability.

Today there is significant knowledge and experience relating to sustainability in the built environment industry. This has given rise to 'zero' carbon dioxide emissions buildings; water- and waste water disposal-autonomous houses; buildings made with low embodied energy and natural materials; and urban environments that enable a high quality car-free lifestyle within a green and aesthetically pleasing environment (Sassi, 2006a). In certain cases building developments have successfully addressed human requirements for quality of life, independence, health and community and leisure facilities, while also addressing energy use, water use and disposal, material use and protecting and enhancing the building site's biodiversity. There is therefore evidence of an aspiration among certain building clients and designers to adopt a comprehensive approach to sustainable design which is also farsighted.

However, to make a significant difference to the health of the planet such comprehensively sustainable approaches have to be adopted on a large scale in mainstream building industry. This is not yet happening. Despite the rhetoric and the signs of a public that is beginning to become involved and even sometimes willing to pay more for sustainable solutions, there is still a significant difference between the largely one-off built solutions that can be regarded as good practice in terms of sustainable design and mainstream construction.

Historic evidence points to the fact that changes in attitudes at a societal scale are slow and today we are confronted with an increasingly urgent need for action. The scientific community suggests that time is no longer a luxury available to address issues of sustainability, in particular global warming (Stern, 2007; International Panel for Climate Change, 2007c). Therefore, the mechanisms to engender change cannot rely on first eliciting the understanding and collaboration from society in general but must implement change while simultaneously educating the public. Historic evidence also points to the fact that the implementation of environmentally safe solutions in society, as in mainstream building practice, has often been subject to legal enforcement. While education is essential in raising awareness, increasing understanding and informing those subjected to legislation, it is through legislation that mainstream changes in the buildings industry were made to happen. Bringing about change in the timescale required to avoid environmental disaster cannot happen without legally binding standards and regulations.

Formulating legislation requires a means of assessment or judgement, it requires quantifiable performance measures, at its most basics a means to affirm whether or not an action has taken place. Setting targets, monitoring progress and reporting are essential to UK government's Sustainable Construction Briefs and to progressing the sustainability agenda forward (Department of Trade and Industry, 2004). Good practice guidance without concrete measurable targets is not enforceable and cannot provide a sound basis for formulating legislation. The technical as well as political complexities related to creating legislation are among the reasons for the limited number of legally binding standard and regulations relating to sustainability issues in the building industry. But the number of standards based on quantifiable measures is increasing in the UK as a result of the ratification of Directives issued by the European Parliament and the Council of the European Union. A recent example is the Directive 2002/91/EC on the energy performance of buildings, known as the Energy Performance of Buildings Directive. Having come into effect in April 2006 the Directive sets out minimum standards for energy performance for new buildings and large buildings being refurbished and requires an Energy Performance Certificate (EPC) to be provided when new or existing buildings are sold or rented. Commercial buildings over one thousand square metres have to display the certificate in a prominent area. The EPCs are based on quantifiable measures (kWh/m^2/an and the annual carbon dioxide emission per square metre of building) and suggest potential improvements in performance and how to achieve them. EPCs provide a means of setting targets and monitoring improvements and offer some limited guidance (Official Journal of the European Communities, 2003). More of such legislation can be expected as the need to adopt more sustainable practice becomes increasingly recognised and urgent.

In respect of sustainability, the built environment could be said to have three spheres of influence, two of which are subject to some regulations, while the latter is largely unregulated. Firstly, building design impacts on resource use for constructing and operating buildings (energy, water and materials) and pollution, including carbon dioxide emissions. Secondly, the design of settlements, whether in an urban or rural situation, influences how land is used and how much and how efficiently it is used. This in turn impacts on the availability and suitability of land for natural habitats and local biodiversity; energy consumption associated with travel; water availability; food availability; drainage and flood risks; and other environmental phenomena. It also affects aspects of human quality of life. The last sphere of influence is on the social structures, community cohesion and human health and well-being both physical and mental, which can be affected by both settlement and individual building designs.

While legislation controlling the way the built environment affects the nature of the community is non-existent, land use is currently subject to legal control through the planning and building regulation control system and aspects of sustainability are finding their way into the Planning Policy Guidance and Statements documents, Local Development Frameworks and building control guidance. Legislation ranges from the requirement for the inclusion of facilities, such as renewable energy sources, to the ban on specific building solutions, such as the increasingly common building control requirement for discharging rainwater on the site through soakaways and banning its disposal to the mains sewer.

The area of building construction and operation is perhaps the most advanced in terms of controls relating to sustainability. In respect of energy use legal controls have been in place as part of the Buildings have already made it possible to ascertain improvements in design have been used to push design ambitions to levels previ inconceivable. Energy consumption targets have been used to establ number of different standards and ultimately legally binding legislation

Water consumption also is controlled through the Building Regulat Current controls on water use through the existing legal limit in WC ci size can only be described as meek. However, the use of mains wate be measured and the Code for Sustainable Homes, while not yet le binding, addresses this issue by setting progressively stringent targe water use (Department for Communities and Local Government, 2 Water use has been shown to be successfully controlled through fina initiatives. The water metering trials undertaken in the Isle of V resulted in a 10 per cent decrease in water consumption purely consequence of increased awareness of the users and a resulting imposed restriction in use (Butler, 2000). Legislation imposing the u water meters could be a very effective means to reduce water use.

Water and energy are easily measured and targets for good practice been set, if not implemented. In respect of other sustainable design is setting measurable targets is less straight forward. Yet a comprehe approach to sustainable design requires all its main aspects t addressed. Quantifiable measures would enable the developme legally binding requirements, which if enforced would play a significan in improving the sustainability of the building industry.

With this ultimate ambition for the building industry in mind the f chosen for this dissertation is on materials in the building industry a particular on the waste associated with building materials. This selection does not suggest a priority in terms of importance or urgency in relation to sustainability, but rather it was identified by the author while in architectural practice in the mid 1990's as an area of sustainable design somewhat neglected in comparison to others. Guidance in respect of reducing waste on site existed (Kasai, 1988; Guthrie and Mallett, 1995), and investigations into recycling individual materials, such as concrete (Collins, 1994) and plastic (Halliwell, 1996), were beginning to be undertaken, but the point of view of the architect was largely overlooked. Sustainable material selection was mainly seen as the focus for the architect; perhaps due to the misapprehension that buildings would last forever, perhaps because the knowledge at the time on materials and waste and their overall impact was limited, or maybe because of the conditioned attitudes by our throw-away society.

By the early 2000s three relevant changes had taken place. Firstly, the Building Research Establishment (BRE) had developed the Environmental Profile system for building materials, which provided a life cycle analysis of construction elements and referred to the recyclability of materials (Anderson *et al.*, 2002). Secondly, design for deconstruction, the building designer's point of view of recycling, was receiving some attention. Thirdly, the Landfill Tax had been introduced which provided an incentive to reduce waste on site. However, the building designer still lacked a system of quantifiable targets for designing buildings that would result in minimal waste. This deficiency still exists today. The lack of quantifiable measures and targets makes it difficult to assess the success of a comprehensive waste minimisation strategy, which takes into account the end of the life of a building, and to encourage improvements. However, the potential for developing measurable targets appears high. Materials can be measured by volume and weight and means of reducing waste, such as recycling, are well understood.

Waste minimisation is one of the essential elements of a comprehensive approach to material design and specification, as suggested by the inclusion of recyclability in the BRE Environmental Profile system mentioned earlier. As such it forms part of a comprehensive approach to sustainable design in general and as part of that comprehensive approach it warrants a detailed study.

Furthermore, taking the cue from the achievements in formulating energy and water consumption targets it is possible to envisage an approach to sustainable buildings that aims for a 'zero' impact construction. It is possible to imagine how a construction could be made to be associated with 'zero' carbon dioxide emissions, 'zero' mains water consumption, be independent from mains sewer connections and also include a 'zero' impact material selection. A definition for a 'zero' impact material is not yet available and consensus on such a definition would be no doubt very difficult to reach. Nonetheless, by adopting a comprehensive and farsighted viewpoint, as advocated previously, it is possible to envisage a construction constituting materials that combine 'zero' impacts in terms of resourcing, pollution (including carbon dioxide), and waste production thus creating a 'zero' material impact construction.

Such farsighted visions may be optimistic but are triggers for rethinking current systems, concepts and assumptions. Research in the field of waste minimisation already asserts such farsighted conceptual ambitions. The concept of a 'zero' waste building, which would be in line with the above mentioned concept of 'zero' material impact buildings, was put forward by Kibert in a paper discussing construction ecology. Here he suggested 'the primary lesson construction industry can learn from nature is to cycle its materials in a closed-loop manner, the goal being a 'zero waste' system' (Kibert, 2000, p.178). The idea of reusing waste in a cyclical system had been put forward by other researchers, who state '[t]he ultimate aim....is to work towards a looped system in which products and waste re-enter the system as an input rather than exit as unwanted waste.' (Smith *et al.*, 1998, p.60). Kibert, however, sets the ambition for zero waste.

Kibert suggests turning to nature for examples of how the waste from one process becomes the building blocks for another. Potentially everything is reused, creating a closed loop cycle (Kibert, 2000). The development of the theoretical concept of a closed loop cycle that forms a 'zero' waste building design into a practical proposition, which allows for quantitative measures to be adopted as part of a building assessment, is the aim of this thesis.

1.2 RESEARCH AIMS

This thesis sets out to identify and define a set of criteria by which building materials and elements can be assessed in terms of forming part of a closed loop material cycle (CLMC). Furthermore, it applies the criteria to analyse selected building constructions for the propose of considering potential targets for closed loop cycle material content in buildings that could be considered good practice in terms of sustainable design and form the basis for legally binding targets.

1.3 RESEARCH OBJECTIVES

The above aim was clarified over time in response to two emerging realisations.

Firstly, sustainable material selection systems in the building industry are subject to a bias based on the values held by each individual that defines and or adopts them. Material impacts range from environmental to social and each individual has different priorities. While the systems therefore vary in emphasis they generally share an approach that appears to give the waste aspect of building design minimal or at least reduced importance in comparison to others. This awareness suggested the need to investigate two questions. Firstly, how existing sustainable material systems and philosophies addressed the issue of waste or if indeed they addressed it at all; and secondly whether the concerns regarding waste were warranted.

The second realisation was that good practice is rarely adopted voluntarily. If this research should result in outcomes that could contribute to improving the sustainability of the building industry, these would have to be more than just the basis for good practice guidance. As so little good practice is adopted for ethical, environmental or even humanitarian reasons, the research outcomes would have to be able to form the basis for enforceable performance targets, such as those proving to be effective in reducing energy or water use.

This study, therefore, first steps back to investigate the wider context of sustainable design and then progressively narrows the research focus. First, the study seeks to establish the relevance of material selection and in particular waste minimisation as an element of a comprehensive approach to sustainable design. It then focuses onto three prominent philosophies that relate or can be related to sustainable material selection and synthesises the approaches into what could be a comprehensive approach to sustainable material design. From this comprehensive approach it distils out the essence of a zero waste or closed loop material cycle construction.

The following six objectives each build on the one preceding them to formulate a set of criteria for CLMC construction, test the criteria and propose targets for CLMC content in mainstream building.

1.3.1 RESEARCH OBJECTIVE ONE - INVESTIGATION OF RESEARCH CONTEXT: SUSTAINABILITY, BUILDING DESIGN AND IMPLEMENTATION OF GOOD PRACTICE (LITERATURE REVIEW AND ANALYSIS)

The first objective is to position the research within the context of sustainability and provide a rational for the research focus.

This includes identifying and analysing historic and recent developments in sustainability thinking that relate to mechanisms for implementing sustainable initiatives and encouraging sustainable approaches and activities. It also includes analysing key sustainable design principles relating to the built environment to understand how these are implemented in practice and the relevance of material selection and in particular waste minimisation.

The key questions to answer as part of Objective One are:

- How are the principles of sustainability introduced and implemented in practice?
- What are the main issues related to sustainability and building design?
- What are the main strategies to achieve a sustainable design?
- What are the main implementation drivers for sustainable design?

1.3.2 RESEARCH OBJECTIVE TWO - FORMULATING A PROTOCOL FOR A COMPREHENSIVE APPROACH TO SUSTAINABLE MATERIAL DESIGN (ORIGINAL CONTRIBUTION BASED ON LITERATURE REVIEW AND ANALYSIS)

Waste minimisation and CLMC construction can only be one part of a more comprehensive approach to sustainable material design. The second objective, therefore, is to outline a potential comprehensive sustainable material protocol that incorporates the principles of CLMC construction.

The intention is to identify how different sustainable material philosophies relate to a more comprehensive approach to material design and to the concept of CLMC construction. It is envisaged that an understanding of current material philosophies, their underlying reasoning, and their assessment criteria will enable the synthesis of principles for a comprehensive approach to sustainable material design and provide a framework within which the concept of CLMC construction can be developed.

The key questions to answer as part of Objective Two are:

- What are the main concepts of sustainable material design as defined by different material philosophies?
- How can the different approaches be combined to form a comprehensive approach to sustainable material design?
- What are the main characteristics of a CLMC construction, when considered as one aspect of a comprehensive approach to sustainable material design?

1.3.3 RESEARCH OBJECTIVE THREE - DEFINING CRITERIA FOR CLMC CONSTRUCTION (ORIGINAL CONTRIBUTION BASED ON LITERATURE REVIEW, PRIMARY RESEARCH AND ANALYSIS)

The third objective is to define CLMC construction and develop a set of criteria to assess compliance with the definition. The intention is that the criteria, developed from and informed by building related sources and other non-building related sources previously studies, should provide guidance for designing and building structures that form part of a CLMC. The criteria should also be able to be used to assess building construction for its compliance with the principles of CLMC construction.

The key questions to answer as part of Objective Three are:

- What are the characteristics of closed loop cycle (CLC) materials?
- What are the characteristics of CLMC construction?

- How can these characteristics be rationalised and measured to form assessable criteria?
- How can the criteria be formulated to form an assessment system?

1.3.4 RESEARCH OBJECTIVE FOUR - TESTING MATERIALS, BUILDING ELEMENTS AND WHOLE BUILDINGS FOR COMPLIANCE WITH THE CLMC CRITERIA (ORIGINAL CONTRIBUTION BASED ON PRIMARY RESEARCH AND ANALYSIS)

The fourth objective is to evaluate a selection of materials, building elements and whole building constructions for their conformity with the principles of CLMC construction. In addition, by using the system to assess the above elements, the assessment system will be tested for the purpose of improving the system itself.

The key questions to answer as part of Objective Four are:

- Which of a selection of materials qualify as CLC materials?
- Which of a selection of building elements qualify as CLMC building elements?
- What is the CLMC content of a selection of building designs?
- Are the criteria able to be used easily and reliably for their intended purpose?

1.3.5 RESEARCH OBJECTIVE FIVE - FORMULATING CLMC CONTENT TARGETS FOR UK MAINSTREAM HOUSING DEVELOPMENTS (ORIGINAL CONTRIBUTION BASED ON PRIMARY RESEARCH AND ANALYSIS)

This fifth objective is to identify the potential for setting targets for CLMC construction that could be applied to mainstream building construction, and in particular to housing construction in the UK. The objective involves building on the preceding research objective to define potential targets for CLMC content in housing construction. The whole building assessment from the previous objective, which analyses three house construction types, is used as a basis for this analysis.

The main question to answer as part of Objective Five is:

- What is a realistic target for CLMC construction in terms of material content in mainstream housing developments in the UK?

1.3.6 RESEARCH OBJECTIVE SIX - DEVELOPING AN AGENDA FOR FURTHER RESEARCH (ORIGINAL CONTRIBUTION BASED ON ANALYSIS)

This final objective is to review the assessment system and the proposed targets and develop an agenda for further research associated with the CLMC concept and the CLMC assessment system.

The review will consider:

- the conceptual framework for the CLMC construction;
- the practical application of the CLMC assessment system;
- the development of CLMC construction technologies and
- the potential uses for the CLMC assessment system

1.4 RESEARCH CONTRIBUTION

The research outcomes could contribute to highlighting the field CLMC construction, help encourage its uptake and consequently contribute to improving the sustainability of the construction industry. Implementing the principles of CLMC construction would ultimately help reduce the waste produced within the building industry and the associated environmental impacts.

Four main contributions are envisaged.

Criteria for the evaluation of CLMC construction.

Development of a set of criteria to evaluate materials, construction elements and whole buildings for their compliance with the principles of CLMC construction. These criteria could form an assessment tool that would enable building designers and construction teams to analyse building designs and increase the amount of materials included in buildings that would form part of a CLMC, reducing the potential for waste production. The assessment tool could also be used by clients, funding organisation and local authorities as a means of benchmarking and target-setting. The assessment results could become part of a building's sustainability profile.

CLMC assessments of selected materials, building elements and whole building constructions.

A selection of materials, building elements and whole building construction will be tested and the assessment results could be of some practical use to building designers and construction professionals aiming to select building systems that minimise waste over the life of a building.

Targets for CLC material content in residential buildings.

Targets for CLC material content will be suggested that are applicable to mainstream residential construction. The proposed targets would be able to form the basis for the development of formal standard and ultimately also legally binding requirements.

An agenda for further research.

An agenda will be developed for further research relating to refining the concept of CLMC construction, developing a user-friendly tool for assessing CLMC construction, and developing the means of encouraging the adoption of good practice in the building industry.

In addition the research includes: a review of a three sustainable material philosophies and a review of current sustainable approaches and solutions in the building industry.

1.5 RESEARCH METHODS

Research methodology statements sometimes give the impression that research begins with a clean slate, free of preconceptions and indeed free of significant prior knowledge. However, this is seldom the case and certainly not the case after more than twenty years of architectural practice. In the 'The structure of scientific revolutions' Kuhn suggests that what researchers see depends on what they know or do not know, which affects their perception, analysis and understanding (Kuhn, 1996, p.198). Prior knowledge forms a basis for understanding and accepting new information and that is why, Kuhn argues, significant innovation in science is more readily accepted by young researchers who have not had the time to develop preconceptions. When researching an approach which departs from current practice, extensive knowledge of this practice can be an obstacle to thinking differently and Kuhn suggests that is why established researchers are often reluctant to give up their paradigms and replace them new ones (Kuhn, 1996, p151).

A challenge in relation to this study was, therefore, to put aside preconceptions and adopt the role the investigator 'one step removed from the object of study' (Groat and Wang, 2002, p.37). Groat and Wang expand this concept, which they define as 'neutrality' and consider an essential characteristic of high quality research, by suggesting that the 'goal for research procedures is to keep the potential bias or interference of the researcher out of the process' (2002, p.37). Groat and Wang suggest three other characteristics that qualify research as of high quality: 'truth value', 'applicability' and 'consistency'. 'Truth value', they argue, is achieved through multiple sources of information and triangulation.

'Applicability' refers to the ability of the research to have wide relevance and give rise to rules of general applicability. 'Consistency' relates to the ability of the research to be replicated, requiring a transparent and logical methodology.

To address the issue of 'neutrality' it was felt helpful to step back and review some basic assumptions before narrowing the attention again to a single focus, accepting that it may not be the one envisaged at the start. Objective One allows for revisiting the wider context and even reconsidering the drivers that instigated the research.

At all stages of the research an attempt was made to address the concept of 'truth value' by investigating multiple sources of information and triangulating results. Where possible both primary and secondary data was collected. For instance, the initial review of the context of sustainable design combines a literature review with field studies of case study buildings including interviews with the building designers and or occupants. The review of sustainable material design approaches was similarly triangulated with case studies of buildings. The study of building technologies that could help create CLMC constructions (Objective Three) included a questionnaire survey, which was able to provide broad range of information plus in-depth interviews to identify facts and views from building designers.

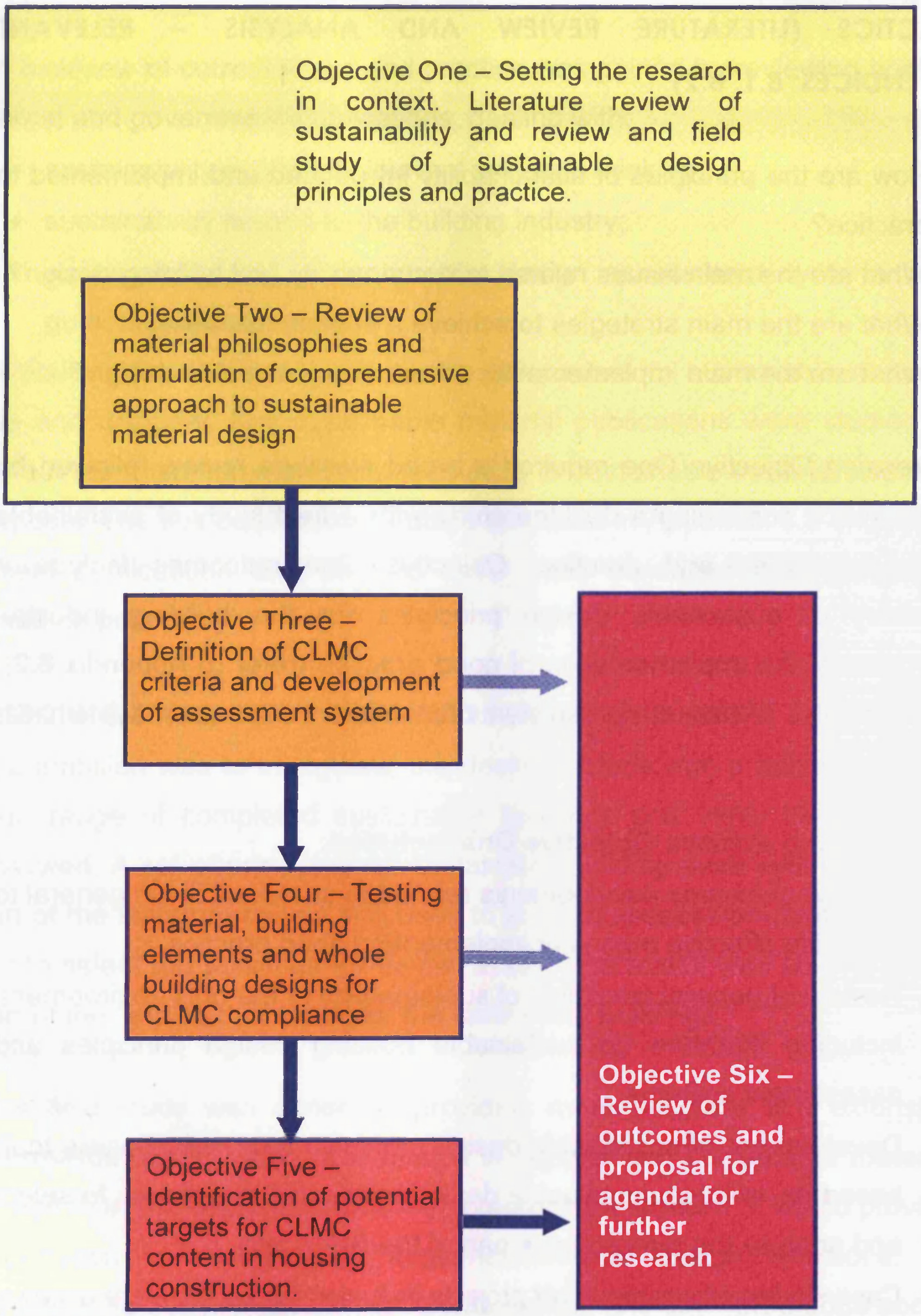
At various stages of the research an attempt was also made to address Groat and Wang's concept of 'consistency' by making use of a number of tools developed to structure the analysis and selection processes. These tools not only facilitate the research process but also provided a replicable as well as a transparent method of research.

Groat and Wang's concept of 'applicability' (2002) relates principally to the outcomes of research. Objective Four investigates the compliance with the CLMC criteria of materials, building elements and whole buildings. This can be described as experimental research involving the use of independent variables and a measurement of outcome using a clear unit of measurement. The measurements are used to provide a comparison of test groups and examine the cause and effect relationships involved. The independent variables are the construction types or element designs; the outcome is the amount and classification of potential waste; the comparison is between different house designs; and the focus is on the relationship between material design and waste potential. This empirical analysis was then followed by Objective Five which required the development of realistic targets for CLMC content in housing. These final research stages offered the opportunity to formulate generalised rules that would have wider applicability and ultimately would address Groat and Wang's 'applicability'.

The various research methods and approaches adopted were selected to achieve a robust and transparent research process. What the research methods cannot however guard against is flawed analysis or deductions. Particularly the qualitative elements of the research are more vulnerable to weaknesses in thought processes. Objectives Two and Three involve a process described by Groat and Wang (2002) as logical argumentation to construct a conceptual system involving a set of rules that apply to defined entities. The research data from Objectives One and Two represents a group of factors that once organised within a framework will help enhance the understanding of their essence and interrelationships. Ensuring a sound thought process is an even bigger challenge than reducing the bias of past experience and prejudices.

The research program involved five stages. The first stage addresses Objective One and Two concurrently. The subsequent stages address one objective each consecutively. The research methods employed in respect of each research objective is expanded below.

Table 01 - **Research Diagram**



1.5.1 OBJECTIVE ONE – INVESTIGATION OF RESEARCH CONTEXT: SUSTAINABILITY, BUILDING DESIGN AND IMPLEMENTATION OF GOOD PRACTICE (LITERATURE REVIEW AND ANALYSIS – RELEVANT APPENDICES: 8.1, 8.2)

1. How are the principles of sustainability introduced and implemented in practice?
2. What are the main issues related to sustainability and building design?
3. What are the main strategies to achieve a sustainable design?
4. What are the main implementation drivers for sustainable design?

Addressing Objective One required a broad literature review followed by an approach combining a desktop study with a field study of sustainable design principles and practice. Objective One outcomes include a summary of sustainable design principles for the building industry, examples of the implementation of good practice (refer to Appendix 8.2), and examples of assessment systems for different aspects of sustainable design.

The stages to achieve Objective One included:

- Review of historic developments related to sustainability in general to establish effective means of implementing good practice.
- Review of general principles of sustainability in the built environment, including literature on sustainable building design principles and assessment systems.
- Development of sustainable design matrix (a research analysis tool) based on existing sustainable design assessment systems, to select and analyse the built projects part of the field study.
- Case studies of selected built projects including further literature reviews, building visits and interviews with building designers and owners.

LITERATURE REVIEW

The broad and building design focused literature review aimed to

- gain evidence to answer the above questions in outline;

- develop a tool to categorise principles of sustainable design; and
- select buildings for further study.

An overview of current views and practice was gained by reviewing books, journal and government publications, dealing with:

- sustainability in general (current and past thinking);
- sustainability related to the building industry;
- sustainability and environmental design assessment systems and guidance documents.

Particular attention was given to the approaches to sustainable material use and disposal. Key sustainable material publications were studied to extract the main common themes relating to sustainable material use and disposal. The key publications studied are listed in Appendix 8.3 and more recent publications and editions have been consulted throughout the research period.

SELECTING CASES STUDY BUILDINGS FOR THE FIELD STUDY

The ambition was to triangulate the desk-top study with a field study of a wide range of completed sustainable buildings and verify the literature reviewed. A set of principles for sustainable building were synthesised as part of the literature review and used to form an assessment matrix (Table 02) to select the buildings for further study. The matrix was also used as part of the field study to analyse the case study buildings.

This field study was aimed at providing more accurate and extensive information about sustainable design in general and sustainable material design than that found in published sources. Furthermore, it would provide information on the practical implementation of design ambitions. By investigating completed buildings it was expected to gain knowledge about

- design philosophies;
- good practice design solutions;
- barriers to achieving good practice in reality; and
- the level of success of the design solutions.

Building visits were undertaken as well as interviews with the architects and building occupants. The interviews with the building designers were intended to identify the design philosophy while the building occupants' interviews aimed at identifying the success of implementation of the design aims. The interviews were semi-structured using the headings of the matrix. The same topics were discussed with all interviewees. The semi-structured nature of the interviews also allowed for additional information to be gathered with could verify and expand the published data.

ASSESSMENT MATRIX

The assessment matrix was developed by combining three existing assessment systems that together would cover the environmental and social sustainability aspects of the built environment. The systems used were the BREEAM, the Planning Checklist for the London Borough of Richmond upon Thames and the RIBA Sustainability Manifesto.

The environmental aspects were mainly covered by the criteria included in the Building Research Establishment Environmental Assessment Method developed at the Building Research Establishment and launched in 1990. This system addresses the use of energy, water and materials plus other impacts, such as pollution, affecting the natural environment. Within this approach people, in other words social aspects, are considered in terms of comfort and health within indoor environments. The system divides the areas of assessment into categories for:

- energy,
- transport,
- water,
- materials,
- land use,
- site ecology,
- pollution,
- health and comfort,
- management.

The BREEAM system of assessment is used to analyse building design during the design and construction phase as well as completed buildings. This assessment system is used by building designers and clients and provides a rating of fail, pass, good, very good, excellent. (Baldwin *et al.*, 1998; Rao *et al.*, 2000). A suite of BREEAM systems have been specially formulated for different building types, including Ecohomes developed for residential developments.

The second more socially focussed assessment system to form part of the matrix was the Planning Checklist for the London Borough of Richmond upon Thames (London Borough of Richmond on Thames, 2001). In the past fifteen years planning departments in the United Kingdom have been developing sustainability checklists that are used to assess built environment developments in terms of how they contribute towards creating more sustainable societies. These checklists focus on people's well-being beyond their level of comfort within buildings and look at quality of life issues including economic well-being. They are intended for use as part of the planning process and, in the case of the Richmond Borough Checklist, the checklist is to be completed and submitted with any planning application. Despite many of the items on the checklist not being legally enforceable, the list serves the purpose of raising awareness.

The third system, the Royal Institute of British Architects (RIBA) Environmental Manifesto, attempts to address both social and environmental issues (Royal Institute of British Architects, 2001). This document, as the name suggests, is a statement of aspiration. It contains broad principles and does not include any detail. For the purpose of formulating an assessment matrix it provided a good overview of good and ambitious practice.

The matrix developed was based on a combination of the above systems and structured using the BREEAM headings and the categories from the Richmond upon Thames Planning Sustainability Checklist (London Borough of Richmond on Thames, 2001). The categories were expanded to include categories from other assessment systems that introduced new concepts. Table 02 lists the main and sub-categories and identifies which systems include each category in their assessment.

Table 02 - **Comparison of sustainable building assessment categories based on the BREEAM headings and the categories from the London Borough of Richmond upon Thames (LBRUT) Sustainability Checklist**

Sustainability categories and sub-categories	BREEAM	EcoHomes	RIBA	LBRUT
COMMUNITY Does the proposal				
contribute to opportunity for all? * (e.g. employment, affordable homes, mixed tenure)		✓	✓	✓
include a local community consultation?				✓
improve public safety / deter crime?				✓
enhance public open space and amenities?			✓	✓
improve safety for pedestrians?				✓
provide full access for all users including those with mobility difficulty?				✓
LAND AND ECOLOGY Does the proposal				
re-use existing buildings / land?	✓	✓	✓	✓
use of land efficiently with appropriate densities?		✓		✓
include new landscape and trees?			✓	✓
include cultivatable space on the building/site?				✓
enhance the natural ecosystem of the site and maximise new wild-life friendly habitat*?	✓	✓	✓	✓
avoid harm to protected species and ecological features on the site?	✓		✓	✓
involve decontamination of land ?	✓			
TRANSPORT Does the proposal				
improve public transport facilities?				✓
provide links/ encourage use of public transport?	✓	✓	✓	✓
provide a car free design?				✓
provide secure cycle storage and other cycling facilities? (eg shower)	✓	✓		✓
provide links to pedestrian /cycle network?				✓
minimise the need to travel by virtue of proximity to amenities and/or work?	✓	✓		
include work-live opportunities?		✓		
HEALTH AND WELL-BEING Does the proposal				
provide a high quality designed space?			✓	
provide optimum comfort?			✓	
provide windows with views at max. 7m?	✓			
affect the local area noise and pollution levels?				✓
improve on building regulations sound proofing requirements?	✓	✓		
provide good indoor air quality, low VOC finishes /treatments and no toxic materials?	✓		✓	✓
make provisions to avoid legionellosis?	✓			
provide good daylighting which can be modified?	✓	✓	✓	
provide openable windows?	✓		✓	
provide good local temperature controls?	✓			
provide for regular maintenance/ cleaning?	✓			
provide for user feedback?	✓			
MANAGEMENT Does the proposal				
make use of a user-friendly not over-complex management system with instructions*?	✓	✓	✓	
provide links in a 'green' procurement chain?	✓			✓
provide a commissioning period?	✓			
establish a company EMS?	✓			
establish a resource monitoring system?	✓			

Sustainability categories and sub-categories	BREEAM	EcoHomes	RIBA	LBRUT
POLLUTION Does the proposal				
avoid the use of ozone depleting substances?	✓	✓	✓	
make use of low NOx emitting appliances?	✓	✓		
provide on site run-off treatment?	✓			
MATERIAL Does the proposal				
provide re-cycling provision on site?	✓	✓		✓
provide organic composting provision on site?		✓		✓
make use of demolition waste?	✓			✓
make use of reclaimed / re-cycled materials?	✓		✓	✓
make use of sustainably-sourced materials (certified timber, FSC, cork)?	✓	✓	✓	✓
make use of low embodied energy materials?			✓	✓
make use of locally produced materials?				✓
provide a flexible recyclable structure*?		✓	✓	
ENERGY Does the proposal				
improve on building regulation thermal performance requirements? (range 10-30%)		✓		✓
achieve a low CO2 emissions? (range from 0-140kg/m²/yr)	✓	✓	✓	
make use of airtight construction?				✓
make use of passive solar design?			✓	✓
make use of low energy cooling ?			✓	✓
make use of energy-efficient lighting?		✓		✓
make use of energy/heat recovery?				✓
make use of energy efficient equipment (ecolabel)?		✓		✓
optimise natural daylight?			✓	✓
provide a drying space?				
maximise potential and/or make use of for energy generation from renewable resources ? (e.g. solar, photo-voltaic, biomass, wind, water, digesters, heat pumps, geothermal, combined heat & power, fuel cells)			✓	✓
WATER Does the proposal				
reduce water consumption? (range from 45m³ to 25m³ /bedroom /yr, 5-20 m³/person/yr in offices)	✓	✓	✓	
make use of water meter?	✓			
make use of leak detection?	✓			
make use of dual /low flush WCs?				✓
make use of compost toilets				✓
make use of air-mix taps and shower heads?				✓
make use of grey water re-cycling?			✓	✓
make use of rainwater collection			✓	✓
separate grey/black waste water?				✓
provide rainwater-permeable landscaping*?		✓	✓	✓

- *BREEAM refers to BREEAM 98 Method for Offices (Baldwin, 1998)*
- *EcoHomes refers to the BRE environmental assessment for homes (Rao, 2000)*
- *RIBA refers to the Environmental Manifesto (RIBA, 2001)*
- *LBRUT refers to the London Borough of Richmond upon Thames (2001) Sustainability Checklist,*

✓ *denotes the inclusion of the sustainability issues in the four source assessment systems*
* *denotes issues considered for inclusion in future revisions of the EcoHomes*

The matrix was first piloted by assessing student work and found to be adequate for evaluating the adoption of sustainable strategies in the design of building projects (Sassi, 2003). As most checklists that provide a basic aide-memoir, it did not provide a means to measure the level of success of the implementation, but could assess whether or not the design strategy in question was adopted in principle.

Following the pilot, the matrix was rationalised into six categories and a reduced number of sub-categories as shown in Table 03. It was used to identify buildings that represented an example of good practice for each of the subcategories. A shortlist of 100 buildings was made and these were analysed using the checklist and a final selection of 60 buildings was made for further study (Appendix 8.2).

Table 03 - **Rationalisation of main and sub-categories for assessing sustainable strategies of building projects**

Main Categories	**Rationalised Sub-Categories**	**Combined Categories From Existing Assessment Systems** *Does the development*
Community	Community participation	*include a local community consultation?*
	Affordable living Promoting training / employment Actively promoting sustainability	*contribute to opportunity for all? * (e.g. employment, affordable homes, mixed tenure)*
	Enhancing community facilities	*improve public safety / deter crime?* *enhance public open space and amenities?*
Land, ecology and transport	Compact city centre living	*re-use existing buildings / land?* *use of land efficiently with appropriate densities?* *involve decontamination of land ?*
	Reduced car dependency	*improve safety for pedestrians?* *improve public transport facilities?* *provide links/ encourage use of public transport?* *provide a car free design?* *provide secure cycle storage and other cycling facilities? (eg shower)* *provide links to pedestrian /cycle network?* *minimise the need to travel by virtue of proximity to amenities and/or work?* *include work-live opportunities?*
	Enhancing flora and fauna	*include new landscape and trees?* *enhance the natural ecosystem of the site and maximise new wild-life friendly habitat*?* *avoid harm to protected species and ecological features on the site?*
	Local food production	*include cultivatable space on the building/site?*

Health and well-being	Indoor air pollutants avoided	*provide good indoor air quality, low VOC finishes /treatments and no toxic materials?*
	Zero potential toxins, e.g. PVC	*make provisions to avoid legionellosis?* *provide for regular maintenance/ cleaning?*
	EMF considered	
	Focus on accessibility	*provide full access for all users including those with mobility difficulty?* *provide for user feedback?*
	Restorative environment	*provide a high quality designed space?* *provide optimum comfort?* *provide windows with views at max. 7m?* *affect the local area noise and pollution levels?* *improve on building regulations sound proofing requirements?* *provide good daylighting which can be modified?* *provide openable windows?* *provide good local temperature controls?*
Energy	Minimise heat loss and passive heating	*make use of airtight construction?* *make use of passive solar design?* *provide a drying space?*
	Passive / natural ventilation and cooling	*make use of low energy cooling ?*
	Maximum natural light provision	*optimise natural daylight?*
	Energy efficient services and equipment	*make use of energy-efficient lighting?* *make use of energy/heat recovery?* *make use of energy efficient equipment (ecolabel)?* *make use of a user-friendly not over-complex management system with instructions*?* *make use of low NOx emitting appliances?*
	Performance assessment or monitoring	*provide a commissioning period?*
	Renewable energy systems	*maximise potential and/or make use of for energy generation from renewable resources ? (e.g. solar, photo-voltaic, biomass, wind, water, digesters, heat pumps, geothermal, combined heat & power, fuel cells)*
Water	Water efficient appliances	*make use of air-mix taps and shower heads?* *make use of dual /low flush WCs?* *make use of water meter?* *make use of leak detection?*
	Waterless toilets	*make use of compost toilets*
	Grey or rainwater recycling	*make use of grey water re-cycling?*
	Rainwater collection for all uses	*make use of rainwater collection*
	Alternative sewage system	*separate grey/black waste water?*
	SUD	*provide rainwater-permeable landscaping*?* *provide on site run-off treatment?*
Materials	Design for longevity and flexibility	*provide a flexible recyclable structure*?*
	Use of waste materials	*make use of reclaimed / re-cycled materials?*
	Use of renewable / certified mat.	*make use of sustainably-sourced materials (certified timber, FSC, cork)?* *provide links in a 'green' procurement chain?* *establish a resource monitoring system?*
	Use of low manufacturing impact mat.	*avoid the use of ozone depleting substances?* *make use of low embodied energy materials?* *make use of locally produced materials?*
	Waste minimisation in construction	*make use of demolition waste?* *provide re-cycling provision on site?*
	Waste minimisation in use	*provide organic composting provision on site?*

1.5.2 OBJECTIVE TWO - FORMULATING A PROTOCOL FOR A COMPREHENSIVE APPROACH TO SUSTAINABLE MATERIAL DESIGN (ORIGINAL CONTRIBUTION BASED ON LITERATURE REVIEW AND ANALYSIS - RELEVANT APPENDICES: 8.2, 8.3)

1. What are the main concepts of sustainable material design as defined by different material philosophies?
2. How can different approaches be combined to form a comprehensive approach to sustainable material design?
3. What are the main characteristics of a CLMC construction, when considered as one aspect of a comprehensive approach to sustainable material design?

The first part of Objective Two was addressed concurrently with Objective One. Sustainable material selection has a number of different dimensions, which while sharing an overall ambition of reducing negative impacts, diverge in the suggested means to achieve these reductions. The initial literature review identified three strands to sustainable material selection (Appendix 8.3 lists the documents reviewed). These were studied through a further literature review and investigated as part of the field study of case study buildings. (Objective Two question one)

The second part of Objective Two involved analysing the information gained and formulating an approach to address sustainable material selection in a comprehensive manner (Objective Two question two) and outlining a concept for CLMC construction. (Objective Two question three)

The stages to achieve Objective Two included:

- Review of general principles and three particular stands of thought in relation of sustainability material design.
- Study of material approaches adopted in selected built projects through a desktop study, building visits and interviews with the building designers and owners.

- Formulation of a protocol for a comprehensive sustainable material design approach based on completed research.
- Formulation of a CLMC construction concept compatible with the protocol for a comprehensive sustainable material design approach.

BUILDING FIELD STUDY

As in Objective One the field study was intended to triangulate the research but also bring an additional dimension, namely the practical dimension. A checklist was developed to structure the assessment of the field study buildings (Table 04). It groups sustainable material design approaches adopted by building designers into five categories of overriding aims. The five categories were derived from the sustainable materials literature studied initially and do not necessarily relate to the three material philosophies studied in detail. Table 04 relates the design approaches to the publications from the initial study.

Table 04 – **Overriding aims and design approaches to minimise the impacts of material design as adopted in practice with reference to sustainable material publications.**

Overriding aims	**Design approach to achieve aim**
	References: **(1)** Borer, P. and Harris, C. 1998 **(2)** Bjørn, B. 2000 **(3)** Woolley, T. et al 1997, 2000 **(4)** Anink, D. et al 1996 **(5)** Anderson, J. et al 2002
Reduce material needs	• Reduce amount of material used • Design for longevity and low maintenance (4) • Design for flexibility
Ensure environmentally sound resourcing and manufacture	• Use of renewable and certified materials (1), (2), (3), (4), (5) • Use of waste materials – recycled or reclaimed (1), (2), (3), (4), (5) • Use mainly materials that require minimal processing ('natural') (1), (2) • Avoid use of materials with high manufacturing or use impacts (1), (2), (3), (4)
Reduce embodied energy	• Use predominantly low embodied energy materials (1), (2), (3), (4), (5) • Use local materials (1), (2), (3), (4)
Protect health	• Use of healthy materials (1), (2), (3), (4), (5)
Waste minimisation	• Waste minimisation in construction (1) • Enable the reuse, recycling of components and materials (1), (2), (3), (4), (5)

FORMULATING A COMPREHENSIVE APPROACH TO SUSTAINABLE MATERIAL DESIGN AND CHARACTERISING CLMC CONSTRUCTION

The second part of Objective Two required

- a critical analysis of the data collected;
- a synthesis of relevant concepts for a comprehensive approach to sustainable material design; and
- a further analysis of the concepts to characterise CLMC construction in outline.

This process of analysis and synthesis consisted of five stages.

Firstly an analysis of sustainable material philosophies studied was structured using the categories from a life cycle analysis (LCA), which enabled a comparison of the different foci of the material philosophies.

Secondly, the processes advocated by the material philosophies to achieve the reduction in impacts were analysed. This created a catalogue of sustainable material design processes. The approaches identified through the case studies were included in the catalogue.

Thirdly, the potential for implementing the sustainable material design processes within a typical building project was considered. The responsibilities of key players in a building project were investigated as well as their potential for influencing the material design. The main documents used in a building development process were considered for their ability to aide the delivery of a sustainable material design.

Having identified the sustainable design processes and how and by whom they could be integrated in a building project the next step was to reorganise the processes in chronological order. By considering the chronology of a building project, the good practice processes were organised in relation to a typical project development programme. This effectively created a protocol for good practice in respect of a comprehensive approach to sustainable material design.

The concluding step involved identifying the characteristics of a CLMC construction and how they related to the comprehensive approach sustainable material design.

1.5.3 OBJECTIVE THREE - DEFINING CRITERIA FOR CLMC CONSTRUCTION (ORIGINAL CONTRIBUTION BASED ON LITERATURE REVIEW, PRIMARY RESEARCH AND ANALYSIS - RELEVANT APPENDICES: 8.4- 8.9)

1. What are the characteristics of closed loop cycle materials?
2. How can these characteristics be rationalised and measured to form assessable criteria?
3. How can the criteria be formulated to form an assessment system?

Objective three involved investigating topics that directly or indirectly relate to the outline concept of CLMC construction by means of a literature review and a second field study of current practice.

The stages to achieve Objective Three included:

- Firstly the characteristics of CLMC construction were investigated, by means of a literature review, a questionnaire, in-depth interviews, a field study of buildings incorporating some of the concepts of CLMC construction and a desktop study of building materials and products.
- Secondly existing assessment systems, guidance documents and standards related to the concept of CLMC construction were considered in relation to formulating criteria for CLMC construction.
- Thirdly a set of criteria was formulated and rationalised into a system that could be used as an assessment system in practice.

CHARACTERISTICS OF CLMC CONSTRUCTION

The initial literature review investigated publications relating to

- design for dismantling and deconstruction;

- design for recycling and reuse;
- design for flexibility adaptability and temporary structures;
- waste minimisation;
- biodegradability of waste and materials;
- recyclability of waste and materials; and
- building element and whole building life expectation.

This review formed the basis for addressing questions one and two.

SEMI-STRUCTURED INTERVIEWS WITH BUILDING DESIGNERS

To expand and verify the information gained from the literature review, primary data was sought from architects and building designers through a questionnaire, ten semi-structured interviews, eighteen building studies and ten building visits. Results of these studies are contained in the Final report to the RIBA Research Trust on the Environmental, social and economic benefits of recyclable technologies (Sassi, 2004a). Some of the most relevant results are included in Appendix 8.7.

The questionnaire was issued by email with the intention to collect basic data and identify subjects for the subsequent interviews. The questionnaire aimed to

- investigate the current practice of designing for dismantling, and reuse or recycling;
- identify existing technologies that could contribute to creating closed loop material cycle buildings; and
- identify the drivers to use such products or building design approaches.

A pilot questionnaire sent to 200 architects registered with the Association of Environmentally Conscious Building received a response of 7 per cent, while the main questionnaire sent to 2000 architects registered with the Royal Institute of British Architects was completed by just over 2 per cent of practices. The difference in response rates seemed to suggest that the topic was seen as a purely environmental concern and this was supported by a number of questionnaires being returned not completed, noting the inability of the respondents to complete the questionnaire due to their lack environmental design experience.

Nonetheless, keeping in mind that most responses came from architects with an interest in environmental issues, the fifty-one questionnaires gave a good impression of a broad range of work undertaken by large and small practices.

The questionnaire together with the Objective One building studies were used to identify a number of architectural practices undertaking a range of different work and a number of buildings that addressed or even implemented principles of design for disassembly and recycling. Ten in-depth interviews were undertaken and including the author's own experience of the health care sector the following types of buildings were considered through the study:

- private residential and social housing
- community and leisure buildings
- offices
- retail
- healthcare buildings
- transport

The semi-structured interviews investigated the barriers to adopting recyclable technologies as well as the opportunities for using them. Ways to overcome the barriers were also considered. The interviews also provided information on general architectural and building practice issues as well as illustrating different perceptions of environmental design and the principle of designing for recycling (Appendix 8.5).

BUILDING STUDIES AND SITE VISITS

Concurrently to the interviews, the eighteen building studies and ten building visits were undertaken to study examples of construction that enables deconstruction and in certain cases suggested compatibility with the concept for a CLMC construction (Appendix 8.6).

REVIEW OF BUILDING ELEMENTS

A further investigation to verify the literature review consisted of a desk-top review of building products and elements. This aimed to establish whether the current building market offers the industry materials and building products that would enable buildings to be built so that the materials could be part of a CLMC.

The building product review was undertaken through a systematic analysis of manufacturers' product literature based on the National Building Specification structure. The products' specifications and in particular their installation recommendations and material characteristics were considered. The products were assessed using the criteria developed to classify construction materials and products according to their ability to be reused, recycled or downcycled (Sassi, 2002) (Appendix 8.8).

ANALYSIS AND SYNTHESIS OF DATA

The information from the above described sources was analysed and synthesised and used to formulate a set of characteristics for construction that can be deconstructed, recycled and recovered through natural processes and can therefore be considered CLMC construction. Building element reuse was considered in relation to the concept of CLMC construction.

REVIEW OF ASSESSMENT SYSTEMS, GUIDANCE AND STANDARDS RELATED TO THE CONCEPT OF CLMC CONSTRUCTION

Once the characteristics of CLMC construction were identified they needed to be formulated into a set of assessment criteria. The development of the criteria was informed by existing assessment systems and design guidance in the field of design for deconstruction, as well as a previous study involving the classifications according to their ability to be reused, recycled or downcycled (Sassi, 2002), the results of which were republished in Addis and Schouten (2004) 'Principles Of Design For Deconstruction To Facilitate Reuse And Recycling CIRIA C607.'

The guidance on design for disassembly included the following assessment systems and guidance.

Sassi, P. and Thompson, M. (1998) - Summary of a study on the potential of recycling in the building industry and the development of an indexing system to assess the suitability of materials for recycling and the benefits from recycling. *Proceedings of Building a New Century, 5th Conference on Solar Architecture and Design, Bonn.*

Crowther, P. (2000) - Developing Guidelines for Designing for Deconstruction. *Deconstruction - Closing the loop. Workshop held at the Building Research Establishment, Watford, UK. May 2000.*

Fletcher, S.L., Plank, R. , Popovic, O. (2000) - Designing for future reuse and recycling. *Deconstruction - Closing the loop. Workshop held at the Building Research Establishment, Watford, UK. May 2000.*

Thormark C. (2001) - *Recycling Potential and Design for Disassembly in Building. TABK— 01/1021.* Sweden, Lund: Lund Institute of Technology.

Sassi, P. (2002) - Study of current building methods that enable the dismantling of building structures and their classifications according to their ability to be reused, recycled or downcycled. *Proceedings of Sustainable Building 2002: 3rd International Conference on Sustainable Building. 23-25 Sep.2002. Oslo, Norway.*

Addis, W. and Schouten, J. (2004) - *Principles of design for deconstruction to facilitate reuse and recycling CIRIA C607* London: Construction Industry Research and Information Association.

Morgan, C. and Stevenson, F. (2005) - *Design for Deconstruction. A SEDA Design Guides for Scotland.* Scottish Ecological Design Association. Available online http://www.seda2.org/dfd/index.htm.

Additional literature reviews were undertaken to establish which existing standards could be adopted as part of the assessment system to establish:

- a quantifiable definition for biodegradability; and
- a quantifiable definition for recyclability.

FORMULATING A SET OF CRITERIA FOR CLMC AND DEVELOPING AN ASSESSMENT SYSTEM

The final step involved an evaluation of the information gained in the previous stages and the selection and or formulation of a set of criteria for CLMC construction.

1.5.4 OBJECTIVE FOUR - TESTING MATERIALS, BUILDING ELEMENTS AND WHOLE BUILDINGS FOR COMPLIANCE WITH THE CLMC CRITERIA (ORIGINAL CONTRIBUTION BASED ON PRIMARY RESEARCH AND ANALYSIS - RELEVANT APPENDICES: 8.10- 8.14)

1. Which of a selection of materials qualify as CLC materials?
2. Which of a selection of building elements qualify as CLMC building elements?
3. What is the CLMC content of a selection of building designs?
4. Are the criteria able to be used easily and reliably for their intended purpose?

Objective Four involved an empirical assessment of selected materials, building elements and whole building constructions in terms of their compliance with the set of criteria for CLMC developed in conclusion of Objective Three.

To undertake the assessment, data on material characteristics, manufacturing and disposal processes, installation and disassembly methods was gained from relevant reference publications and building materials manufacturers' literature and cross-referenced with the data collected from the building designers as part of Objective Three.

The assessment criteria and assessment system developed as part of Objective Three were used to make the evaluations of selected materials and building elements. The whole building assessment compared three different building construction systems in terms of their CLMC construction content. By making use of the assessment systems it was also possible to assess the system itself and adjust it in order to achieve the required extent and ease of assessment.

The stages to achieve Objective Four included:

- Selection and development of dwelling design and construction systems to be analysed, including producing full detailed drawings of the development and measuring material quantities.
- Research of the material characteristics of the materials included in the building construction options and assessment of their ability to be disposed of in a CLC using the criteria developed.
- Assessment of building elements included in building construction options for their compliance with CLMC construction criteria.
- Quantifying the material included in the three building construction options that complies with CLMC criteria.
- Review of assessment system.

MATERIAL ASSESSMENT

The materials selected for the first assessed included the materials required to undertake the following assessments. These were categorised using the classifications in Maguire's Construction Materials (Maguire, 1981), including cementing and masonry materials, glass and plastics, metals and materials of wood (Table 05).

The characteristics of the materials were researched by referring previous research and to texts on building materials, research journal and other publications related to recycling and environmental characteristics of materials. The outline of general information about the materials plus that required to analyse the materials and evaluate them against the CLMC criteria include:

- recycling or recovery process and efficiencies (including natural cycles);
- environmental impacts and benefits of recycling or recovery; and
- barriers and hazards including environmental hazards to recycling or recovery.

Table 05 – **Categories of materials and materials tested for compliance with closed loop material cycle principles**

Cementing and masonry materials	Plastics / oil-based products	Metals	Materials of wood and other natural sources
fired clay gypsum cement concrete ballast mineral wool insulation	thermoplastics PE/ PP thermoplastics PVC thermosetting plastics glass	steel	timber cork recycled cellulose fibre

BUILDING ELEMENTS ASSESSMENT

The second assessment exercise was to evaluate building elements and their integration into a building. The building elements and methods included in this assessment would form the constituent parts of the three building designs to be used for the whole building assessment. Some of these are typical and some atypical building examples of the UK building industry.

The review analysed the building elements in terms of their composition, installation system, dismantling process and disposal options. Using the assessment criteria and tables developed the building elements were evaluated them in terms of their compliance with the complete set of CLMC criteria.

Information on the selected materials and products was sought from the product manufacturers and was verified by using generic publications on material technology.

WHOLE BUILDING ASSESSMENT

By using the results of the previous two assessments the third assessment could compare three different residential construction systems in terms of their CLMC construction content.

A three bedroom house design was used as a basis to develop three different construction specifications including:

- House 1, a traditional brick clad timber framed construction;
- House 2, a contemporary timber framed construction with render and timber cladding finish; and
- House 3, an alternative construction constituting a timber framed with predominantly natural materials.

The house design was based on a development designed and built by the author (Appendix 8.6, case study 4 and 8.13). The three construction variations maintained an identical thermal performance and the structure was timber in all cases, but the other elements varied. The material specifications for House 1 and 2 are based on completed projects studied as part of Objective One. House 1 comprised materials typically used by UK housing developers, and is based on the 21st Century homes in Aylesbury by Briffa Phillips Architects for Hightown Preatorian Housing Association (Sassi, 2006a). House 2 is a contemporary mainstream design with some atypical features such as external render but keeping in line with current aesthetic expectations and is based on the Toll House Gardens in the Fairfield estate, Perth, Scotland, by Gaia Architects for Fairfield Housing Co-operative (Sassi, 2006a). House 3 maximises the use of biodegradable materials choosing where possible but not limiting the choice to the most commercially realistic materials.

All three house structures were detailed and the quantity in weight and volume of materials used for each building design was measured using standard Building Quantity Surveying methods. Services and fixtures and fittings were not included in the assessment. This was considered acceptable in view of the limited contribution that services in house design make to the total weight and volume of waste and also the fact that the three construction options would have included virtually identical services.

The assessment did not consider economic aspects and assumed time would be available for the careful deconstruction.

The main differences in the house types include:

- House 1 has a concrete ground floor bearing slab, while House 2 and House 3 have suspended floors and House 3 includes timber piles.
- The external cladding material in House 3 is timber, while House 1 also has brick cladding and House 2 also has render elements.
- The internal finishes in House 1 and 2 are applied (skim finish to plasterboard), while in House 3 mechanically fixed self-finished products are used.

All the building materials and products used for each of the three designs were assessed. A first iteration was undertaken by identifying the maximum amount of biodegradable material that could be included in a building (Sassi, 2006b) and a second iteration used the criteria developed as part of Objective Three and compared the quantity of CLMC and non-CLMC construction material destined for landfill (Sassi, 2008).

This quantitative analysis enabled a comparison of the current and potential disposal costs providing basic data to consider different levels of increase in disposal taxes and the resulting economic incentive for the use of closed loop material cycles.

This stage completes the empirical study.

1.5.5 OBJECTIVE FIVE – FORMULATING CLMC CONTENT TARGETS FOR UK MAINSTREAM HOUSING DESIGN (ORIGINAL CONTRIBUTION BASED ON PRIMARY RESEARCH AND ANALYSIS)

The fifth objective entailed a critical analysis of the previous stages of the research to formulate realistic targets for CLMC content in mainstream housing construction. This research stage also draw conclusions in relation to the original research aims.

1.5.6 OBJECTIVE SIX - DEVELOPING AN AGENDA FOR FURTHER RESEARCH (ORIGINAL CONTRIBUTION BASED ON ANALYSIS)

This final objective also entailed a critical analysis of the research undertaken to identify knowledge gaps, unsatisfactory conceptual formulations or other omissions or errors that would benefit from further

	Research objective	Research methods					Research activity	Key outcome
		L	T	F	E	A		
1	**Investigation of research context: sustainability building design and implementation of good practice**	■	■	■	■	■	• Review sustainability texts • Review sustainable design and construction documents • Development of selection and analysis tool • Field research of sustainable building case studies • Analysis of sustainable case study buildings	• Outline of sustainable design principles • Examples of sustainable design implementation approaches
2	**Developing a comprehensive sustainable material design protocol that incorporates the principles of CLMC construction**	■		■		■	• Review literature on sustainable material philosophies • Field study of buildings adopting sustainable material design • Analysis and development of protocol for comprehensive approach to sustainable material	• Protocol for comprehensive sustainable material design • Principles for CLMC construction
3	**Defining criteria for CLMC construction**	■	■	■	■	■	• Review of existing guidance on design for recycling, deconstruction and design for environment • Field study of buildings integrating technologies for demountability, recyclability and reusability • Questionnaires and interviews with architects • Development of set of criteria for CLMC buildings	• Assessment criteria for design for CLCM construction
4	**Testing materials, building elements and whole buildings for compliance with CLMC criteria**				■	■	• Assessment of materials, building elements and whole building construction for compliance with criteria for closed loop cycle material and construction	• Ratings for CLMC compliance for selected building products • % CLMC compliance of three house construction systems
5	**Identifying potential targets for CLMC construction content**					■	• Analysis of research outcomes to formulate targets for CLMC content as a percentage of total materials used	• Targets for CLMC content in housing
6	**Review of research work and agenda for further research**					■	• Review of research work and outcomes	• Agenda for further research

Table 06 – **Summary of research objectives, methods and outcomes**

Key:
L = Literature review
T = Development/ use of assessment tool
F = Field study
E = Empirical measurements
A = Analysis

1.6 LIMITATIONS

There are a number of limitations to this study worth briefly discussing.

1.6.1 RAPIDLY CHANGING TIMES OUTDATING INFORMATION

This study has been undertaken part time over six years. In this period the social context relating to sustainability has changed significantly towards what can be generally described as a more sustainable direction. New regulations, guidance and practice were produced in this time that represent a step change. The effect this has had on this study is to regularly outdate documents studied and sections of completed writing.

In contrast the more focused area of design for deconstruction, recycling, reuse and CLMC construction is suffering from a lack of attention, no doubt at least partially due to the increasing alarm related to global warming that effectively detracts attention and funding from other research areas. This disappointing lack of interest in this field has however meant that this study has been able on the whole to keep pace with changes in this field. So while some of the documents relating to sustainability in general discussed in this dissertation may by the time it is read be superseded, those relating to design for CLMC construction should still represent the latest in the field and indeed this dissertation still represents the only identified assessment system for CLMC building construction. Only one related assessment system has been identified. Launched in 2008 by Bill McDonough and Michael Braungart of McDonough Braungart Design Chemistry (MBDC), the Cradle to Cradle assessment is aimed at product designs and takes into account material recycling, including natural recovery, and the pollution impacts of the processes (MBDC, 2008). This work is conceptually the closest to that proposed in this research, and even though its main focus is not on whole building design any further work in this field would have to analyse McDonough and Braungart's work in detail.

Another area in flux affecting this research is that related to the recycling industry. There is an environmentally driven trend towards making building elements recyclable. Kingspan's composite metal and mineral wool insulation cladding panels are being recycled today (Steel Construction Institute, 2007) when only ten years ago such an initiative appeared without a future. Conversely, some of the promising technologies have not materialised. Smith *et al.* (1998) reported on a promising technology able to grind up used concrete and mix the resulting powder with new cement to make new concrete without wasting any of the recovered concrete. This technology has not yet been successfully adopted in practice. Due to these rapid and unpredictable changes any materials and building elements assessment undertaken would have to be reviewed in the near future.

1.6.2 EXPANDING THE LIMITED PERSPECTIVE

In theory the process of logical argumentation adopted at a number of stages during this research process may have resulted in acceptable conceptual rule systems, which have the desired 'applicability' as defined by Groat and Wang's (2002). However, in practice such conceptual rule systems have to be developed by groups of individuals not single individuals to take into account the wide and complex diversity of issues that impact on the built environment industry. While this study is as much about the research process as the research outcome, it is important to be conscious of the limitations of undertaking such research in, what is ultimately, isolation. This is not to suggest that the outcomes have no 'applicability', but it does suggest that the results will have been shaped by a particular perspective regardless how impartial one tries to be. To remove this partiality the logical argumentation process would have to be repeated by at least one other individual. The suggestions made as part of the agenda for further research would go some way to provide a means to overcome the limitations of a limited perspective.

1.7 STRUCTURE OF DISSERTATION

The dissertation is structured in line with the research objectives.

This introductory chapter sets the scene by stating the aims and expanding on the objectives and research methods adopted. It also gives a brief contextual justification which is expanded in Chapter Two.

Chapter Two reviews the context within which the research is situated and provides a brief historic justification for the focus on legislative measures as a means of promoting sustainability (Objective One). It also includes an overview of sustainable design practice based on the synthesis of principles for sustainable design obtained from existing literature and from the good practice case study buildings investigated. Particular attention is put on assessment systems and legislation.

Chapter Three explores three material philosophies relating to the built environment and other industries. These form the basis for the development of a protocol for a comprehensive approach to sustainable materials and from this approach the concept for CLMC construction is derived (Objective Two).

Chapter Four investigates the characteristics of CLMC construction and assessment systems and design guidance related to design for deconstruction, recycling and reuse. A set of criteria for CLMC construction are formulated, discussed and structured to create an assessment system for assessing compliance with CLMC principles (Objective Three).

Chapter Five reports on the empirical assessment employing the criteria developed in the previous chapter. An assessment is undertaken of a selection of construction materials for their ability to be recycled or recovered naturally; a selection of building products or elements for their compliance with CLMC requirements; and three building constructions for their content of CLC materials compared to materials destined for landfill or incineration (Objective Four). Chapter Five concludes with a proposal for targets for CLMC content in housing designs (Objective Five).

Chapter Six concludes the research in relation to the original thesis.

Chapter Seven reviews the research contributions and suggests an agenda for future research in the field of closed loop cycle materials.

2 INVESTIGATION OF RESEARCH CONTEXT: SUSTAINABILITY, BUILDING DESIGN AND IMPLEMENTATION OF GOOD PRACTICE

Chapter Two reviews the context within which the research is situated and provides a brief historic justification for the focus on legislative measures as a means of promoting sustainability.

It also includes an overview of sustainable design practice based on the synthesis of principles for sustainable design obtained from existing literature and from the good practice case study buildings investigated. Particular emphasis is placed on assessment systems and legislation.

(Related Appendices: 8.1, 8.2)

2.1 TOWARDS A SUSTAINABLE SOCIETY

> 'Sustainable:
> Capable of being upheld or defended; maintainable.
> Capable of being maintained at a certain rate or level.'
> (Oxford University Press, 2008)

The Oxford English Dictionary's definition of 'sustainable' describes a process or status that could go on in its current state for a long time even perhaps in perpetuity. The potential for keeping an ethically questionable status in operation in perpetuity does of course exist, but today's use of the term 'sustainability' implies a status that is ethically sound. 'Sustainable' has gained a positive significance. As will be touched on later, how and to what the concept of sustainability is applied is a question of personal ethics, but the most widespread understanding of sustainability focuses on creating an environment that is sustainable for the benefit of humans safeguarding the ability of the planet to support human needs. However these needs may be defined, the implication is that a sustainable status is one that ensures human needs can be addressed in a foreseeable future.

If the concept of sustainability essentially reflects a concern with the well-being of humans how is it that so little progress has been made towards creating a sustainable society? This section addresses this question by considering some historic trends and draws some conclusions about effective methods for promoting action towards a more sustainable society.

2.1.1 SUSTAINABILITY'S SLOW DEVELOPMENT

The current understanding of sustainability and the achievements towards creating a sustainable society are the result of both human philosophies and human activities and indeed inactivity. Society is a collection of individuals with many contradictory characteristics: humans possess ingenuity but also ignorance; inventiveness and the fear of change; self-interest but also generosity and empathy; humans can be visionary but also short-sighted. These human traits have steered society towards but also away from the developing notions of a sustainable society. Consequently the process of formulating a concept and methods for achieving sustainability and even more so implementing such methods has been slow.

As early as the industrial revolution, concerns were voiced that related to issues we would now classify as associate with sustainability. These included philosophical unease regarding the relationship between humans and the environment and practical concerns regarding the dependence or overdependence of humans on the limited capacity of nature and the degradation of the human quality of life through technological innovation. Human well-being, pollution, overpopulation and economics were some of the topics of debate.

The growing population resulting from the industrial revolution was identified by Reverend Thomas Malthus in his 'Essay on the Principle of Population' first published in 1798 (Malthus, 1985) as a probable source of death for humans. He warned of the impossibility of arithmetically increasing food production to satisfy the geometrically increasing population. He suggested the potential for a cyclical process occurring where population growth outstrips food supplies resulting in famine and the consequential drops in population, followed by an increase in food supply per person and population growth and so on.

In respect of pollution, ill-health and social deprivation warnings were also voiced at the time. Thinkers such as John Ruskin discussed the potential dangers to humans and nature from industrialisation in his writings, such as 'Undo this last' published in 1862 (Ruskin, 1997). William Morris pioneered the Arts and Craft movement in the UK as a reaction to the excessive mechanisation of the creative processes and the resulting loss of social well-being.

The possibilities offered by the new technologies changed the aspirations of society, and these too were questioned. Transcendentalism, a movement based in the United States, opposed materialism and utilitarianism. Transcendentalists such as Ralph Waldo Emerson in his essay 'Nature' (Emerson, 1991) published in 1836 and Henry David Thoreau in 'Walden' (Thoreau, 1908) published in 1854 revered nature and advocated a simple way of life. Thoreau went further to suggest that a simple way of life was in fact the only way to really experience life and aimed to demonstrate as much by living in a simple timber hut in the woods (Thoreau, 1908).

Even political and economic problems were identified as early as the 1800s by individuals such as John Stuart Mill in his 1848 book 'Principles of Political Economy' (1998) where he puts forward the advantages of a 'stationary state economy' in order to maintain resources and improve the well-being of the masses.

The slowness of change means that many of these writings deal with issues that are as relevant today as they were then. Mill's 'stationary state economy' was reformulated in Herman Daly's 1977 book 'Steady State Economics' (1992) and other publications (Daly, 1968; Daly and Cobb, 1989) where he considers the advantages of a non-growth economy and forms the basis for the adoption of alternative economic assessment methods, such as the Index of Sustainable Economic Welfare ISEW in place of the criticised Gross Domestic Product GDP (Ayers, 1996; Daly and Cobb 1989; Max-Neef, 1995).

The industrial revolution concerns over pollution and the condemnation of new technologies were no different to the concerns voiced by Rachel Carson in her book 'Silent Spring' (1962) where she condemned the use of pesticides and highlighted their accumulative effect in the food chain in nature. Malthus's concerns regarding the carrying capacity of the earth were echoed in Paul Ehrlich's 'The Population Bomb' (1968) and in Meadows *et al.*'s 'The limits of growth' (1972), a report for the Club of Rome that assessed the world's resources, considering the population, agricultural production, natural resources, industrial production and pollution and concluded that current human activities are surpassing available resources.

Considering the recurrence of concerns it may therefore not be surprising that today's most commonly quoted definition of sustainability, formulated by the World Commission on Environment and Development chaired by Gro Harlem Brundtland that defines sustainable development as

> '[D]evelopment that meets the needs of the present without compromising the ability of future generations to meet their own needs.'
>
> (World Commission on Environment and Development, 1987, p.43)

has a notable antecedent. This contemporary definition is in essence similar, bar the theological underpinning, to John Ruskin's sentiments expressed nearly 150 years previously regarding the built environment in 'The Seven Lamps of Architecture' (Ruskin, 1889, p.185-186)

> 'God has lent us the earth for our life; it is a great entail. It belongs as much to those who are to come after us, and whose names are already written in the book of creation, as to us; and we have no right, by anything that we do or neglect, to involve them in unnecessary penalties, or deprive them of benefits which it was in our power to bequeath.'

For every visionary thinker there have been many people who resisted change. Ruskin's 'Undo this last' essays published in 'Cornhill Magazine' in 1862 received severe criticism and complaints and the first edition failed to sell (Ruskin and Wilmer, 1997, p.161). Yet his influence, as it emerged later, was significant: '[w]hen the first twenty-one Labour MPs were elected to the House of Commons in 1906 a questionnaire was circulated among them which showed, according to Clement Attlee, that the book they considered had influenced them most deeply was 'Undo This Last." (Ruskin and Wilmer, 1997, p.30). Decades had to elapse before his ideas could find acceptance.

When society is confronted with concepts that are new and question the status quo it often reacts negatively towards them. The writings of visionary thinkers do, nonetheless, raise awareness and slowly directly and indirectly contribute to shifting the consciousness of society as a whole. But change of this nature is slow.

2.1.2 WHY THE SLOW PROGRESS ?

The slowness with which new concepts are accepted in a field of study is discussed in Røpke's review of the early developments of ecological economics (Røpke, 2004). Any change in the way society thinks and acts takes time. The same is true for the concepts of sustainability to gain general acceptance. Røpke traces the key ideas of ecological economics to before the 1970 and points out that it was not until twenty years later that the field was formalised and twenty years after that it became only one of a number of heterodox economic philosophies, and one which is still intensely questioned. Røpke believes the long gestation period was due to the need for a basic degree of general acceptance of the ideas before researchers who are well established in the field could feel inclined to devote time to a theory that ultimately went against the dominant thinking. This view echoes Kuhn's analysis of paradigm changes in scientific research (Kuhn, 1996). Røpke further suggests such change also required the support of appropriate personalities to advocate the ideas and a new unbiased generation to be open to explore the ideas. After forty years partial acceptance of the principles was achieved but the general practice remains unaffected (Gowdy and Erickson, 2005).

As with ecological economics, the acceptance of new ideas related to sustainability into mainstream practice can only occur once these ideas have gained sufficient support and a good general level of awareness has been attained. Furthermore, understanding the concept and the need for action to achieve sustainability involves some unpalatable facts that may be difficult to understand.

UNDERSTANDING COMPLEX LINKS

Firstly there is a genuine lack of understanding of the impacts of human activities (Goudie, 2000). For instance, the 'green revolution' in agriculture in the 1960s and 70s was driven by sound intentions of increasing and securing food production and did succeed in vastly increasing crop yields. The side effects caused by increased pesticide and fertiliser use were not foreseen. Nor was it understood that the introduction of monocultures and loss of diversification brought with it a reduced resilience of the agricultural output and increased the risk of a wholesale loss of crops. More recently the over-reliance on the car, a tool to ease mobility for everyone, combined with the availability of cheap food has had the unexpected side effect of fuelling an epidemic of obesity (World Health Organisation, 2002).

The mechanisms associated with environmental issues and social issues are complex and the outcomes sometimes unexpected. Furthermore, some of the outcomes are difficult to understand. The increased risk of crop failure only becomes fully understood when it occurs.

Secondly, in addition to the difficulty in understanding impacts that are displaced in time, in the same way a crop failure might be, environmental impacts can also be displaced in terms of location. Impacts, such as those associated with climate change, can occur remotely in time and location and the cause and effect may not be simple to imagine. The concept of global links can be difficult to visualise. Similarly difficult to understand and accept is the concept of accumulative impacts; in other words, the impact one individual's activities may be negligible but the same activity adopted by millions may be unsustainable.

Reactions to issues that are close and tangible are very different. The Clean Air Act of 1956 was brought in after public outcry and a public enquiry following 4,000 deaths in London during a six day period in December 1952 with extreme levels of air pollution (McNeill, 2000). The public concern was not only triggered by the fact that the pollution was visible and the deaths outrageous. It was so strong because it engendered empathy and also fear. It was close enough to be able to happen to 'you'. Humans, whether through excessive optimism or lack of imagination, often believe catastrophic events, including environmental ones, are likely to happen to 'someone else'. Therefore action feels neither essential nor urgent.

ESTABLISHING VALUES AND THE NEED FOR ACTION

Even once the cause and effect have been understood, there are still other barriers to overcome before unorthodox thinking is translated into mainstream action. The second stage to generate sustainable behaviour requires accepting responsibility for the detrimental impacts. Impacts can only be considered detrimental if they disadvantage someone or something worth of consideration. The object of consideration may be human, non-human or a non-living entity, such as a landscape. In each case, it will receive different levels of consideration depending on the value put on it.

Environmental ethicists have classified different human perspectives or philosophies of the environment in three main categories: the anthropocentric philosophy, the non-anthropocentric or ecocentric philosophy and the mixed theory philosophy. The anthropocentric view believes that nature exists for the benefit of humans and that when a choice has to be made between human and environmental interests, human interests should always be put first. Mixed theorists put human life, but not other human benefits before environmental welfare. Non-anthropocentric views put sentient beings, living beings and nature as a whole on equal standing, deserving equal priority (Attfield,1999; Shrader-Frechette, 2003).

The non-anthropocentric views formulated in the last decades assert that nature has intrinsic value. Humans are seen as part of nature and dependent upon nature; and their intelligence does not give humans rights, but rather the responsibility of stewardship. Therefore, non-anthropocentric views not only advocate taking action to address environmental problems, whether they affect humans, non-human living beings or non-living being, but accept the possible need to compromise human quality of life to prevent environmental degradation. Pioneers of this way of thinking include the Norwegian philosophers Arne Ness, who coined the term 'deep green' to describe an approach involving a fundamental investigation of the nature of the relationship between humans and the natural world, and George Sessions and Michael Tobias who supported and promoted these concepts (Sessions, 1995). Arne Naess contended that any fundamental and sufficiently deep investigation of the relation of humans and nature would inevitably conclude that humans and nature are on an equal standing. Furthermore he suggested that having understood this relationship, humans would want to protect the environment like they would protect their own life.

Most humans do not share this philosophy. Consequently the perception of a need to take action to protect the environment has been accepted on a large scale only once the welfare of humans was seen as threatened. It follows that the most commonly quoted definitions of sustainability, the Brundland definition, is deeply anthropocentric, advocating respect and care for other humans and the guardianship of planet earth for the human benefit. Humans can relate more easily to the need to protect the environment so that their grandchildren might have a future with a high quality of life, than they can understand the reasons for protecting the environment for its own sake.

PRIORITISING INTERESTS

Understanding the problems and accepting that action should be taken does not imply that action will be taken. The investment in taking action has to be weighed against other priorities.

When it comes to actively following ones interests, it appears sustainability is not a priority in many people's mind. A survey of consumers' awareness of information about sustainable products undertaken in the UK by the Consumer Council showed that only less than one fifth of the over 1800 individuals interviewed actively sought information about the sustainability of products (Steedman, 2005). In the briefing document 'Motivating Sustainable Consumption' for the Sustainable Development Research Network, Jackson (2005) identified that the symbolic nature of consumer goods allows individuals to express status, identity, social cohesion, and allows the pursuit of personal and cultural meaning. Moving away from unsustainable consumerism could therefore deprive certain individuals of their sense of place within society. Prioritising the health of the environment over ones cultural identify appears to be an unlikely proposition for many people.

Personal financial interests can also hamper the introduction of regulations aimed at making the planet more sustainable and indeed improving the survival chances for humans. A case in point is the banning of ozone depleting substances. As with other environmental concerns, in the last century the scientific community repeatedly raised the alarm in respect to the depletion of the ozone layer before governments finally formulated and introduced legislative controls. As early as in 1974 scientists Sherwood Rowland and Mario Molina put forward the theory that chlorofluorocarbons (CFCs) might destroy the ozone layer. The prospect of a decrease in protection against ultra-violet radiation, which could ultimately affect crop growth, was of enough concern for the governments of the USA, Canada and Sweden to ban CFC aerosol sprays. However, this had virtually no impact in terms of reducing the ozone depletion and in 1985 J.C.Farman observed that the ozone shield over the Antarctica had become thinner, and a thinning was also recorded over the northern hemisphere. Due to the perceived severity of the issue an immediate convention was organised and in 1987 the Montreal Protocol was signed which banned the production of CFCs by 1995. HCFCs, CFCs substitutes that are also ozone depleting substances albeit less potent in their effect, were also banned, but only as of 2015 (McNeill, 2000). Despite the perceived urgency of the matter, the banning of ozone depleting substances was programmed over a twenty year period due to the industrial interests.

2.1.3 CARROT AND STICK

Motivating people to change and adopt a more sustainable way of life has to be done by making sustainability understandable as a principle and comprehensible in respect of the associated dangers and the benefits it brings. Most importantly it should not be seen as negatively affecting the personal interests of individuals. The less change affects what are perceived as being the current values the more likely it is to be accepted. It is therefore seen as imperative to address environmental issues while also addressing social and economic issues. This approach is reflected in the UK government definition of sustainability in the 2003 document 'Achieving a better quality of life. Review of progress towards sustainable development', which describes sustainable development as being about ensuring 'a better quality of life for everyone, now and for generations to come', and sets out four objectives for the UK and globally:

- 'Social progress which recognises the needs of everyone.
- Effective protection of the environment.
- Prudent use of natural resources.
- Maintenance of high and stable levels of economic growth and employment.'

(Department for Environment, Food and Rural Affairs, 2003, p.16)

A more recent UK government document 'Sustainable Indicators in your pocket 2004' further confirms the need for:

> 'reconciling aspirations for social progress, economic development, protection of the environment and conservation of natural resources, and the integration of these into decision-making, so that progress in one does not adversely affect another.'
>
> (Department for Environment, Food and Rural Affairs, 2004, p.6)

Social progress, effective protection of the environment and prudent use of natural resources are appealing aims that are unlikely to be fundamentally disputed in a modern western society, but remain difficult to quantify. Attempts are being made to quantify these as part of the UK government's Sustainability Indicators (Department of the Environment, Transport and the Regions, 2008), but the benefits best understood are those that can be assessed using well-established economic value systems.

Reliance on economic value systems has been shown to be associated with limitations. Daly and other ecological economists highlight the fact that the use of Gross Domestic Product (GDP) as a measure of progress fails to distinguish between positive and negative spending, such as crime prevention, war expenditure or disaster relief. Different approaches do exist and are supported by increasing research suggesting that, in developed countries, economic growth is no longer inextricably linked to increased well-being (Daly, 1989; Max-Neef, 1995; Layard, 2005). Research has shown that economic wealth, often perceived as a measure of personal success, has failed to provide increased happiness. Individuals, particularly in the USA, are no happier now than they were in the 1950s, despite relative wealth having greatly increased (Layard, 2005). This is in contrast to developing countries where an increase in economic wealth is still essential to provide a basic standard of living. Once a basic quality of life is achieved, the benefits of economic growth begin to decline: quality of life and happiness are not perceived to increase with rising economic wealth. This view, supported by the World Commission on the Environment & Development's (1987) recommendations to redefine growth and adopt alternative ecological economic principles, may be gaining popular interest but for now remains adopted only by a minority.

As long as the perception remains among most of society that their happiness is related to economic wealth and its display (Jackson, 2005), an approach that is effectively supported by overly conciliatory of government rhetoric, then only initiatives that do not affect economic wealth are likely on the whole to be adopted voluntarily. However, to address sustainability on a wide scale and with the urgency it is now seen to require, these voluntary actions will not suffice. A carrot and stick approach that combines legislation and economic incentives is now necessary.

LEGISLATION AND TAXATION (STICK)

Legislation is one of the essential elements required to engender action, particularly when action is required within a limited time frame. The UK is becoming increasingly subject to environmental and related legislation, introduced to implement European Union policies and international treaties. These have proved to be effective measure to introduce sustainable behaviour.

INTERNATIONAL LEGISLATION

In 1972 the United Nations created the United Nations Environmental Programme (UNEP) with the aim

> 'To provide leadership and encourage partnership in caring for the environment by inspiring, informing, and enabling nations and peoples to improve their quality of life without compromising that of future generations'
>
> (United Nations Environmental Programme, n.d.)

This and the United Nations Conference on the Human Environment held in Stockholm in the same year marked the beginning of a coordinated international influence on international and national policies regarding environmental issues. The implementation tools adopted include agreements and protocols signed by countries in agreement with their principles and prepared to implement them through national legislation.

International conferences related to the environment have notably included the United Nations Conference on Environment and Development in Rio in 1992 at which the Framework Convention on Climate Change was agreed. This led to the internationally legally binding Kyoto Protocol to the Framework Convention on Climate Change. Formulated at the Kyoto Conference in 1997, the Bonn Agreement of 2001 saw its signatories agree to reduce their collective emissions of greenhouse gases by at least 5 per cent below 1990 levels by 2008-2012 (United Nations, 1998), despite recommendations from the scientific community for a reduction of 60-80 per cent of greenhouse gases by the 37 more developed countries (Department of Trade and Industry, 2003). The European Union 15 countries agreed a target of emissions reduction of 8 per cent below 1990 levels, and the UK set a national target of 12.5 per cent reduction.

While the Kyoto Protocol has been severely criticised for including targets for carbon dioxide emissions that are insufficient to reduce greenhouse gas concentrations to safe levels, it succeeded in inducing government action. In the UK, despite the initial limited ambition, long terms plans set out in the 2003 Energy White Paper published by the Department of Trade and Industry (2003) do include reductions of 60 per cent of carbon emissions by 2050 compared to 1990 levels. Implementation initiatives include economic support and knowledge transfer to encourage energy efficiency as well as strategies for low carbon emissions energy supplies.

Other international agreements related to the building industry that have had a significant impact on society's behaviour include the:

- the Stockholm Convention on Persistent Organic Pollutants adopted in 2001 and entered into force in 2004, which requires signatory countries to reduce the emissions of Persistent Organic Pollutants into the environment;
- the Montreal Protocol on Substances that Deplete the Ozone Layer signed in 1987 and discussed earlier; and
- the Asbestos convention adopted in 1986 and entered into force in 1989, which required signatory countries to introduce legislation to protect workers against the health hazards associated with exposure to asbestos. (Kurukalasuriya *et al.,* n.d.)

These and other agreements dealing with transboundary air pollution, marine pollution, biosafety, biological diversity, desertification, preservation of marine biodiversity including fishery and more have proved to be effective legislative measures to control human behaviour.

EUROPEAN LEGISLATION

Similarly to international agreements, European Directives are implemented by each member state in whatever means they consider appropriate for their national context. Some of the directives relevant to the building industry such as the Directive 2002/91/EC on the energy performance of buildings, which came into force in 2006 and has successfully implemented the requirements for EPCs (Official Journal of the European Communities, 2003c), have proved to be very effective means of introducing good practice to mainstream building industry.

Relevant to this research are two Directives. Firstly the Directive 2006/12/EC on waste, which was amended in 2008 and is due to come into force in 2010, will set targets for reuse, recycling and recovery of 70 per cent of construction and demolition waste by 2020. (Department for Business, Enterprise & Regulatory Reform. Construction Sector Unit, 2008). This would strongly support the concept of CLMC construction. Secondly, the Directive 2003/108/EC waste electrical and electronic equipment (WEEE), which aims to reduce waste by placing the financial responsibility for recovering and recycling of electronic equipment on the producers of such equipment (Official Journal of the European Communities, 2002; ibid 2003a), indirectly encourages producers to design their products in a way that will facilitate their disassembly and recycling at the end of their life. Other European Directives are outlined in Appendix 1.

While the full impact of the latter two directives still remains to be seen, the Directive 2003/108/EC WEEE is already having some impact by forcing the infrastructure for the recycling of electrical equipment to be put in to place.

ENVIRONMENTAL TAXATION

Legislation, such as that used to implement the Directive 2003/108/EC WEEE has a predictable effect, while taxation, including environmental taxation, is a less predictable economic instrument as it relies on conditioning behaviour rather than imposing behaviour. Environmental taxation is defined as 'compulsory unrequited payments to general government levied on tax bases deemed to be of particular environmental relevance' (Organisation for Economic Co-operation and Development, 2001, p.15). The aim of environmental taxation is to discourage demand of limited resources and reduce waste (Organisation for Economic Co-operation and Development, 2000). Environmental taxation is recognised as having the potential to provide a double dividend effect where the tax can affect behaviour and reduce pollution, resource use or both (the first dividend) and the revenue can offset other taxation that could slow economic growth, such as employers' contributions, and also fund environmentally beneficial initiatives (the second dividend) (Patuelli *et al.,* 2005). An example of the double dividend effect can be seen with the Climate Change Levy which taxes commercial energy consumption and the revenue is used to offset National Insurance Contributions and fund the Carbon Trust and its activities to promote energy efficiency and renewable energy systems.

Studies into the effectiveness of environmental taxation concluded that taxation can be effective in conjunction with Legislation, Regulation or Directives. (Organisation for Economic Co-operation and Development, 2001; Her Majesty's Treasury, 2002; Smith, 1992; Bosquet, 2000). Non-governmental organisations, such as Friends of the Earth support these findings and approach (Friends of the Earth, n.d.).

A very successful example of how environmental taxation can affect behaviour is the Irish tax on plastic bags. In 2002 the Republic of Ireland placed a €0.15 tax on every plastic carrier bag. In one year (2003) the revenue generated was €12.7m (Lamb and Thompson, 2005) and the consumption of plastic bags dropped by 90 per cent from 1.3 billion (Litter

Monitoring Body, 2004). The success of the Irish implementation of a tax on plastic bags would suggest that taxing is an assured success; this however is not necessarily the case as the effects of taxation on behaviour are hard to predict and therefore establishing the effective level of taxation is difficult (Organisation for Economic Co-operation and Development, 2001).

THE LANDFILL TAX

Of particular relevance to this study is the Landfill Tax. The Landfill Tax was introduced in 1996 to provide an economic incentive for waste minimisation in all sectors and reduced use of landfill as a waste disposal option. The Tax was levied on licensed landfill operators and passed on to end users. In 1996 it was set at £10 per tonne of active waste and £2 per tonne for inert waste. In 1998 an escalator of £1 per tonne of active waste per year was introduced, which was increased in 2004 to £3 and again in 2008 to £8 per tonne of active waste per year. This is due to be reviewed again in 2011 when the tax per tonne of active waste will have reached £48. The tax on inert waste was increased to £2.50 per tonne in 2008. Following the same model used with the Climate Change Levy when the Landfill Tax was introduced employers' national insurance contributions were reduced by 0.2 per cent in addition 20 per cent of the tax revenue is used to support environmental schemes (Department for Environment, Food and Rural Affairs, 2002; Advisory Committee on Business & the Environment, 2001).

The Landfill Tax did not initially have the desired effect. In the 2001 report prepared by the Advisory Committee on Business & the Environment (ACBE) (2001) 'Resource productivity, waste minimisation and the Landfill Tax' the ACBE concluded that while the Landfill Tax had had some success at increasing the amount of inert waste recycled on site, it has had little success at reducing active waste and increasing recycling. The cost of waste disposal varies significantly and the 2001 cost of £19-£29 per tonne of mixed waste to landfill including collection & gate fee, still made it cheaper than composting (£42-£103) and incineration (£30-£40), and on a par with paper and board recycling (£19-£25). The report recommended a further increase of the tax in line with other European countries, which benefit from far higher recycling rates (Advisory Committee on Business & the Environment, 2001). A similar assessment was made by the Environment, Food and Rural Affairs Committee who described the tax as 'too small an incentive to change established behaviour significantly: it is little more than an irritant to those making provision for waste management' (2001, p. xlviii) and suggested a threshold of £25 per tonne to engender a change of attitudes.

The initial lack of success of the Landfill Tax was also attributed to other issues, in particular the lack of alternative options for disposing of waste. Composting is technically a viable alternative to landfilling waste including construction and demolition waste. This was identified as early as 1992, but with it came the realisation that facilities in the UK for commercial composting were inadequate (Department of the Environment, 1992). This continued to be the case and the 1999-2000 figures show the UK lagging behind other EU countries in respect of the use of composting as a waste disposal option even only at municipal level. A 2003 review highlighted a lack of progress in this field (Environment, Food and Rural Affairs Committee, 2003) and stated that for composting to be applied on a large scale to be able to deal with building waste a fundamental change in the government's approach to waste disposal would be necessary.

The difficulties in adopting alternative approaches to waste disposal are in sharp contrast to the ease of avoiding the need for plastic bags. If it is simple to adopt the non-taxed alternative route, individuals will take the alternative route even if the tax is relatively low. Where an additional effort and cost is required to avoid the tax, the balance between savings and effort is the determinant for action.

As expected, as the tax increased changes were recorded and in certain sectors of the economy the waste disposal habits changed. By 2003 thirteen per cent less of the commercial and industrial sector waste was going to landfill than in 1999; and more waste was being recovered than landfilled. Similar behavioural changes are expected as the landfill tax increases towards the target of £48 per tonne in 2010. Already in 2007 more waste recycling and energy from waste facilities were being planned and the number of merchant facilities to take waste from municipal and private sector were increasing (Department for Environment, Food and Rural Affairs, 2008).

If set to an effective level, the Landfill Tax could present a strong financial incentive for the construction industry, this is particularly the case in respect of those sections of the industry that suffer from low profit margins such as the housing industry. Taking into account that the total cost of waste includes, not only the disposal cost but also the purchase cost of the material wasted, its delivery, and the cost of handling it, reducing construction material wastage from 10 per cent to 5 per cent could save the house building industry £1400 per house unit (Building Research Establishment Centre for Resource Management, 2003; McGrath, 2000). Further increases in the landfill tax may well mean that it will become cheaper for organisations including those in the buildings industry to separate and recycle their waste than landfill it. If or perhaps when this occurs the aim of the tax can be said to have been achieved.

FINANCIAL INCENTIVES (CARROT)

Financial incentives represent encouraged change rather the forced change. They include economic grants and free provision of services. Free service provisions address environmental behaviour by offering sustainable solutions which require minimal effort from those who utilise them. Domestic waste recycling, subsidised public transport and free cycle schemes are examples of services that can act as incentives to adopt a more sustainable lifestyle, which reduces pollution and waste production. An example of a free cycle scheme can be found in Copenhagen's city centre. The scheme makes 2500 bicycles available between April and December. They can be taken at specific racks by leaving a returnable deposit and used within the centre for an unlimited time (Brophy, 2000).

The city of Freiburg, in Germany provides its residents with travel cards that give them access to the whole of the transport infrastructure in the Freiburg Region for a fixed price, which is lower than using a car. Visitors are given free travel cards at their hotels (Sassi, 2006). In the UK, an example of a service that reduces environmental impacts is the municipal recycling facilities and the curb collection of recyclables. In all these cases the service provider, often the local authority, carries the financial burden and the general public benefits from a free service.

Financial support in the UK for environmental initiatives is available mainly to reduce energy consumption and install renewable energy systems. Grants are available to individuals for energy saving measures and for the installation of selected renewable energy technologies. Companies can offset investments in energy efficiency and saving measures in the first tax year through the Enhanced Capital Allowance Scheme and can apply for zero interest loans for the same (Energy Saving Trust, n.d.). New financial subsidies are devised and existing ones amended or replaced regularly to respond to uptake and government finances available.

2.1.4 CONCLUSION ON SELECTING EFFECTIVE METHODS FOR IMPLEMENTATION

This section considered how changes in thought and attitude in relation to sustainability have evolved very slowly and change in society as a whole has followed suit at the same slow pace. Within this context one effective way to accelerate change is through economic pressure. Economic instruments, while requiring to be appropriately calibrated, have shown to be effective and have therefore gained the support of the European Environmental Agency and other non-governmental organisations. The experience with the Landfill Tax suggests that it is difficult to formulate a tax that is felt sufficiently to engender a specific change in behaviour, but it also suggests that achieving such a change is by no means impossible.

Furthermore, when a tax or a financial incentive is 'designed' optimally it can achieve the desired outcome and achieve it quickly. The challenge is not adopting the instrument in principle, but developing the instrument in detail. The gains experienced from abiding to new legislation or avoiding taxes on unsustainable practice by adopting sustainable approaches have to significantly offset the additional cost and effort associated with changing behaviour.

2.2 REVIEW OF SUSTAINABLE DESIGN GOOD PRACTICE PRINCIPLES AND ASSESSMENT SYSTEMS

The rest of this chapter narrows the focus of the study down to the building industry. It sketches the sustainable design context for this research by providing a review of the principles and practice of sustainable design in the building industry. An underlying consideration throughout this section is the potential for developing legislative instruments to encourage the adoption of good practice.

2.2.1 IDENTIFYING THEMES FOR SUSTAINABLE DESIGN STRATEGIES

The built environment is the concrete context within which social interactions occur. As such it has a significantly influence on the ability of individuals to adopt a sustainable lifestyle. Furthermore, the built environment in terms of the construction, use and disposal of buildings is associated with appreciable impacts on the natural environment. A Building Research Establishment 2000 review of the social, economic, environmental and resource implications of construction in the UK, 'Sustainable construction: The data.', (Howard, 2000) published the following UK statistics which effectively sketch out the relation between the building industry and the environment:

- Buildings are responsible for 50 per cent of primary energy consumption.
- Buildings account for 25 per cent of sulphur and nitrogen oxides emissions and 10 per cent of methane emissions.
- In 1997, the construction industry was responsible for 16 per cent of the water pollution incidents in England and Wales.
- Construction work on site is responsible for 4.7per cent of noise complaints.
- 6 tonnes of materials per person are used for construction.
- 30 million tonnes per year of excavated soil/clay waste are estimated to arise from construction site preparation.
- 30m tonnes of waste arise from demolition work each year.

These and similar statistics reinforce the notion that adopting sustainable practices should be a key aim for the building industry. In response to such evidence the UK Department of the Environment, Transport and the Regions published 'Building a better quality of life. A strategy for more sustainable construction' (Department of the Environment Transport and the Regions, 2000). This identified sustainability issues for the construction industry to consider and suggested sustainable approaches. This document complemented 'A Better Quality of Life: a strategy for sustainable development for the UK' (Department of the Environment Transport and the Regions, 1999), which marked the start of a monitoring and reporting process by the UK government of the progress made towards sustainable development in general.

'Building a better quality of life. A strategy for more sustainable construction' was followed by two briefing documents for the construction industry, 'Sustainable Construction Brief 2003' and 'Sustainable Construction Brief 2, 2004' (Department of Trade and Industry, 2003a;

2004). These identified the following objectives for the construction industry:

- 'design for minimum waste
- lean construction & minimise waste
- minimise energy in construction and use
- do not pollute
- preserve and enhance biodiversity
- conserve water resources
- respect people and local environment
- monitor & report, (i.e. use benchmarks)'

(Department of Trade and Industry, 2004, p.1)

The government documents that followed adopted a broader view that considered the procurement of buildings and provided more detailed guidance. The 'Sustainable construction strategy report 2006', published by the Department of Trade and Industry, (2006) includes business and economic consideration and describes a built environment that supports sustainable development as one that:

- 'minimises adverse impacts on the environment, during construction and in use, whilst enhancing the natural surroundings;
- maximises the positive contribution to business activity through the whole life of the building;
- helps to encourage productivity through being flexible for future use, building cost-efficiently and improving people's working environment;
- takes fully into account the impact of construction on the surrounding environment by seeking to maintain biodiversity within the location and avoiding any unnecessary pollution;
- wherever possible makes use of modern methods of construction to improve building efficiency and minimise environmental effects on construction sites.'

(Department of Trade and Industry, 2006, p.5)

The most recent 'Strategy for sustainable construction. June 2008' published by Department for Business, Enterprise & Regulatory Reform. Construction Sector Unit, (2008) sets targets, defined as the 'Ends', and suggests the 'Means' to achieve these. The 'Means' include outline objectives. The previous 2003 and 2004 briefing documents had only included general aims related mainly to environmental aspects of the construction, use and end of life disposal of buildings. Instead the 2008 strategy sets out measurable targets for 'Reducing total UK carbon dioxide emissions by at least 60 per cent on 1990 levels by 2050 and by at least 26 per cent by 2020' (Department for Business, Enterprise & Regulatory Reform. Construction Sector Unit, 2008, p.7); reducing water consumption to 130 litres per person per day by 2030; and reducing construction and demolition waste by 50 per cent by 2012 compared to 2008. In addition to formulating some measurable targets, the means for measuring them are provided.

The Department of Trade and Industry 2004 themes vaguely point towards the social aspects of architecture and the need for buildings to make a positive and appropriate contribution to the social environment they inhabit. The 2008 strategy only mentions people as part of their drive for educating the industry and suggests an interest in the general public where it states that '[t]he overall objective of good design is to ensure that buildings, infrastructure, public spaces and places are buildable, fit for purpose, resource efficient, sustainable, resilient, adaptable and attractive. Good design is synonymous with sustainable construction' (Department for Business, Enterprise & Regulatory Reform, 2008, p.7).

This greater emphasis on resource and waste issues is, as discussed in previous sections, the logical conclusion of a government seeking to engender good practice which can be legally enforced. It is perhaps understood that the environmental and the social aims are interlinked, no matter how energy- and water-efficient a building might be, it becomes a waste of resources and a potential detriment to the community if no one wants to occupy it. The way the community perceives their environment has an impact on the sustainability of the community: buildings which are loved become part of the community's own culture, have long lives and are economically sustainable. Sustainable buildings are ultimately those that can be an asset to the community for many years. The 2004 'respecting people' theme may well imply a responsibility to enhance the environment for the benefit of the community, which in turn would help improve their

Table 07 – **List of six sustainable design themes used to structure the analysis of the case study buildings and related design approaches.**

Sustainable design theme	**Sustainable design objectives**
Land use and the natural environment	Design for compact city centre living Reduce car dependency Enhance flora and fauna Facilitate local food production
Community and quality of life	Facilitate community participation Provide affordable living Promote training and employment Enhance community facilities Actively promote sustainability
Health and well-being	Avoid indoor air pollutants Avoid potential toxins Provide accessible environments Create restorative environment Consider electromagnetic fields
Energy use	Minimise heat loss and provide passive heating Provide passive and natural ventilation and cooling Maximise the provision of natural light Provide energy efficient services and equipment Provide performance assessment and monitoring Include renewable energy systems
Water use and disposal	Install water-efficient appliances Consider the use of waterless toilets Install grey or rainwater recycling Consider the use rainwater collection for all uses Consider installing alternative sewage system Provide sustainable external drainage
Material use and disposal	Design for longevity and flexibility Use of waste materials Use of renewable and certified materials Use materials with low manufacturing impact Minimise waste in construction Minimise waste in use

psychological and physical well-being. While not explicit, the 2008 strategy could be interpreted to include this same aim.

A review of the sustainable design context therefore needs to consider the environmental but also the social aspects associated with the building industry. The following sections outline what constitutes good sustainable design practice and where available means to assess it. Six sustainable design themes derived from government and other documents on sustainable design are structured in line with the development processes typically associated with the built environment, which begin by addressing site and land issues and community needs in relation to programmatic aspects of the development, then focus onto the building design and construction, which affect the building inhabitants' health as well as resource use (Table 07).

2.2.2 LAND USE AND THE NATURAL ENVIRONMENT

Physical space (land and sea) is considered by the Commission of the European Communities (2003) as a key resource. Society is both dependent on the way land is used and its sustainability can also be measured by its use of land. The way the built environment is configured and how the land is used affects how people live and, together with the resource implications of buildings, affect the environmental impact of each individual.

LAND USE AS A UNIT OF MEASURE

An individual's environmental impact can be measured by using the system of ecological footprinting developed by Rees and Wackernagel (1996) which effectively uses the earth's surface as unit of measure. According to Rees and Wackernagel an ecological footprint is the measure of the land and sea needed to sustain human activities in the long term, by providing food, water, energy, materials and assimilating waste. This concept of measure has been used to calculate the ecological footprint of individuals, specific activities, buildings, cities, countries and more. Using this system it was calculated that to sustain the average U.S. American lifestyle an area of 9.6 hectare of land is required. The typical European's ecological footprint ranges between 3 and 6 hectare and that of the average Indian is 1 hectare. The ecological footprint of the total population of the US is in excess of country's total land area. Even considering populations with low ecological footprints such as that of India, the mere number of inhabitants means that the ecological footprint for that whole country is 50 per cent larger than the country's productive land area. Today most cities and several countries have ecological footprints which are larger than the land available to them, including the UK with an ecological footprint three times its surface area. The ecological footprint of the planet is currently 30 per cent bigger than the available land worldwide (Chambers, 2000; Girardet, 1999, 1999a).

INCREASING PRESSURE ON A LIMITED RESOURCE

Rees and Wackernagel's calculations, as well as subsequent ecological footprinting calculations by others, illustrate the value of land. As the per capita consumption and the world population grow simultaneously, an increasing demand is put on the use of land to provide resources and assimilate waste. While improving technical efficiencies reduce the resource use necessary to provide specific services (von Weizsacker *et al.*, 1998), the assimilation of waste still largely relies on natural land-based processes. Reliance on dwindling land resources to assimilate an increasing amount of waste produced by a growing population is one of the reasons why waste production is seen as a more serious issue than resource depletion (Edwards and Du Plessis, 2001; Colombo, 2001; Smith *et al.*, 1998).

Land use within the confines of cities is of particular importance as most of the population growth world-wide is concentrated in urban areas. It is anticipated that 60 per cent of world population will be living in cities by 2030 (Girardet, 2004). In many developed countries already more than two thirds live in cities (World Bank, 2004). Even in high urbanised countries in Europe urban areas have expanded by 20 per cent in the last twenty years while the population has only increased 6 per cent (Commission of the European Communities, 2003); and in Britain such growth is transforming 6300 hectares of green space each year (Campaign to Protect Rural England, 2003). Such encroachment not only destroys the land's potential for providing useful services, but it also endangers biodiversity. Concerns regarding biodiversity often focus on equatorial regions with the highest numbers of different species (Wilson, 2002), however habitat loss occurs world wide. In the UK since 1945, 97 per cent of wildflower meadows, 98 per cent of peatland raised bogs, and 50 per cent of ancient woodlands, heaths, farmponds, fenland and coastal marshes have been cleared. 1,666 wild species in the UK are of environmental concern and 3,612 are endangered or rare. (Friends of the Earth, 1997)

Not only do built environment developments use land which in certain cases could otherwise be used as a source of resources or to absorb waste or simply as a space for wildlife; but also the configuration of those developments has repercussions on resource use. The configurations of settlements have been shown to affect the resource consumption and waste disposal of its inhabitants (Torrie, 1993; Newman, 1999).

ADDRESSING THE IMPACTS ASSOCIATED WITH LAND USE FOR THE BUILT ENVIRONMENT

To reduce both land and other resource use linked to land use two main strategies are advocated: firstly confined and controlled use of greenfield and indeed any land, and secondly, resource-efficient configuration of urban spaces. Lock (2000) concisely summarises the key design aims for cities that address land use, travel and quality of life to include:

- 'compact, medium to high density forms (but not high rise)
- mix of land uses based upon overlapping zones of living, working, leisure and shopping
- public transport oriented urban design
- pedestrian friendly streets
- well defined public spaces

- integration of development and nature on site
- development patterns dictated by walking or cycling distances'

(Lock, 2000, p.39)

These approaches are supported by research into the impact of city forms in particular that of the compact city. Cities that have a high density of persons per hectare and are supported by the provision of public transport effectively reduce car dependence and research shows a link between urban density and transport fuel consumption. A comparison of European, Australian and US cities shows the five main Australian cities with average densities of up to 30 persons per hectare consuming 30,000 to 45,000 MJ (MegaJoules) of transport fuel per year; US cities, which generally have similarly low densities, consuming between 40,000 and 80,000 MJ of fuel per year; while European cities with densities varying from 50 to 125 persons per hectare consuming between 10,000 and 22,000 MJ of fuel per year (Newman and Kenworthy, 1989). Rees and Wackernagel (1996) relate the advantages of sustainable transport to the land required to support different means of transport. Their comparison of a person cycling, taking the bus and driving to work shows the cyclist requiring less than half as much land as the person who takes the bus and less than ten times that required for driving. Whereby the land required for the cyclist is mainly for food production while the other two options relate to carbon sequestration.

Overall energy use per capita is also reduced in compact cities where energy efficient building forms, such as terraces or flats predominate. A comparison of per capita carbon dioxide emissions from US and European cities, on average proved to be 12.7 tonnes and 8.4 tonnes respectively (Torrie, 1993). The proximity of buildings not only reduces the amount of energy used, but also the extent and consequently the cost of infrastructure. District heating, for instance, becomes viable above densities of 40 dwellings per hectare. Other services such as recycling and community composting are also more economically viable at higher development densities. Compact developments not only reduce land use by virtue of their more intense use of land, they also reduce the need for land for roads connecting developments. Research in the USA has shown that, based on the same house sizes, dispersed low density developments can require twice as much road area as compact development and four times as much development land (Maurer, 1998).

In addition to improving resource use Lock acknowledges the need for quality. Public transport oriented designs, pedestrian friendly streets, well defined public spaces and the integration of nature in developments creates an environment that is desirable and ultimately more likely to house a cohesive community. A model development in respect of these latter points is the solarCity in Linz (Appendix Two).

ASSESSING GOOD PRACTICE TO REDUCE IMPACTS RELATED TO LAND USE FOR BUILT ENVIRONMENT

Assessing settlement designs for their ability to address sustainability can involve attempting to quantify an overall concept that is intangible. 'well defined public spaces' and 'pedestrian friendly streets' as advocated by Lock, may be possible to describe but difficult to measure. Significant effort is being invested in formulating indicators relating to aspects of land use that are difficult to objectify, however, not all principles of sustainable land use and design are intangible and not quantifiable. In particular the concepts of urban development density and that of developments based on walking distances are supported by quantifiable good practice. In order to understand the characteristics of effective assessment systems the assessment for development densities should be investigated.

As discussed above the potential for reductions in resource use as a result of increasing development densities is well understood and in the Planning Policy Statement 3 (Housing) the UK government has set out minimum housing development densities of 30 dwellings per hectare (DPH). (Communities and Local Government, 2006). While these are conservative requirements, particular in the light of recent developments that have

successfully increased densities to 80 and even 100 DPH, they are only possible because a unit of measure exists.

Table 08 - **Comparison of development densities using three different assessment methods.**

References: Newman, 1999; Barton, 2000 (2); Hall, 2001 (3); Campaign to Protect Rural England, 2003 (4).

Development examples	Density measured in dwellings per hectare (DPH)	Density measured in people per hectare (PPH)	Density measured in habitable rooms per hectare (HRH)	Comments
Broad acre, typical in areas of USA	2.5			
Garden City	15			
Average densities in rural England	22			
Average densities in UK 1997-2001 (4)	27	50-60		Supports a school/ post office
Minimum density in areas designated for development in the Netherlands	33			
Minimum target for development in England set by UK government Planning Policy Guidance note 3 (Housing)	30			
Older UK suburbs (3)	35-40			Supports combined heat and power and bus services/ 50 dph is maximum density to ensure good solar access in UK (2)
solarCity Linz including infrastructure	40	100		
Higher development densities encouraged by UK government Solarcity Linz	40-50	100		
New development in Harlow, east London	45-80			
Victorian terraces, Hertfordshire (3)	80			
9% of UK population live in densities of 85+ dph	85			
London Bloomsbury and Regents Park	100			
Greenwich Millennium Village with infrastructure	106			
The Point development in Bristol	114		400	500 pph = maximum recommended density, 1000pph is possible, but not advisable

As a unit of measure DPH is simple to use, but as with many systems of measurement it is not fail proof. A dwelling could be a studio flat or a five bedroom house. It provides no measure of the number of people in the dwelling. It is therefore recommended to use DPH in conjunction with other measurements as shown in Table 08. Even if three separate density calculations were required for each development, the strength of this assessment system remains its simplicity. A calculation of a development density is technically undemanding and the information required, number of dwelling and area of site, is readily available. This makes it possible for clients, designers, local authorities and others to undertake the same assessment and make it reasonably quickly. In other words, the combination of two factors, firstly that the cost and time requirements to make the assessment are minimal and secondly that the information required is available, facilitates widespread use of the assessment system.

2.2.3 SUSTAINABLE COMMUNITIES

If the built environment is the concrete context for human activity, communities form the abstract structure for human life. Communities can be defined by shared interests, activities or physical environment. The built environment represents a shared interest for the community that inhabits it and the concrete context and the abstract structure are interdependent. A community can be affected both positively and negatively by its environment and in turn the community influences the form of the built environment (Wedge and Prosser, 1973; Edwards, 2000; Barton, 2000).

CREATING SUSTAINABLE COMMUNITIES

The Department of Environment Trade and the Regions publication 'Our Towns and cities: the future. Delivering an urban renaissance' (2000b) summarises some of the characteristics of a sustainable community in their vision for a new urban living, which includes:

- 'people shaping the future of their own community, supported by strong and truly representative local leaders;
- people living in attractive well kept towns and cities which use spaces and buildings well;
- good design and planning which makes it practical to live in a more environmentally sustainable way, with less noise, pollution and traffic congestion;
- towns and cities able to create and share prosperity, investing to help all their citizens reach their full potential;
- good quality services - health, education, housing, transport, finance, shopping, leisure and protection from crime – that meet the needs of people and business wherever they are.'

(Department of Environment Trade and the Regions, 2000b, p.30)

The implication is that sustainable communities should provide for basic needs such as homes, health, education, employment, but also for an attractive and safe environment, a prosperous economy, good public services and open space to ensure a quality environment and ultimately a high quality of life. '[H]elp[ing] all their citizens reach their full potential' implies communities that are also inclusive and just, people have to be put first (Department of the Environment, Transport and the Regions, 2000b).

Furthermore, sustainable communities should be resource efficient and preferably resource autonomous, sourcing water, energy and materials as much as possible from the local environment. Sourcing products and services from the local community, within the socio-economic limitations of a global economy, is equally desirable.

Life within such a sustainable community would be different to what most people are currently accustomed to. A sustainable community with a more locally based life has to offer an alternative lifestyle which appears equally satisfying, if perhaps in different ways, to the one people are used to. Life within an active and safe community, offering access to culture, education, work, leisure and time for friends and family, presents a possible alternative with potential for lower environmental impacts. Vibrant communities can substitute material interactions with human interactions. Community interaction can offer personal fulfilment derived from the realisation of having developed as a person, having been able to help others, or simply having enjoyed the company or the contributions of other individuals. A personal investment in a community can not only help support the community but also be a source of satisfaction. Self-interest put ahead of communal goals can conversely disrupt communal harmony and as Smith *et al.* suggest 'be considered irrational and ultimately self-harming.'(1998, p.171).

Putting communal interests first may be encouraged by engendering a feeling of communal ownership. According to Girardet (1999), a feeling of communal ownership and direct involvement are essential parts of a holistic process towards sustainable development. The 'inclusive, participatory and democratic' (Smith *et al.,* 1998, p.171) characteristics of sustainable communities are also vital to their resilience, and quality of life is vital to its permanence; resilience and permanence being key elements of sustainable communities.

The built environment as the context for sustainable communities has a distinct role to play in achieving the above aims. According to Barton (2000), the built environment context to support a desirable and sustainable community encompasses a place that engenders a feeling of belonging, an attractive and healthy place within a convivial community, a safe place that is pollution-free, uncongested, planted, less frenetic and offers a more locally based life with a balance of privacy and community interaction.

Changes in attitudes, lifestyles and processes are clearly pivotal in achieving sustainable communities, and the built environment can help support these changes and implement some such processes, examples of which include community consultations and participation in building projects. The concrete built environment can also provide opportunities to adopt a sustainable life style, however, by turning on its head Edwards' (2000) positive remark in this respect, which suggests that '[l]ifestyle change cannot be imposed, but it can be encouraged by good design'; it also becomes clear that while it is important to encourage change, encouraging on its own has limited powers of persuasion. The potential for the built environment to create sustainable communities is therefore limited.

ASSESSING SUSTAINABLE COMMUNITIES

Communities are complex entities with numerous variables, which have to be assessed within their social and physical context. As opposed to the sustainable use of energy and water which will be discussed later, an easily measured and comprehensive set of criteria for what constitutes a sustainable community has not been agreed. The complexity and the lack of consensus on definition mean that assessing communities for their sustainability compliance is difficult if not impossible.

In the 1999 the UK government formulated a set of headline and core indicators to be used to report on progress towards a more sustainable society. These replaced indicators formulated in 1996 for sustainable development (Department of the Environment Transport and the Regions, 1999). The indicators have been revised regularly (Department of the Environment Transport and the Regions, 2003; 2004; 2007; 2008) and by 2008 68 indicators relevant to four themes one of which is sustainable communities had been established. Table 09 lists the indicators that are considered to be relevant to sustainable communities and their relation to the built environment.

The indicators adopted have to be measurable and make use of data available from local authorities and statistics agencies, and this limits what can be included in the assessment. Assessing aspects such as 'feeling of belonging', 'community interaction' or whether or not a community is 'frenetic' is somewhat subjective and not part of the assessment. Yet some of the less concrete aspects of communities are vital in terms of their sustainability. Furthermore, some of the indicators are symptoms rather than causes. For instance, while development density is a 'cause' of how much land is used, homelessness is a symptom of lack of housing,

Table 09 – **List of sustainable development indicators published by the Department of the Environment Transport and the Regions (2008) that are considered to be relevant to sustainable communities and their relation to the built environment.**

Heading	Indicators	Relation to the built environment
Society	37. Active community participation 38. Crime 39. Fear of crime	Limited to consultations and designing to prevent crime
Employment and poverty	40. Employment 41. Workless households 42. Economically inactive 43. Childhood poverty 44. Young adults 45. Pensioner poverty 46. Pension provision	None to limited by encouraging the use of local labour
Education	47. Education 48. Sustainable development education	Limited to demonstration
Health	49. Health inequality 50. Healthy life expectancy 51. Mortality rates 52. Smoking 53. Childhood obesity 54. Diet	Indirectly by providing environments that support an active and healthy lifestyle
Mobility and access	55. Mobility 56. Getting to school 57. Accessibility 58. Road accidents	Direct relation to settlement design
Housing	25. Land recycling 26. Dwelling density 62. Housing conditions 63. Households living in fuel poverty 64. Homelessness	Direct relation to housing and building design in general
Social justice and environmental equality	59. Social Justice 60. Environmental equality 61. Air quality and health 65. Local environment quality 66. Satisfaction in local area 67. UK international assistance 68. Wellbeing	Indirect relation to settlement and building design
Contextual	32. Economic output 33. Productivity 34. Investment 35. Demography 36. Households and dwellings	Limited and indirect

employment as well as other social problems. Therefore some indicators can be directly related to a policy or measure, while others can only be indirectly related to several policies, measures and social aspects.

Due to the above mentioned issues, the indicator system is weak as a means of setting targets or imposing standards. Furthermore, the targets relate to the status quo rather than being aspirational and ultimately do not acknowledge the need for a step change to achieve sustainability. As a means to provide and communicate an overview of progress may be successful, however without well considered targets, progress could be mistaken for good practice which in may cases it is not.

The indicators suggest a number of issues of interest when considering assessment system in general. Primarily it is difficult to assess changes that are affected by several variables as well as intangible phenomena, and consequently it is also difficult to relate such changes and phenomena to useful guidance, which could in turn form part of legislative measures. The complexity of the measurement process could be said to be inversely related to its ability to be translated in targets and legislation. Simplicity is advantageous in this respect.

Some of the case studies analysed (for instance Fairfield Housing Estate in Appendix Two) attempted to assess the success of the community aspects of the project in a simple manner. Measures adopted include the number of people applying to live in a refurbished housing estate, the number of young residents staying in education, and the feedback from residents on their sense of satisfaction.

Where an assessment involves so many aspects that the evaluation process becomes cumbersome, it may be necessary to prioritise what is evaluated. A selection has to be made to determine what data would be most helpful in providing a reliable overall assessment and the data considered useful but not vital is omitted. A balance between the extent and detail of an evaluation versus a complexity that makes it unworkable has to be struck to develop an assessment system that is reliable but also user-friendly.

2.2.4 HEALTH AND WELL-BEING

Seventy per cent of deaths world wide are related, not to infectious and parasitic disease, but to environmentally and socially linked aspects of life (World Health Organization, 2003). The World Health Organization describes environmental health as comprising 'those aspects of human health, disease, and injury that are determined or influenced by factors in the environment. This includes not only the study of the direct pathological effects of various chemical, physical, and biological agents, but also the effects on health of the broad physical and social environment, which includes housing, urban development, land-use and transportation, industry, and agriculture.' (World Health Organization, 1997).

This definition recognises that the character of an environment can determine and influence lifestyle choices, the proximity of individuals to pollution, the potential for contact with viruses and bacteria, the opportunities for social interaction, the sense of self-worth of individuals, and much more: all which affect human well-being.

The UK Government's White Paper on health issued in 1999 identifies four main health issues of current concern: mental health, accidents, cardiovascular related illness and cancer (Department of Health, 1999). These illnesses are linked to lifestyle and environmental health issues, and can often be prevented. Among the UK government's initiatives to address the causes of these illnesses was the introduction of healthy living centres that focus on preventing ill-health by encouraging healthier lifestyles through education, physical exercise, counselling, drug prevention programmes, stress management, child and parent support, dietary advice, gardening and other community activities. In certain cases improving personal health may not be in the power of an individual. Other aspects of life, such as poverty, social exclusion, lack of employment and education, and poor housing have been recognised as having a significant impact on human health (Molyneux, 2001; Department of Health, 1999).

Nonetheless, when many individuals suffer from the same problems, such as cardiovascular disease or depression, the cause for their ill-health is unlikely to be only personal, and may also be linked to the built environment they inhabit (Jackson, 2003). The design of the built environment, both internal and external and personal and public, can affect an individual's health.

HEALTH AND WELL-BEING AND THE BUILT ENVIRONMENT

While political initiatives are necessary to tackle many of the health-related aspects of life, the design of the built environment has the potential to provide healthy environments and support the implementation of a healthier lifestyle. For instance, building projects can help address social exclusion, which can be linked to mental ill-health; creating environments that encourage walking and cycling helps address inactive lifestyles associated with cardiovascular health problems; integrating green spaces in cities provides both amenity spaces and encourages healthier life styles. According to Srinivasan, O'Fallon and Dearry (2003) many aspects of sustainable communities and buildings are thought to contribute to good health and well-being.

The way in which the built environment impacts on human health can be categorised into four groups.

- The provision of healthy indoor environments.

Buildings can affect health by the way they are designed in relation to ensuring sufficient natural light, good indoor air quality, sufficient protection from noise, a thermally comfortable environment and an environment that has a healthy relative humidity that does not support mould growth or dust mites, and an environment that avoids bringing the building inhabitants in contact with toxins and other health hazards.

- Means to encourage a physically healthy lifestyle.

Built environment facilities can be designed to encourage people to adopt healthy living habits such as cycling and walking and spending time outdoors undertaking sports activities or playing or relaxing or working in allotments.

- Approaches to address mental health.

The built environment can positively contribute to mental health by providing restful places and those in contact with nature to reduce stress; spaces that enable disadvantaged individuals to be independent; places that feel safe and that provide the occupants with a feeling of ownership and belonging; places that would allow individuals to grow old comfortably and without disruption; and places designed with care which show consideration for the occupants to avoid stress and resentment.

- Approaches to help address social causes of deprivation.

The construction process provides opportunities for training and education, which in turn can create opportunities for employment. Housing designs can ensure low running cost, that help reduce the limitations of poverty.

ASSESSING THE IMPACT OF THE BUILT ENVIRONMENT ON HEALTH AND WELL-BEING

Assessment approaches in respect of issues affecting health and well-being highlight another effective barrier to creating realistic assessment systems, namely people themselves. For instance, the requirement for thermal comfort and noise protection are dealt with very differently. Providing adequate noise protection within dwellings is a legally binding requirement of the Building Regulations. The construction has to either prove equivalence to certified construction details or, and in certain cases also, has to be tested in situ. Thermal comfort on the other hand is not addressed by any legislation, neither as part of the Building Regulations nor as part of landlord's requirements, yet inadequately heated houses are associated with tens of thousands of additional deaths in winter compared with the yearly average, primarily due to cardiovascular and respiratory disease (Wilkinson *et al.*, 2000). In 2002, 24,000 additional deaths were recorded and, of these, over 21,000 were people over the age of 65, who are likely to be less physically aware of their environment, including constant low indoor temperatures (Thakrar, 2003). However serious the potential outcomes are, certain activities cannot be legislated against or imposed. Whether someone chooses or can afford to heat a space adequately is impossible to dictate. In other words an assessment is only useful in achieving a specific aim if the relevant standard can be implemented.

Another aspect of setting targets or legislation in respect of health-related issues is the significance of evidence. For instance, in respect of indoor air quality there is a research pointing to a rise in indoor air pollutants resulting from the increased use of new and untested materials installed in buildings designed to be increasingly airtight and mechanically ventilated. Indoor air pollution, the sources of which are both internal, including building materials, equipment and consumables, and external, including traffic pollution, radon and pollen, can be as much as ten times more polluted than outside air (Wolverton, 1997; Coward *et al.*, 2001). Research in the field of health and indoor air pollution has made links between volatile organic compounds and asthma and sick building syndrome, and recommendations by the medical profession on how to improve indoor air quality do exist and unequivocally require the removal of the pollution sources (Institute of Medicine, 2000). Nonetheless, since there is no evidence of serious health impacts, such as death, associated with poor air quality it remains uncontrolled by legislation. When evidence does eventually emerge, especially if associated with fatalities as with asbestos and lead paints, legislation is introduced and often involves an outright ban. To introduce in an industry new standards and legislation the drivers need to be convincing and strong.

2.2.5 ENERGY USE

The environmental issues associated with energy use are currently considered the most pressing issues that need to be addressed globally. The international scientific community overwhelmingly supports the view that global warming is the result of human activities, in particular the carbon dioxide emissions from burning of fossil fuel to provide energy, and that its effects will be both of great financial and human cost. It has also become clear that global warming is taking place at a faster rate than previously believed. It is therefore necessary to address energy use, worldwide, as a priority (Stern, 2007; Intergovernmental Panel on Climate Change 2007c).

Half of the global warming effect is due to carbon dioxide. Levels of carbon dioxide began to sharply rise during the industrial development, when carbon dioxide levels were between 200-275 ppmv and have continued to rise reaching levels of 316ppmv, in the 1950s, 375ppmv in the early 2000s and continue to rise at 2ppm per year. The European Union members have agreed to aim to prevent concentrations from exceeding 550 ppm, which would limit the rise in temperature to no more than 2°C above the pre-industrial levels (Department of Trade and Industry, 2003). One of the concerns is that increases above a certain level will result in a self-perpetuating process, where rises in temperature, due to global warming, reduce the ability of natural sinks such as the oceans and plants to absorb carbon dioxide. This, in turn, further increase carbon dioxide levels in the atmosphere which further exacerbate global warming and further reduces carbon dioxide sinks.

The impact of climate change can be seen already, and has been the cause of significant human and financial costs. In the UK, in last five years storm and flood losses have totalled £6billion, twice as much as the previous five years (Friends of the Earth, 2004), and the floods in the autumn of 2000 cost £1billion (Department of Trade and Industry, 2003). In 2003, 14,800 people died in France from the effects of a heat wave, where temperatures repeatedly rose over 40°C (Worldwatch, 2004) and fatalities have also occurred as a result of flooding, storms and other extreme weather events. More widespread and frequent heat waves, violent storms, forest fires, droughts, and flooding are to be expected as global warming increases. In the UK, rising sea levels, shifting rain patterns, and associated storm conditions are expected to have the biggest impact. Rainfall is expected to increase up to 35 per cent in winter and decrease in summer by up to 35 per cent. The reduced summer rainfall combined with increases in summer temperatures, of up to 3°C, will increase the incidence of water shortages and affect the need for agricultural irrigations (Holman *et al.*, 2002).

ENERGY USE AND BUILDINGS

In the UK, operating buildings is responsible for 45 per cent of all carbon dioxide emissions (Department of Trade and Industry, 2006) and construction processes for 10 per cent (Rao *et al.*, 2000). To minimise the environmental impact of energy use a three stage approach is required. The first stage involves analysing how energy is used in buildings and minimising these energy requirements by implementing passive design strategies and building fabric solutions. Secondly, services systems should be selected that use energy in an efficient way. These two approaches alone can significantly reduce carbon dioxide emissions as stated in the Third Assessment Report of the International Panel for Climate Change, which estimated that a 30 per cent reduction in projected increases of carbon dioxide emissions could be achieved by 2020, and 60 per cent of these reductions could be achieved through more efficient appliances and increased insulation (International Panel for Climate Change, 2001).

Thirdly, the energy requirements, which have been reduced as a result of the previous two approaches, should be provided by alternative, low carbon dioxide emitting energy sources. By first minimising the energy requirements, the use of renewable energy to provide the, very much reduced amount of energy, becomes feasible. Carbon dioxide emissions neutral designs are both desirable and achievable.

ASSESSING ENERGY USE IN BUILDINGS

As opposed to the tentative guidance for sustainable settlements, the aim in respect of energy use is very clear and requires energy consumption and carbon dioxide emissions to be reduced as much as possible and if possible to zero. The legally binding standards set by the Building Regulations are far from achieving this ideal, but some voluntary standards ultimately aspiring to the zero carbon dioxide emissions ideal have formulated achievable and stringent targets.

Among these standards are the German Passivhaus standard, widely adopted in Germany and Austria, the Swiss standard Minergie and the AECB Gold Standard in the UK. The latter of these was based on the Passivhaus standard and has not yet been achieved in practice, while the German and Swiss standards have a significant uptake.

The Passivhaus standard, the oldest of these standards, has been in operation since 1996 and sets targets for heating energy and overall energy use of building. Originally developed for housing, the standard has also been used for other building types. Passivhaus buildings exist in many countries, but in Germany alone the number of buildings constructed to Passivhaus standards is expected to rise to 137,000 by 2010 (Institut für Baubiologie Österreich, 2004). Freiburg is just one of many German cities where both residential and commercial buildings designed to Passivhaus standards can be found (Appendix Two). These buildings are, as the name suggests, passive solar, but typically make use of some 'active' technology such as: mechanical ventilation with heat recovery, photovoltaic panels and solar thermal. The construction systems range from timber frame to concrete with external insulation, and the completed buildings show that the standard does not restrict design freedom. The Passivhaus aims are to provide a comfortable environment without auxiliary heating and supply all energy requirements by alternative energy forms.

The standard (Feist *et al.*, 2004) recommends the following design approach and specification.

- The building envelope should be compact and well insulated with U-value of less than 0.15 W/m^2K and minimal cold bridging.
- U-values of windows including glass and frame should not exceed 0.8W/m^2K
- Living spaces and maximum glazing should face south, and overshadowing should be minimised in winter while maintaining the option of shading in summer.
- Fresh air entering the building should be passively pre-heated (e.g. through earth ducts).
- Mechanical ventilation with heat recovery with over 80per cent efficiency should be used.
- Water should be heated through alternative heat sources such as solar panels and heat pumps.
- Energy efficient appliances should be used.

However, the actual requirements to comply with the standard are only three.

- The maximum heating requirement is 15 kWh/m^2a.
- The maximum total primary energy requirement is 120kWh/m^2a.
- The building envelope should provide a maximum 0.6 air changes per hour at 50 pascals.

From a construction point of view achieving the level of insulation may increase building costs, and achieving the levels of airtightness may require increased attention and time on site, nonetheless the standard has a simplicity and allows a freedom of implementation that explains its popularity. It can be considered a model of a standard.

This is in sharp contrast to complexity of the energy performance assessment included in the Code for Sustainable Homes (Department for Communities and Local Government, 2007) that, among other things, requires a new house design to achieve a percentage improvement compared to the energy performance of a design which has the same building fabric configuration but a more basic fabric specification. This approach that indirectly attempts to impose a reduction in carbon dioxide emission has not only been criticised for its complexity, but also for the fact that it does not encourage good practice in terms of passive design measures, gives preference to specific types of energy sources that do not necessarily result in lower carbon dioxide emissions (May, 2008), and is, despite its complexity, not able to account for some of the most advanced systems appropriate for ultra-low energy homes, such as mechanical ventilation with heat recovery which is only used in winter. The complexity of this assessment has failed to achieve a system that strictly encourages the ultimate aim of reducing carbon dioxide emissions. The attempt to take into account peripheral aspects associated with the design of houses, in particular the house design configuration, has introduced variables which have proved difficult to control. On the other hand, the direct approach adopted by the PassivHaus standard, which measures exactly what is being attempted to reduce, is easier to apply and more accurate.

2.2.6 WATER USE AND DISPOSAL

Water is a fundamental necessity for humans and other living beings, yet human activities are endangering the availability of water suitable for human consumption, increasing levels of pollution in watercourses and disrupting the natural water cycle. These effects combined result in significant environmental damage and human suffering. The built environment has a role to play in reducing some of these environmental and social impacts.

While water is plentiful on the planet, 97.25 per cent is contained in salty seas and not directly fit for human consumption. Of the rest, 2.05 per cent is contained in glacial icecaps, 0.7 per cent in aquifers, and 0.008 per cent is available through rainfall on watershed areas for consumption by humans (Postel, 1997; Mackenzie, 1998). To satisfy basic water needs, estimates of up to 700 cubic metres of fresh water per capita per year have been suggested (Postel, 1997). Since in order to maintain a stable ecosystem only 30-50 per cent of available surface freshwater should be extracted, it follows that availabilities of less than 1700 cubic metres of fresh water per capita constitute water stress (Perkins, 2002). Current estimates of people living in water-stressed areas range from 430 million to 733 million and this figure is expected to rise to between 2.4 and 3.4 billion people by 2025 with growing population and per capita water consumption (United Nations Population Fund, 2004; Postel, 1997). There are also 1.1 billion people without adequate access to clean water, defined as 20ltrs per person available less than 1 kilometre away from their dwelling; 2.4 billion without adequate sanitation (Worldwatch Institute, 2003); and 2.0 million people, of which 90 per cent are children, dying from diarrhoeal diseases transmitted through inadequately clean water (World Health Organisation, 2003a)

The use of ground water rather than rainfall and surface water is increasing, but this too has significant environmental impacts. Extracting excessive amounts of ground water can reduce the water table levels, which in extreme cases can cause subsidence, while in coastal regions over-extracting from aquifers can result in their contamination with salt water, which can subsequently cause land salination and affect agriculture (Goudie, 2000). In addition, replenishing ground water reserves takes hundreds even thousands of years and some aquifers are becoming depleted, for example in the UK, in the Anglia, Severn and Trent, Thames Valley, and Southern regions and in the North China Plain, where the level of ground water is dropping at 1-1.5 metre per year (Worldwatch Institute, 2004). Another alternative source of fresh water is desalinated seawater. With costs of desalination dropping to $0.54-3.50 per cubic metre of water, compared to $0.11 for conventional treatment in the US, desalination is becoming a potential source of fresh water for the future; however desalination is very energy intensive and over-reliance on it would aggravate the climate change impacts (Joynt and Poe, 2003).

Water sources and water environments are also being increasingly polluted. Sources of water pollution include urbanisation, contaminated land, industrial processes, mining, fire, agricultural fertilisers, pesticides and soil particles, sewage, and domestic chemicals. Agriculture is a major pollutant of water courses, with fertilisers containing nitrates and phosphates causing eutrophication of watercourses. Sewage also contributes to eutrophication through nitrates and phosphates from metabolic processes and from detergents. Eutrophication, a process where water bodies receive surplus nutrients that stimulate excessive plant growth of seas, can cause excessive algae growth in estuaries, which can prove toxic to marine life (Goudie, 2000). Sewage also contains pesticides and metal pollutants, such as nickel, copper, lead, and zinc, which derive from water pipework, cosmetics, cleaning fluids, and medicines (Environment Agency, 1998). Industrial processes, as well as landfill sites, are responsible for metal pollution which are harmful to human health and to aquatic life. Industrial and agricultural processes also contribute persistent synthetic organic pollutants (POPs), which are assimilated and increase in concentration as they are transferred up the food chain. POPs have been linked to cancer, allergies and hypersensitivity, endocrine, nervous system and liver damage, reproductive disorders and disruption of the immune system. Stormwater runoff in urban areas can contain rubbish, vehicle liquids, industrial processes, garden chemicals and animal excrement (Goudie, 2000).

WATER AND BUILDINGS

Building design can contribute to alleviating water related environmental impacts mainly in four main ways. First, the need for fresh water can be reduced by installing water efficient appliances in buildings. Secondly, sources of water other than mains water, such as rainwater and greywater, can be used where appropriate. Thirdly, black and grey water can be recycled and or treated on site, or avoided altogether by installing waterless systems in order to reduce environmental impacts associated with waste water treatment. Fourthly, rainwater can be disposed of on site, reducing pressure on stormwater systems and the environmental impacts associated their inability to cope with storm events and flash floods.

Buildings that combine all four approaches could achieve water and waste water autonomy. This implies the provision of fresh water independent from mains supply and on-site sewage and stormwater treatment and disposal, obviating the need for a sewer connection. A number of buildings have successfully implemented such a strategy. Notable examples include two residential developments in Nottinghamshire by Brenda and Robert Vale (Appendix Two).

ASSESSING WATER USE AND DISPOSAL IN BUILDINGS

The Code for Sustainable Homes (Code) sets targets for water consumption. To achieve a Code levels three or four the water consumption per person per day must be 105 litres or less, and for levels five and six it must be 80 litres or less. This could be verified post-occupancy but the Code does not require this. The assessment is made based on assumptions of use and technical data relating to the sanitary appliances (Department for Communities and Local Government, 2007).

The assessment is relatively simple and easy to undertake, which should encourage its use, even perhaps if a full Code assessment is not undertaken. On the negative side, it is based on assumptions of use that in reality will vary depending on the occupants' habits. For instance how many times the kitchen sink is used depends on personal, even cultural, habits and preferences. Therefore, even if an efficient tap is installed, how often it is used and how long for is going to affect the overall use as much or even more than the selection of the tap itself.

The assessment does not take such human variables into account and this is its main weakness. It essentially only considers one of two variables, the installation, and disregards the second variable, user of the installation. Whether an assessment system that only takes into account 50 per cent of the variables that affect the outcome can be considered sound is debatable. The assessment's limitation is that it has to make use of measurements that are available at the time of making the assessment, which takes place at design stage, and these cannot assess the user's real actions. It does not have the data to measure actual use and can only measure the potential consumption.

A system that only measures potential for good practice may appear to have limited scope, but in certain instances this may be the only practical option. Furthermore a system that maximises potential is not without merit simply because it does not ensure good practice. Additional other measures, including financial and educational, may be necessary to take advantage of that potential, but without creating the potential the other measures alone would also probably fail to achieve the desired effect.

An assessment system can contribute to improving performance by working as one of a number of measures that have to work together.

2.2.7 MATERIALS

As suggested in Section 2.2.2 any consumer good has its own ecological footprint and this includes building materials. Materials, their resourcing, manufacture, transport, installation, maintenance and disposal are associated with environmental impacts of varying nature and gravity. The building industry is associated with 50 per cent of the material consumption and over 50 per cent of the waste production (Anink *et al.*, 1996).

This section follows the structure of previous sections but provides a little more detailed information, since materials are the focus of this research. It begins by outlining the environmental impacts associated with materials, then points to three examples of good practice in respect of sustainable material design and finishes by discussing a sustainable material assessment system developed in the UK.

2.2.7.1 ENVIRONMENTAL IMPACTS OF BUILDING MATERIALS

This section outlines some of the main environmental impacts associated with material in the building industry. It considers the resourcing, manufacturing and energy requirements to produce materials for the industry, and the impacts associated with materials once installed in buildings. The impacts associated with the disposal of building materials will be discussed in Chapter Three.

RESOURCING BUILDING MATERIALS AND ASSOCIATED ENVIRONMENTAL IMPACTS

Building products are derived from natural materials that are harvested or extracted and then processed. A fundamental environmental risk associated with material use is that of depleting resources. Resource scarcity inflates purchase prices and a total depletion of resources requires developing or using alternatives which are also often more costly (Heinberg, 2003). The ethical implications of resource depletion should also be considered but this is outside the scope of this research.

Materials are usually classified as renewable and non-renewable materials. Non-renewable materials include those with generation processes lasting millennia (e.g. stone, coal, oil, metal ores) and renewable materials include those with regeneration cycles of decades or less (e.g. timber, flax, hemp, cork). Materials can be plentiful or scarce: sand is considered to be a plentiful resource, while oil reserves are limited and are estimated to last anything between 30 and 60 years depending on consumption rates and finding new reserves (Meadows *et al.*, 1992; Worldwatch Institute, 2004). Renewable resources are generally considered plentiful. However, if a renewable material is overharvested it may become scarce and ultimately even depleted, cork and timber being relevant examples. The bark of cork trees can be harvested every 8 to 15 years. While more frequent harvesting would not necessarily deplete the resource indefinitely as the trees would regenerate within a decade, it is likely to endanger the cork industry by creating a revenue gap of several years, which in extreme cases could result in the replacement of cork oaks with another crop. In respect of other renewable resources, such as timber, overharvesting could temporarily deplete the resource and in extreme cases cause it to become extinct.

Apart from the amount of resource available, the extraction or harvesting process itself can affect the surrounding environment and can be associated with pollution, the destruction of natural habitats and the reduction of biodiversity (Goudie, 2000). The effects of small scale quarrying or mining on the local ecology can and often are restored, as with clay or sand pits restored to wetlands. Large scale mining, on the other hand, can cause more permanent changes: mining of bauxite strip to produce aluminium is associated with flooding of valleys to produce hydroelectric power schemes, causing loss of rainforest habitat and consequently the loss of biodiversity. Pollution of water, soil and air can also be a consequence of material extraction: the extraction of oil is associated with air pollution from flaring and marine or groundwater pollution from oil leaks and spills (Ethical Consumer Research Association, 1995, 1995a).

MANUFACTURING BUILDING MATERIALS AND ASSOCIATED ENVIRONMENTAL IMPACTS

Materials are rarely used in their completely natural state. Some preparation or manufacturing is generally necessary to create a usable building product. The impacts associated with manufacturing can include pollution to air, water and ground. Manufacturing also generally requires energy, which is mainly derived from fossil fuel and is associated with global warming and pollution.

At one end of the environmental impact scale there are classified as 'natural'. These are materials that are found in nature (e.g timber or stone) and that require minimal processing before use. A material with such minimal manufacturing impacts is the adobe brick made with earth and water and dried in the sun, a process that makes use of a plentiful naturally occurring material, uses manual labour and the sun's heat rather than burning fossil fuels and consequently produces virtually no pollution or waste (Keefe, 2005).

At the other end of the scale there are highly manufactured materials such as metals and plastics. The metal smelting industries and the chemical industry are the two of the most polluting industries in terms of total emissions of toxins to the environment, including pollution of the air, land and water. The production of polyvinylchloride, a plastic commonly found in the building industry, is associated with emissions of organochlorides, dioxins, furans, ethylene dichloride, vinyl chloride monomers and mercury pollution resulting from the production of chlorine (Smith *et al.*, 1997; Woolley *et al.*, 1997, 2000; Greenpeace, 1997, 1998).

ENERGY AND BUILDING MATERIALS

Unlike the example of the adobe construction, most building materials require energy for extraction and manufacture. Energy is also required to transport the material to site, maintain it and finally dispose of it. The total energy used to produce building materials including transport to site is known as the embodied energy. This will be further discussed in section

3.3.1. Energy is still mainly produced by burning fossil fuels and is therefore associated with global warming and pollution. A significant reduction in the building's total embodied energy can be made by reducing transport requirements. The transportation of materials to the building site is generally by road and is associated with carbon dioxide emission and air pollution. Smith *et al.* (1997) suggest that buildings constructed and materials sourced locally can reduce the total environmental impact by a factor of 3.5.

In addition to the embodied energy as a source of carbon dioxide emissions, carbon dioxide can result from chemical reactions, such as those involved in the manufacture of cement. More than half of the carbon dioxide emissions associated with cement result from the chemical process and rest from the energy used for manufacturing (Howard, 2000). The cement industry is associated with 8 per cent of the global carbon dioxide emissions.

BUILDING MATERIALS IN USE

During the life of a building, building alterations, upgradings and maintenance require both energy and materials and are associated with impacts similar to those associated with the construction of buildings albeit at a smaller scale. Materials can also affect the building users in terms of health, in particular due to their impact on the indoor air quality.

DISPOSAL OF BUILDING MATERIALS

At the end of a building's life, its constituent materials have to be disposed of. The environmental impacts associated with such disposal, that relies primarily on landfilling and secondly on incineration as means of disposal, are associated with land use, toxic materials leaching into groundwater, emissions of explosive gas, structural instability and pollution to air. The UK construction industry is annually responsible for 90 million tonnes of inert construction waste, 15–20 million tonnes of non-inert and mixed waste, 60 million tonnes of waste arising from construction-related quarrying and 1.7 million tonnes of hazardous waste, which represents 32 per cent of all hazardous waste produced in England (Department for Environment, Food and Rural Affairs, 2007, Annex C3). The environmental impacts associated with waste will be discussed in Chapter Three.

2.2.7.2 ACHIEVING GOOD PRACTICE IN RELATION TO MATERIAL DESIGN

The field study of sustainable good practice case studies identified a number of approaches adopted to minimise the environmental impact associated with material use in construction (Sassi, 2006). None of the building designers used a formal system of targets as, until recently formalised targets did not exist. The design and material specification approaches adopted for the design and construction of these buildings are based on guidance documents and the ultimate wish to reduce the impacts associated with the resourcing, manufacturing, transport, use and disposal of materials.

However, the focus and to a degree the terminology differs from the earlier to the more recent project. For instance, today's focus on carbon dioxide emissions associated with materials is a more precise interpretation of the older concept of embodied energy. It is more precise because it focuses on the cause of environmental damage, the carbon dioxide emissions, rather than the typical but by not inevitable source of carbon dioxide gas, namely energy production; and also because it acknowledges the production of carbon dioxide from sources other than energy production (e.g. the chemical reaction that forms cement). Certain issues have only gained widespread attention in recent times and the older projects have omitted to consider them. A case in point is waste minimisation.

Some of the most commonly adopted approaches include using renewable resources, primarily wood products, and using recycled materials. Also relatively widespread were attempts to address indoor air pollution and energy use, either through the use of low embodied energy materials or through the use of local materials. Less common were approaches aimed at reducing the amount of material used and the waste produced during construction and at the end of the building's life. Table 10 lists the sixty case study buildings and the sustainable material design approached taken in each case, and the next two sections outline three case studies, one which attempts to adopt a comprehensive approach to sustainable material design and the other two that attempt, to some degree, to reduce the waste impacts associated with the disposal of a building.

COMPREHENSIVELY ADDRESSING SUSTAINABLE MATERIAL DESIGN

An example of a project designed to comprehensively address the material resourcing and manufacturing impacts is the Phillip Merrill Environmental Centre situated on Chesapeake Bay south of Annapolis, USA. The building houses the headquarters for the Chesapeake Bay Foundation, a 35-year old organisation with more than 115,000 members, whose mission is to restore and protect Chesapeake Bay's ecosystem and resources, currently threatened by habitat destruction and increasing pollution. The centre, which is sited in one of the Foundation's restoration projects, was therefore to be a model of sustainable construction and is designed to be energy and water efficient, provide a healthy interior environment and make use of sustainable materials.

The building design and material specification addresses the environmental impacts associated with resourcing and manufacturing of building materials and components. The amount of material used to build was minimised by exposing the structure and avoiding unnecessary design features. Renewable materials, such as cork, timber and bamboo flooring, were used. Many materials made from recycled products were used including: parallel strand lumber beams made of small timber sections, roof and cladding materials made of galvanised recycled steel, acoustic tiles made of 78 per cent recycled mineral wool and cellulose fibre and reinforcement bars in the concrete structure made of 90 per cent recycled steel. Reclaimed timber from old pickle barrels was used to make the shading trellis. All new timber came from Forest Stewardship Council certified forests or sustainably managed forests. The embodied energy of the materials was also kept as low as possible by sourcing more than 50 per cent of materials from a 300 mile radius, this distance, which in Europe would be considered excessive, was considered good practice in the US.

The Phillip Merrill Environmental Centre building designers did not however exclude the use highly polluting materials such as polyvinylchloride, nor did they address waste during construction and potential waste at the end of the building's life.

The focus on sustainable material selection, with all its variations in terms of details, was widespread among the case study projects, while addressing waste was less common. Of the case studies very few addressed issues of site waste and even fewer addressed waste at the end of the buildings life or attempted to reduce the quantity of materials used overall. Only two projects, addressed the end of use impacts of the building: Barling court and the National Trust Visitors' Centre at Glencoe.

ADDRESSING MATERIAL WASTE

The Barling Court housing by PCKO, which is a volumetric construction, was designed to be able to be taken apart and reerected in a new location. The reusability of the system was tested by Buma, the manufacturers, by re-erecting a unit several times without detriment to the building. While reusable, this system consists of a high proportion of steel, a high embodied energy material associated with significant pollution, and the finishes were not selected for their low environmental impacts and are fixed in a way that make the structure difficult to recycle. As the materials are also generally non-biodegradable the whole structure will eventually have to be landfilled or incinerated.

Table 10 – **Case study projects and their particular aims in respect of achieving a sustainable material design as reported by the building designers and identified in published material.**

Overriding aim of approach / Specification / design approach / Sustainable design project	Reduce material needs: Reduce amount of material used	Reduce material needs: Design for longevity and low maintenance	Reduce material needs: Design for flexibility	Ensure environmentally sound resourcing and manufacture: Use of renewable and certified materials	Ensure environmentally sound resourcing and manufacture: Use of waste materials – recycled or reclaimed	Ensure environmentally sound resourcing and manufacture: Use mainly materials that require minimal processing ('natural')	Ensure environmentally sound resourcing and manufacture: Avoid use of materials with high manufacturing or use impacts.	Reduce embodied energy: Use predominantly low embodied energy materials	Reduce embodied energy: Use local materials	health: Use of healthy materials	Waste minimisation: Waste minimisation in construction	Waste minimisation: Enable the reuse, recycling of components and materials
Adam Joseph Lewis Centre, Oberlin College, Oberlin, Ohio, USA - Architects William McDonough and Partners		•		•	•					•		
Argonne Child Centre, San Francisco, USA, - 450 Architects				•	•					•		
Barling Court housing, Stockwell, London - Architects PCKO												•
Beaufort Court Zero Emissions Building, RES, Kings Langley, Hertfordshire - Studio E Architects		•		•	•							
Bed ZED, Beddington - Bill Dunster Architects				•	•				•			
Carlisle Ln. housing, London - Architects Pringle Richards Sharratt				•								
Dyfi Eco Park, Machynlleth, Wales - Acanthus Holden Architects				•	•			•				
EcoVillage of Loudon County, Taylorstown, Lovettsville, Virginia, USA, following principles of design by Ensar group		•		•	•					•	•	
Ellenbrook, Perth, Western Australia - LWP Property Group				•							•	
Environmental Centre, SantaRosa, CA, USA - Arch. Obie Bowman		•		•								
Environmental Home, Phoenix, AZ, USA - Jones Studio, Inc				•	•					•		
Gallions Ecopark, Thamesmead, London - Splinter Architechon				•								
Greenwich Sainbury's, Greenwich, London - Chetwood Associates					•							
Integer house, BRE, Watford - Cole Thompson Associates			•	•	•						•	
Lothian gridshell, Goethean Science Centre Craft Workshop, Pishwanton, Scotland, Architect: Christopher Day				•	•	•		•	•	•		
National Trust Visitors' Centre, Glencoe - Gaia Architects				•	•	•		•	•			•
Phillip Merrill Environmental Centre, Annapolis, Maryland, USA - Architect SmithGroup Inc.	•	•		•	•	•		•	•	•		
Piney Lakes Env. Centre, Perth, W. Australia - Ecotect Architects				•	•	•		•				
Plusenergiehaus®, Solarsiedlung Freiburg, Germany - Rolf Disch			•	•							•	
Resourceful Bld. Emeryville, CA, USA - Siegel & Strain Architects	•	•		•	•					•		

Table 10 cont. – **Case study projects and their particular aims in respect of achieving a sustainable material design as reported by the building designers and identified in published material.**

Overriding aim of approach / Specification / design approach / Sustainable design project	Reduce material needs: Reduce amount of material used	Reduce material needs: Design for longevity and low maintenance	Reduce material needs: Design for flexibility	Ensure environmentally sound resourcing and manufacture: Use of renewable and certified materials	Ensure environmentally sound resourcing and manufacture: Use of waste materials – recycled or reclaimed	Ensure environmentally sound resourcing and manufacture: Use mainly materials that require minimal processing ('natural')	Ensure environmentally sound resourcing and manufacture: Avoid use of materials with high manufacturing or use impacts.	Reduce embodied energy: Use predominantly low embodied energy materials	Reduce embodied energy: Use local materials	health: Use of healthy materials	Waste minimisation: Waste minimisation in construction	Waste minimisation: Enable the reuse, recycling of components and materials
Robin Hood Chase Centre, Nottingham - Architects Carnell Green				•	•	•		•				
Sanders Eco-Renovation, Phoenix, USA - Architects Sol Source				•	•							
Slateford green, Edinburgh - Hackland Dore Architects				•	•			•				
solarCity Linz, Linz, Austria – Herzog, Rogers, Foster etc.				•			•			•	•	
Thurgoona Campus, Charles Sturt University, Albury, New South Wales Australia - Architect Marci Webster-Mannison					•	•	•	•				
Toll House Gardens, Fairfield estate, Perth - Gaia Architects				•	•	•		•		•		
Uluru-Kata Tjuta National Park Cultural Centre, Northern Territory, Australia - Gregory Burgess Architects					•	•			•			
Weald and Downland Gridshell, Chicester - Edward Cullinan Arch.	•	•		•					•			
Winter Garden, Sheffield - Architects Pringle Richards Sharratt		•		•				•				
Wolken Education Centre, Hidden Villa, Los Altos Hills, California, USA, by architects San Luis Sustainability Group				•	•	•		•		•		
York Road housing, Cheam, UK - ECD Architects		•										

The second example, the National Trust Visitors' Centre at Glencoe in Scotland designed by Gaia Architects, adopted a more comprehensive approach addressing material selection as well as some aspects of the end of life disposal of the building (Appendix 8.6). It remains, however, an exception to the general trend of addressing material resourcing and manufacturing impacts or, rather than and, the disposal impacts in a comprehensive way.

The practice examples illustrate a variety of approaches derived from different philosophical points of view and different understanding of environmental impacts associated with materials. The existence of such a wide range of approaches suggests a possible difficulty in formulating any basis for good practice standards or targets as is discussed in the next section.

2.2.7.3 ASSESSING THE SUSTAINABILITY OF MATERIAL DESIGN

Guidance on sustainable material selection is relatively plentiful. Key texts available in the UK typically provide generic background information and guidance (Borer and Harris, 1998; Bjørn, 2000; Woolley *et al.*, 1997, 2000; Anink *et al.*, 1996) but less commonly suggest a rating system (Anderson *et al.*, 2002; Woolley *et al.*, 1997, 2000; Anink *et al.*, 1996). These rating systems typically use a broad scale, in other words there may be as few as four levels to the ratings scale to indicate: a preferred solution; a good solution; an adequate solution; and a not advisable solution (Woolley *et al.*, 1997, 2000; Anink *et al.*, 1996). 'The Green Guide to Specification' (Anderson *et al.*, 2002) provides ratings from A (best solution) to C (worse solution) based on the Eco-labels for consumer goods. The latest edition of 'The Green Guide to Specification' is due to be published in 2009 and will provide a rating of E to A+. 'The Green Guide to Specification', as will be discussed later, has limitations, but is increasingly popular not least as it has been integrated in the Code for Sustainable Homes, which was made mandatory in May 2008 for housing funded by the Housing Corporation and will be adopted as part of the Building Regulations in its next revision.

Most of the above systems are based on a life cycle analysis, which will be further discussed in section 3.3.2, of the material. As outlined in the previous sections, the resourcing of materials, their manufacturing processes, transport requirements, use, maintenance and final disposal can involve wide-reaching environmental and social damage, including global warming, pollution, depletion of natural resources, destruction of natural habitats, extinction of plant and animal species, waste production, destruction of communities and health problems. The assessment of these environmental impacts, as they occur through the life of a material, is known as a life cycle assessment. 'The Green Guide to Specification' illustrates the stages considered through a life cycle analysis by listing the processes associated with the construction and life of a brick wall as follows (Anderson *et al.*, 2002, p.7):

- The extraction and transport of clay to the brickworks
- The manufacture and transport of ancillary materials
- The extraction and distribution of natural gas for the brick kiln
- The mining and transport of fuels for the generation of electricity for the use in the factory
- The production and transport of raw materials for the packaging
- The manufacturing and transport of packaging materials for the brick
- The manufacturing of the brick in the brickwork
- The transport of the bricks to the building site
- The extraction of the sand and production of cement for the mortar
- The building of the brick wall
- The maintenance of the wall, such as painting or repointing
- The demolition of the wall
- The future of the materials in the waste stream

In the 1990s the Building Research Establishment, in consultation with the building manufacturing industry, developed the Environmental Profile Methodology and Database, a method designed to evaluate the life cycle impacts of construction elements. The system considers and quantifies the impacts of the use of materials on climate change, fossil fuel depletion, ozone depletion, waste disposal, water extraction, mineral extraction and pollution to humans and ecosystems. The results are the basis for 'The Green Guide to Specification', which, as a result of its link to the Code for Sustainable Homes, is effectively becoming an industry standard.

The Code for Sustainable Homes has six levels, the first three equating to the superseded Ecohomes assessments Pass, Good and Very Good and levels four to six being considered 'advanced' (Stroma, 2008). It assesses the designs based on nine categories, as set out in Table 11, of which materials is one with a 7.2 per cent contribution potential (Department for Communities and Local Government, 2007).

Table 11 - **Code for Sustainable Homes credits available for each environmental category including the weighting factor and the weighted value for each credit**

(Department for Communities and Local Government, 2007, p.20)

Categories of environmental impact	Total credits in each category	Weighting factor -% points contribution	Approximate weighted value of each credit
Category 1 – Energy and CO_2 emissions	29	36.4%	1.26
Category 2 – Water	6	9.0%	1.50
Category 3 – Materials	24	7.2%	0.30
Category 4 – Surface Water Run-off	4	2.2%	0.55
Category 5 – Waste	7	6.4%	0.91
Category 6 – Pollution	4	2.8%	0.70
Category 7 – Health and Wellbeing	12	14.0%	1.17
Category 8 – Management	9	10.0%	1.11
Category 9 – Ecology	9	12.0%	1.33
Total	104	100.0%	-

The Code for Sustainable Homes sets some mandatory targets for materials which require at least three of the five main building elements (roof, external walls, internal wall, upper and ground floors, and windows) to achieve a 'Green Guide to Specification 2009', rating of E to A+. While this is not particularly demanding, in order to achieve the higher levels 5 and 6 of the Code, which require 84 and 90 per cent of the credits respectively, it is necessary in practice to achieve virtually all the material credits (Department for Communities and Local Government, 2007).

Superficially, the 'Green Guide to Specification 2009' guidance implemented through the Code for Sustainable Homes would appear to provide a sound system of setting targets and providing guidance for good practice in material selection. However, the Environmental Profile Methodology on which 'The Green Guide to Specification 2009' is based has significant limitations. The methodology does not consider a number of issues such as social issues; it makes a number of assumptions, for instance the life of the material and building is assumed to be 60 years, while in reality it varies from less than twenty to well over one hundred; and the impacts are weighted thus putting a bias on particular environmental issues. In respect of the latter point the Environmental Profile Methodology gives a 46 per cent weighting to global warming and fossil fuel depletion. While the methodology was agreed with industry partners, it is still questionable whether a different context driven by different values would have resulted in the same emphasis.

By providing designers with full environmentally assessed construction systems 'The Green Guide to Specification' has attempted to overcome the criticism directed at life cycle assessments that are considered a 'complex and slow process' which 'means that it can be an unwieldy design tool, and out of reach of most building professionals' (Smith *et al.* 1998, p.60). Yet this has made the system opaque and consequently open to criticism in terms of the assessment results for specific products.

Furthermore, life cycle assessment systems by definition provide a means to compare one material to another and do not evaluate the design in a broader manner. For instance, an efficient use of materials would reduce the total amount of materials and consequently may reduce the impacts associated with the building to a much larger degree than through material substitution. Smith *et al.* support this view and suggest that 'to make our buildings environmentally benign, we cannot just replace one material with another. Rather, what is needed is a different approach to the construction and use of buildings' (1998, p.58).

The 'Green Guide to Specification 2009' illustrates how assessment systems that are complex can perhaps be simplified for the user, but this simplification can bring distortions in the assessment process which may in extreme cases invalidate the system. Furthermore, despite its complexity the system still fails to assess all design aspects that affect the environmental impacts associated with materials.

2.3 CHAPTER CONCLUSION - ENCOURAGING GOOD PRACTICE IN RELATION TO SUSTAINABLE MATERIAL DESIGN

This chapter focused on the main issues related to sustainability in general and to the built environment in particular and attempted to indentify how good practice in these areas could be encouraged and if possible measured. In doing so, a number of issues relevant to this research were identified.

It is clear that achieving sustainable built environments, which are designed to minimise the negative impacts associated with their construction, use and end of life disposal and at the same time make a positive and appropriate contribution to the social environment they affect, requires a change in practice in how urban design, building design and the procurement processes are addressed.

Historic developments suggest that it is a human characteristic to be reluctant to change particularly if change is associated with additional effort, cost and a potential reduction in a perceived quality of life. Historically change has occurred very slowly and has been driven by regulations and financial incentives.

To engender change in individuals, let alone mainstream practice, which is disruptive, costly in time and effort, and potentially detrimental to a perceived quality of life, requires clear and strong instruments. Guidance can support the process but targets and legislation form a framework and the detail to compel the adoption of good practice.

Having considered aspects of sustainability and community creation, land use and ecology, health, energy use, water use and disposal and materials, it also becomes evident that some aspects of sustainable design can and have been addressed in a structured and measurable way while other aspects of sustainable design are far more difficult to quantify and to systematically implement. The sustainability aspects with a potential for a structured and measurable approach are those concerned with resource use, in particular water and energy, while the aspects more difficult to standardise and measure are concerned with people, including community issues and settlement designs. Consequently we find quantifiable targets when considering energy and water use, and primarily recommendations, guidance and indicators for community and urban design. And indeed there is legislation controlling energy use and, to a degree, water use.

It also becomes evident that the more measurable interventions are those that relate to building design as opposed to urban or community strategies. Buildings are more clearly defined and self-contained entities than communities and cities and their performance can be measured and their impacts assessed once suitable measurements have been established. While indicators are used in relation to community issues to monitor improvement from a baseline that could be poor to begin with, buildings are analysed in term of their potential environmental impacts and some performance targets have been successfully set.

All of the assessment systems analysed, whether indicators, design targets or design legislation, appeared to follow some similar patterns. Concepts that are easily understood and measured, such as the density of a development or the inclusion or exclusion in a development of a particular material, such as asbestos, are likely to be widely used and even included in government guidance and legislation. Concepts that are difficult to define and to measure, such as the success and sustainability of a community, are difficult and even perhaps impossible be translated into a tool to drive good practice.

Assessment systems have to operate with a clear definition of what is to be achieved, and where possible this ultimate aim should be the unit of measure. For instance, increased density safeguards land for other uses so the measure should be the land use per unit of service provision, in this unit of development. Equally, carbon dioxide emissions are directly linked to global warming so the measure should be carbon dioxide emissions. Assessment systems that assess the means to achieve an outcome rather than the outcome itself can more easily be flawed. This latter point is illustrated by comparing the successful Passivhaus assessment that measure primary energy, broadly equivalent to carbon dioxide emission, and the cumbersome Code for Sustainable Homes energy performance assessment that dictates the construction of a development rather than measuring the outcome of the design. Simplicity appears to be a characteristic that helps make assessment systems accessible and ultimately useful.

However, certain concepts are complex and cannot be simplified. The sustainable material design assessment studied is complex but still fails to address all relevant aspects. How to address such a dilemma is considered in later chapters.

Finally the Code for Sustainable Homes water assessment highlighted the fact that some assessment systems do not assess good practice as such but rather the potential for good practice. In respect of the water assessment, the water system, which is the object of the assessment, if affected by the users, who are not assessed. The fact that users have a significant impact on the performance suggests a need to assess their actions, but whether this is at all possible remains to be seen.

2.3.1 FOCUSING ON MATERIALS

This initial research has also shown that the environmental impacts associated with materials are extensive and significant and therefore material design merits sufficient attention and effort to reduce these. The use of a sustainable material assessment system to support good practice is therefore important, but the existing systems are limited in scope and prioritise some environmental issues and strategies for sustainable materials design, while neglecting others; and or are complex to use. This goes some way to explain why the case study projects have generally not been addressed in a comprehensive way. Rather than eliminating the environmental impacts associated with the use of materials, the focus has been on reducing or eliminating one or some of the many different impacts associated with material use. While aspirational targets exist for energy use and water use and disposal, for materials there is as yet no clear holistic and realistic ideal.

It seems clear that to build buildings the use of materials is unavoidable and therefore zero material buildings are not possible. However, designing buildings that use zero new materials and produce zero waste may be possible and such a concept could be quantified. This, while not ensuring a zero material impact design could be a possible starting point towards that goal. A building that uses only reclaimed or recycled materials would avoid the environmental impacts associated with virgin materials resourcing, and much of the manufacture and associated transport. A building that is designed so at the end of its life no part of it would have to be landfilled or incinerated would prevent the environmental impacts usually associated with these disposal methods. Combining measurable targets relating to resource depletion and material waste with quantifiable targets for carbon dioxide emissions and pollution could begin to develop a set of comprehensive quantifiable targets for sustainable building material design. Kibert's concept of a closed loop cycle applied to materials would appear to have potential.

2.3.2 THE WAY FORWARD

Taking into account that

- due to the slow pace of change in public perception and personal action, change in mainstream construction towards a more sustainable building practice will require regulations and therefore means of measuring performance; and

- that assessment methods and standards, in respect of certain aspects of sustainable design, have successfully encouraged and supported the adoption of good practice,

- but to date a comprehensive system to assess sustainable material design is outstanding,

it seems that a comprehensive and quantifiable system to assess the sustainability of material design in buildings could positively contribute to the sustainability of the built environment. Furthermore, a system that aims to reduce the waste associated with buildings would also be highly desirable. However, considering the existing evidence two questions appear very relevant to this study.

Firstly, in view of the multiplicity of issues to consider and approaches adopted to create buildings which are more sustainable in their use of materials, is it feasible to rationalise this multiplicity of approaches to form a comprehensive framework or system to evaluate the sustainability of the material use of a building?

Secondly, can such a comprehensive approach incorporate the principles of closed loops cycles found in nature applied to building materials as advocated by Kibert?

Chapter Three begins to address these two questions by analysing different philosophies that relate or can be made to relate to sustainable materials in the building industry.

3 FORMULATING A PROTOCOL FOR A COMPREHENSIVE APPROACH TO SUSTAINABLE MATERIAL DESIGN MATERIALS

The previous chapter discussed the use of a LCA system to evaluate the sustainability of materials. LCAs only represent one method to identify and select sustainable materials. In this chapter other philosophies are explored pertaining to materials in the built environment and in other industries. These form the basis for the formulation of an outline comprehensive approach to sustainable materials. From this approach the concept for CLMC construction is derived and further expanded in Chapter Four.

(Related Appendices: 8.2, 8.3)

3.1 SUSTAINABLE MATERIAL PHILOSOPHIES

Many of the publications relating to general principles of sustainable material selection for the built environment are books written as guidance documents for building designers. These often discuss building elements individually providing specific rather than general guidance. Where general guidance is provided it is often kept to a minimum. Bjorn Berge introduces 'The Ecology of Building Material' by referring to the four principles of The Natural Step, a movement founded in 1989 by Dr. Karl-Henrik Robèrt an oncologist concerned with the increase in childhood leukaemia that he believed was caused by the growing quantities of toxins in the environment. Together with John Holmberg, Robèrt developed four conditions for a sustainable society based on the Laws of Thermodynamics. Berge relates the four conditions as described by Hedeberg of The Natural Step (Berge, 2000, p. xv):

> Condition One – Do not take more out of the crust than can be replaced.
>
> Condition Two – Do not use man-made materials which take a long time to decompose.
>
> Condition Three – Maintain the conditions for Nature to keep its production and its diversity.
>
> Condition Four – Use resources efficiently and correctly – stop being wasteful.

Berge then proceeds by immediately relating these principles to practical aspects of building design and expands in individual chapters the principles of

- materials and energy resource protection;
- prevention of pollution; and
- material processes for social and economic benefit.

General guidance relating to building materials is also kept to a minimum in Anink *et al.*'s 'Handbook of sustainable building', which consists primarily of specific information about individual building elements. The general guidance included is:

1. prevention of unnecessary use and efficient use of materials
2. use of renewable and recycled sources
3. selection of materials with the least environmental impacts.

(Anink *et al.*, 1996, p.10)

The reason for the limited amount of general guidance typically provided is made clear in the introduction to the materials section of 'The Whole House' by Borer and Harris (1998), who contend that 'there are no simple, cut-and-dried solutions to the complex problem of how human activity impacts on ecological systems............The process of evaluation is almost always a balance of pros and cons, and on the scales are qualitative as well as quantitative criteria' (Borer and Harris, 1998, p79). In other words the assessment may have to take into account aspects of materials that are quantified with difficulty and may relate to personal ethics and the resulting priorities.

However, quantitative assessments are seen by many researchers as the way forward and, as seen in the previous chapter, essential to encourage implementation of principles in mainstream practice. Lacasse's review of research presented at the 1998 CIB Gävle Conference identified one of the four main areas of research into sustainable materials to be environmental assessments, such as life cycle analysis and mass and energy accounting. Other aspects being researched included material performance, durability, service life, and maintenance management (Lacasse, 1999); reflecting an interest in factors that directly and indirectly affect the sustainability of materials and relate to processes as well as products.

Therefore, while the overriding aim to achieve a 'materials technology that would harmonize with the environment, i.e. minimize the environmental load in life as a whole' (Yagi and Halada, 2001, p. 143-146) is a principle shared between researchers into sustainable materials, the approaches to achieve this aim vary.

The different focuses adopted by researchers into sustainable materials can result from individual philosophies and or experiences. For instance, for certain individuals the focus on health in buildings developed as a result of personal experiences of ill-health associated with contact with specific materials or environments. Parker-Laporte *et al.* (2001) recount how individuals who have suffered incidents of acute exposure or long term low level exposure to pollutants resulting in sensitisation and chronic ill health, have subsequently devoted their life to educating others by sharing their experience. For others a philosophical position has steered the development of the approach to material selection, be it the preference for natural materials as a means to create a stronger link with nature, or the adoption of a tool that enables the measurement of some aspects of material selection so as to provide, as far as possible, an unbiased selection process. Certain approaches have only become feasible to implement in practice as environmental information on material impacts have increased.

The rest of this chapter investigates three prominent categories of approaches to sustainable materials. The first category, focusing on natural building technologies and health, may be said to have antecedents in the movements of the sixties and a particular desire to develop closer and more harmonious links with nature driven by a particular ethical position but also the conviction that such links will benefit humans. The assessments of the impacts associated with materials are largely qualitative rather than quantitative.

The second category, focusing on scientific approaches to quantifying environmental impacts, consists of a pragmatic response to questions about reliability of guidance. The objective figures for embodied energy, ecopoints or emergy enable the comparison between materials, replicable testing and a relatively unbiased assessment of materials, keeping in mind that as discussed in the previous section, seemingly unbias systems tend to have a bias due to the inevitable need to choose what to include in the assessment and what to omit. However, for practitioners wanting 'hard' facts, these measurable approaches provide confidence of reliability and for the scientific community they provide the objective data which contributes to increasing the overall understanding of the subject matter. These approaches to selecting materials have only become possible with the increasing data on individual material impacts.

The third, more recently developed, category draws on well established principles of systems thinking and sustainability modelled on balanced and cyclical ecosystems that exist in nature. Structuring industrial systems based on natural ecosystem principles, a process known as Industrial Ecology, has been implemented with some degree of success as far back as the 1960s, but examples of such implementations are still rare. Despite the relatively low take-up of these approaches architects and researchers have begun to consider how to transfer such principles to the construction and built environment industry. Kibert *et al.'s* book 'Construction ecology: Nature as the basis for green building' published in 2002 begins to draw links between Industrial Ecology and the built environment.

3.2 NATURAL BUILDING

> 'Natural building is any building system that places the highest value on social and environmental sustainability. It assumes the need to minimize the environmental impact of our housing and other building needs while providing healthy, beautiful, comfortable, and spiritually uplifting homes for everyone. Natural builders emphasize simple, easy-to-learn techniques based on locally available, renewable resources. These systems rely heavily on human labour and creativity instead of capital, high technology, and specialized skills.'
>
> (Smith, 2002, p.6)

The benefit of adopting natural building technologies, according to their supporters, is the resulting well-balanced relationship between the building, its inhabitants and nature. This on one side produces building solutions that have low or minimal environmental impact and on the other side provides an environment that is healthy for humans because of the proximity to nature and the use of benign natural building materials (Pearson, 1998; Adams and Elisabeth, 2000; Parker-Laporte *et al.*, 2001; Van der Ryn and Pena, 2002; Woolley, 2006).

In the introduction to 'The Natural House Book', Pearson suggests the 'sense of belonging and being part of the natural world...is the source of true well-being' and he promotes a way of building that creates natural buildings 'integrated with the natural systems around [them]' (Pearson, 1998, p. 12). He considers the absence of a contact with nature to be detrimental to health: '... when we are denied this rich and natural world of subtly changing light, colours, and scents, as well as the special sounds of the wind through leaves and the visual indicators of the changing seasons, we are diminished' (ibid, p. 242).

While Pearson's views are derived from personal emotional experience, the relation between human health and nature has been extensively researched. Natural environments have been shown to be calming and reduce stress due to their less complex nature with reduced numbers of stimulants compared to urban environments (Thwaites *et al.*, 2005). The positive effects of nature on human health are also thought to come from a deep seated evolutionary preference for natural environments, in particular savannah-like landscapes that resemble the environment where primitive humans first developed (Kaplan, 1995). The restorative effects of nature have been illustrated in numerous studies. Feelings of fear and anger were found to be reduced and positive feelings were increased among students under pressure due to exams who had views of planted landscapes (Ulrich, 1979). Physiological impacts, such as reduced blood pressure, skin conductance and muscle tension, were also measured after only a few minutes of viewing nature and plants (Ulrich, 1999; Harting and Evans, 1993). Other studies found that stressed individuals actively seek out nature and feel calmer and more balanced after being in planted environments (Francis and Cooper Marcus, 1999) and the sense of wellbeing of office workers was found to be positively affected by the presence of plants (Leather *et al.,* 1997; Larsen *et al.*, 1998).

In addition to integrating nature within buildings and buildings within nature, the buildings themselves are argued to enhance human physical wellbeing. Elizabeth (2000, p.3) describes natural building as 'healthful' and Woolley as 'more attractive, [it] creates more beautiful and harmonious buildings and generally makes the occupants feel better'. Also 'natural materials appear to be healthier, less polluting and available locally' (Woolley, 2006, p.8).

While the human benefits present a convincing argument to adopt natural building technologies, Elizabeth (2000, p.3) believes the decision to build this way is often 'underpinned by a worldview that treats the earth as not sacred, but alive'. As touched on in the previous chapter, most existing philosophical positions in relation to nature acknowledge the importance of nature for the survival of humans, and only some philosophies got beyond that concept and attribute intrinsic value to nature. Such ecocentric, as opposed to anthropocentric, philosophies suggest that nature's interests may in certain cases have to be given priority ahead of human interests, and this translated into building practice redefines the building designer's and builder's responsibility, as described by Elisabeth (2000, p.9): 'The job of shaping the built environment comes with a responsibility beyond the wants of the paying client, and beyond our personal wants as well'. Adopting natural building technologies addresses and discharges some of the responsibilities towards nature. This alone attracts certain individuals. Woolley believes that '[m]ost of the people that are attracted to natural building techniques share a concern to behave more responsibly towards the environment...' (Woolley, 2006, p8).

It is interesting to note that this virtuous circle of respecting and protecting nature and in turn benefitting physically and psychologically is the core message of the deep ecological movement articulated by Arne Naess. Neass argues that understanding that nature is equal to humans and protecting nature is life-enhancing and improves humans' psychological well-being by giving it a sense of purpose and achievement (Sessions, 1995; Naess, 1989; Rothenberg, 1993).

It is therefore not only that 'natural building offers a range of alternatives [to conventional building solutions], which use much less energy and resources that cause less environmental damage' (Woolley, 2006, p10) and that the material do not negatively affect human health, but also that the implications of making such choices are psychologically enhancing. The following sections investigate the reduced environmental and health impacts associated with natural building materials.

3.2.1 REDUCING ENVIRONMENTAL IMPACTS THROUGH THE USE OF NATURAL BUILDING TECHNOLOGIES

Natural building technologies focus on providing building solutions that minimise resourcing and manufacturing impacts by using materials that are as natural as possible, renewable and or plentiful and local. While natural builders may 'use renewable energy when appropriate and affordable, [they] are primarily trying to develop lower impact outcomes' (Woolley, 2006, p.10).

The typical natural building materials according to their advocates (Adams and Elisabeth, 2000; Kennedy *et al.*, 2002; Woolley, 2006) include:

- Earth-based technologies: building with unburnt clay including, cob building, wattle and daub, rammed earth, unburnt clay brick, light earth construction; earth bag construction.
- Timber construction: timber frame, cord and log construction.
- Using renewable materials (other than timber): thatch, bamboo, sisal, hemp, flax, coir, straw.
- Using local plentiful materials: building with local stone, slate.

It is important to accept that all building materials have an environmental impact, even so-called natural materials. However, these materials on the whole have significantly smaller impacts than more synthetic and manufactured materials and products (Woolley, 2006; Adams and Elizabeth, 2000). The main environmental advantages of natural building technologies include:

- the protection of natural resources from depletion;
- the protection of natural habitats and biodiversity; and
- reduced pollution and energy consumption from manufacturing processes.

These issues will be discussed in turn below.

RESOURCE DEPLETION

The building industry is one of the biggest consumers of materials. In Great Britain the industry is responsible for the extraction of 260 million tonnes of minerals, equivalent to 90 per cent of minerals extracted annually for non-energy purposes (Addis and Talbot, 2001) and uses a total of 400 million solid materials each year (Department for Environment, Food and Rural Affairs, 2008). The aim for sustainable material selection in respect of resource depletion is to avoid the over-exploitation of limited resources. Table 12 lists the estimated reserves for some non-renewable resources based on current consumption patterns and technological efficiencies and suggests that current economically viable and known stocks of certain materials will be depleted in as little as a single generation. Historic prediction, such as those published in 'The limits of growth' (Meadows *et al.*, 1972) have been proved too pessimistic, often because 'at any given time, reliably known reserves are only a fraction of total physical reserves' (Commission of the European Communities, 2003, p.11) and 'process improvements mean that a greater proportion of the resources present in reserves can be extracted' (ibid. p.12). For these reasons the Commission of the European Communities is not concerned about the seemingly very limited reserves, and indeed considers some of the renewable resources to be more endangered in comparison.

Table 12 - **Outstanding resources of selected materials**
(Data from Commission of the European Communities, 2003)

Non-renewable limited resources		**Plentiful resources**
Copper	27	Sand
Iron	133	Gravel
Lead	21	Stone
Nickel	44	Clay
Silver	16	Earth
Tin	49	Gypsum
Zinc	24	Lime
Coal	200+	Perlite

Renewable resources are those that regenerate, mainly through photosynthetic activity, within a human lifetime or less (Wenzel *et al.*, 1997). They are also biodegradable if appropriately treated and not combined with non-biodegradable materials.

Renewable materials, including plants and grasses, which grow anew every year or season, trees that require several decades to mature, and animal hairs, can be used for a multitude of functions. In mainstream construction timber is the renewable material most used. In natural buildings straw and bamboo are used for structural purposes; mixtures of hemp or straw are used to infill external wall frames; straw, cork, flax and sheep's wool make good insulation materials; timber and soya can be made into finishing or structural boards; timber is commonly used to make fittings and can even be used to make bathtubs and sinks; jute is used for carpet backing and wall coverings; seagrass, sisal, coir, cotton and wool are made into carpeting; flexible floor finishes are made of pure cork and cork mixed with wood flour, powdered limestone, linseed oil and natural resin to make linoleum; bamboo and timber make rigid floor finishes; and roofs can be covered with timber and thatch.

Renewable resources can only be considered a environmentally sound option if not over-harvesting by adopting inappropriately frequent harvesting intervals. For instance, in its natural environment, bamboo grows 25 and 30cm in one day once the plant is well established. When the bamboo has reached its full size, it transforms the sugars and water into cellulose and silica in three years, after which it can be harvested. Plants such as jute, soya, seagrass, sisal, hemp, flax and cotton are cultivated and can be harvested one or more times each year. Timber thinnings can be harvested every 5-20 years, while mature deciduous trees can be harvested after 30-60 years, and some hardwoods need to be over 100 years to mature. Harvesting at more frequent intervals risks depleting a resource and in the cases where the resource requires longer periods to regenerate, as with timber, over-harvesting can jeopardise the resource as a whole and significantly impact on the natural habitat.

To encourage sustainable harvesting frequencies and processes a number of certification systems have been developed primarily for timber. According to the Friends of the Earth, the Forest Stewardship Council (FSC) is the most stringent timber certification system currently in existence (Friends of the Earth, 2002). It considers environmental and social issues relevant to the local communities, the workers, and indigenous people. Other programmes exist, for instance The Programme for Endorsement of Forest Certification (PEFC), previously known as the Pan-European Forest Certification, is a rapidly expanding scheme which groups together 13 national certification schemes.

Historic vernacular buildings relied on renewable and plentiful building materials that are not threatened from depletion, such as earth, clay and stone, all which would typically be found locally. Contemporary natural builders advocate these same building principles and in addition to renewable materials make use of rammed earth, cob, stone and preferably unfired bricks. With the exception of glass, a non-renewable material which is however made from a plentiful resource, and possibly some plastics or metals for service connections, natural buildings can be virtually completely made of local renewable and plentiful materials. One such example is the Pishwanton Gridshell located south of Edinburgh and designed by Christopher Day. Built almost exclusively from local stone, timber and earth the only non-renewable and highly manufactured materials used are the glass for the windows and metal fixings and fittings.

A low environmental impact alternative to the use of renewable and plentiful building materials is the use of recycled materials. Using recycled materials can reduce the requirements for primary resources, consequently extending the life of material reserves and helping to prevent shortages of renewable resources (Commission of the European Communities, 2003). Using recycled materials is also acknowledged as an effective way to avoid the environmental impacts of material resourcing activities (Lin and Lin, 2003). The preference for natural building advocates is the reuse of plentiful materials such as stone, or renewable materials, such as timber, rather than the recycling of plastics, metals and other highly manufactured materials. In other word, even when considering reclaimed and recycled materials, natural materials are preferred.

ENVIRONMENTAL IMPACTS OF RESOURCING ACTIVITIES

The aforementioned certification schemes not only help prevent resource depletion, but critically help protect the natural environment and the biodiversity it supports, which is too often negatively affected by resourcing activities such as mining and harvesting as well as the associated transport.

Changes and in particular the loss of habitat, whether as a result of farming, mining, building, or tourism, are a cause of plant and animal extinction. This continuous encroachment into the natural environment by human activities is now understood as the major cause for the increasing levels of species extinction (Wilson, 1992, 2002; Leakey, 1996; Bush, 1997). Leakey's review of the predicted rate of extinction finds wildly varying estimates 'which ranged from 17.000 species lost a year to more than 100,000' (Leakey, 1996, p.236). Despite these varying figures there is consensus that this level of extinctions constitutes a mass extinction event, the sixth in the earth's history. Previous extinction events, including the most recent Cretaceous extinction 65 million years ago, are thought to have been caused by major natural catastrophes such as asteroid collisions or volcanic eruptions. This time the destruction can be traced back to human activity (Seager, 1990; Wilson, 1992, 2002; Leakey, 1996; Bush, 1997).

The natural builders' preference for materials as close as possible to their natural state means that materials such as metals and plastics are kept to a minimum. The resourcing of highly manufactured materials and the associated transport can have significant impacts on the local biodiversity. For instance, bauxite strip mining to produce aluminium relies on hydroelectric power schemes made by flooding valleys and destroying further rainforests. The processing of bauxite is also associated with large quantities of waste 'red mud' that, though highly polluting, is discharged locally affecting the natural environment (Ayres and Ayres, 1996). Synthetic plastics are mainly manufactured from oil and '[oil pollution is a serious problem for marine coastal fauna and flora' (Goudie, 2000, p.101).

The plentiful and renewable sources preferred by natural builders are not without their problems and some of their resourcing methods can be destructive. Quarrying for minerals, such as sand, stone or clay are associated with changes of the landscape, dust, noise, reduction in habitat for flora and fauna, pollution into the watercourses and increased traffic. These impacts tend to be local and may be controlled and reversed (Clough and Martyn, 1995). The cultivation of renewable materials, unless organically grown, makes use of pesticides and fertilisers, which are persistent organic pollutants known to affect human health (United Nations Environment Programme, 1999).

Control over the extraction, harvesting and transport activities is necessary to ensure minimal environmental impacts are associated with such activities. Control can be gained through the certification systems mentioned previously and through the selection of operators that implement sound environmental management. While, the impacts associated with natural building technologies may be reduced compared to other materials, precautions are still required.

ENVIRONMENTAL IMPACTS OF MANUFACTURING PROCESSES

Perhaps the most significant benefit of natural building technologies is the reduced environmental impact achieved by avoiding the use of highly manufactured materials. All building products are derived from natural materials; even those considered synthetic are made from a natural material, for instance synthetic plastics are manufactured from oil or natural gas. However, the manufacturing processes range from minimal to extremely complex. Timber needs minimal processing, while steel derived from iron ore, which is cleaned, sintered, smelted out, and reduced at 1700-1800°C, is associated with far more intense processes. All manufacturing processes involve the transfer of materials for processing and may result in waste and pollution to air, water and ground. The more complex the manufacturing processes, the more likely they are to be associated with environmental impacts.

For instance to produce 1 tonne of copper 500 tonnes of material has to be moved and 165 tonnes processed. Copper smelting operations account for 23.6 kMtonnes of copper emissions into the atmosphere which is significantly higher than the 6 kMtonnes of copper that are produced naturally (Ayres and Ayres, 1996). The manufacture of aluminium include emissions to air of nitrous oxides contributing to global warming, acid rain and photochemical smog; sulphur dioxide associated with acid rain; discharges of heavy metals into sewers, discharges of sludge containing fluoride and carbon to land; emissions of fluoride and carbon monoxide to air; emissions of fluorine, hydrocarbons and solids to water (Ethical Consumer Research Association, 1995).

Manufacturing processes also require energy that typically associated with further emissions. The manufacture and transport of construction materials in the UK is responsible for 10 per cent of carbon dioxide, 0.7 per cent of volatile organic compounds including methane, 2.5 per cent of nitrous oxides and nearly 8 per cent of sulphur dioxide emissions to air (Howard, 2000).

The choice of material affects all these emissions. Clay bricks can be sun dried or kiln dried, the difference being the amount of energy used, which increases by 0.2MJ/kg for every 100°C increase in firing temperature (Berge, 2000), and the pollution from the firing process, which produces sulphur and nitrogen oxides, as well as fluoride and chloride gases depending on the type of clay. The environmental impacts of the mechanised manufacture of fired bricks are therefore far higher than those of hand-made air dried bricks. So while both burnt and un-burnt bricks are made of the same basic material, un-burnt bricks are closer to the material in its unprocessed state and therefore associated with far fewer manufacturing impacts.

Some building materials include individual components associated with high environmental impacts. For example, concrete, external renders and mortars can all contain cement, which is associated with high carbon dioxide emissions. The manufacture of cement involves firing the raw materials (limestone or chalk, silica and clay containing alumina) in kilns at peak temperatures of 1400°C, where the calcium carbonate from the limestone or chalk is transformed into the oxides of calcium, silicon, aluminium and iron, while giving off large quantities of carbon dioxide. Due to this process, the cement industry is responsible for 8-10 per cent of carbon dioxide emissions globally (Ethical Consumer Research Association, 1995a).

Replacing cement with a suitable alternative, such as lime, can help reduce the carbon dioxide emissions. Like cement, lime manufacture is also associated with carbon dioxide emissions, albeit reduced compared to cement. However, unlike cement, its curing process reabsorbs a significant amount, up to 70 per cent, of the carbon dioxide emitted as a result of the chemical reaction. Lime renders and mortars can replace cement renders and mortars and lime can substitute cement in the manufacture of concrete for slabs and screeds (Berge, 2000).

While lime represents a reduced impact and is therefore more attractive from a natural building perspective, it is still associated with a significant impact. To reduce the impacts further may sometimes require not only a change of material but a change of building principle. For instance rather than substituting lime for cement in a concrete foundation, a natural building advocate would create a stone foundation and perhaps have a suspended timber floor further reducing the foundation material required.

In addition to selecting materials made with manufacturing processes with reduced environmental impacts, such as air-dried bricks or lime, it is possible to select materials with reduced environmental impacts resulting from improved efficiencies of the manufacturing processes and improved production methods. Increasing environmental awareness has driven some building material manufacturers to consider how to reduce the environmental impacts of their manufacturing processes, formulate an environmental policy and implement it by means of an environmental management system, defined as 'the part of the overall management system that includes the organisational structure, planning activities, responsibilities, practices, procedures, processes and resources for developing, achieving, reviewing and maintaining the environmental policy' (Swedish Standards Institution, 1996).

In 1993 the European Commission issued the Eco Management and Audit Scheme (EMAS) regulation and in 1996 the International Standardisation for Organisation issued the ISO14001:1996 environmental standard and other 14000 standards based on the 14001. Both standards aim to make manufacturing and other commercial processes more environmentally friendly and utilise environmental management systems to help achieve this aim (Official Journal of the European Communities, 2001). EMAS and the ISO14001:1996 Environmental Management System not only provide a system to improve environmental performance, but also a means to evidence the implementation of such systems and therefore offer building material specifies a formal means of recognising commercial enterprises that include environmental considerations in their decision-making.

It is also important to note that these systems formalise and monitor improvements against targets set by the organisation, not an external body, and therefore can be set as high or as low as the organisation wishes. It does not therefore guarantee high environmental ambitions.

Furthermore, the actual improvements that can be implemented depend on the manufacturing processes in question. A process associated with significant pollution is unlikely to be rendered entirely benign, however even highly environmentally problematic processes can be improved. For instance, steel is typically produced in oxygen furnaces with only a small percentage of the steel manufacture employing electric furnaces. However, electric furnaces use one-tenth of the fuel, one-eighth of the water, one-fifth of the air and less than one-fortieth of other materials compared to oxygen smelting (Liedtke and Merten, 1994). Similarly, Ayres and Ayres report on a number of aluminium smelting technologies that would reduce the energy consumption and environmental impact of aluminium production. In particular the ALCOA process is thought to reduce the electric consumption by 30 per cent. The early versions of the ALCOA process were associated with the production of toxic chlorinate aromatics, such as chlorobenzenes, polychlorobiphenyls (PBCs) and dioxins, which were however considered possible to contain with suitable waste treatment methods. These alternative production systems have not been implemented on a large scale basis due to commercial rather than technical reasons and Ayres and Ayres believe the technical potential is high (Ayres and Ayres, 1996).

Despite the potential for reducing manufacturing impacts through technological improvements, the natural building advocates prefer to rely on well tested and minimally manufactured materials.

3.2.2 REDUCING HEALTH IMPACTS THROUGH THE USE OF NATURAL BUILDING TECHNOLOGIES

Considering health is a fundamental aspect of the natural building philosophy, which aims to maintain the health of both the natural environment and the building occupants. The natural building preference for materials that are close to their natural state, the characteristics of which are well understood and that are integrated in a way that is conscious of the potential health impacts on building occupants, counteracts the current trends in building that are thought to have negative effects on human health.

BUILDING MATERIALS AFFECTING THE BUILDING OCCUPANTS' HEALTH

In the last fifty years in the US, the spread of air-conditioning in homes, offices and public spaces and more airtight constructions, combined with the increased use of synthetic building products has brought unprecedented number of chemicals into the home and workplace (Parker-Laporte *et al.*, 2001; Bower, 2001). In Scandinavia the increased energy efficiency standards also drove building construction to become increasingly airtight and mechanically ventilated. Both trends resulted in increased occurrence of poor indoor air quality, which in certain cases affected the building occupants' health. Research into indoor air measured indoor air to be as much as ten times more polluted than outside air (Wolverton, 1997).

The effects of indoor air pollution on health are also exacerbated by contemporary lifestyles in developed countries where people can spend more than 90 per cent of their time in their homes, work places and cars (Parker-Laporte *et al.*, 2001; Bower, 2001). The increasing contact with chemicals and biological agents of disease is thought to be associated with the rise in numbers of people with allergies. Individuals with immature, weakened or declining immune systems, including unborn babies, infants up to 5 years old, those suffering from illness and elderly people, are more liable to develop a sensitisation when coming into contact with biological agents, such as dust mites or mould, or chemical pollutants. This sensitisation may remain undetected for years, and later develop into an allergy (Crowther, 1994). In extreme cases as a result of a severe incident of exposure to pollutants or exposure during a period of immune deficiency through illness or stress, a hypersensitivity to chemical gasses, known as MCS (Multiple Chemical Sensitivity), can develop among some individuals. Individuals suffering from MCS often suffer reactions and a set of symptoms that are not recognisable as a typical allergy. The symptoms can occur when in contact with synthetic materials and gases, including car fumes, fragrances, plastics, and printers. Due to their hypersensitivity MCS sufferers may develop reactions at extremely low chemical concentration levels, which may not even be measurable (Bower, 2001).

Indoor air quality is not the only building aspect that affects human health. Buildings have physical, chemical and biological characteristics that affect the physiological and psychological health and well-being of their occupants. Spatial design can affect the ability to undertaking everyday tasks and the psychological state of people's mind. The operation of buildings can affect the sense of control and the indoor comfort levels.

Radiation such as radon is known to negatively affect human health and electromagnetic fields are thought to impact on health as well (Saunders, 2002). Furthermore the combination of certain building characteristics, such as poor air quality, lighting, controls, together with personal circumstances, such as low job satisfaction, can have detrimental heath effects when experienced simultaneously. This phenomenon, known as building-related sickness, can cause symptoms, such as allergies, asthma, eye, nose and throat irritation, fatigue, headache, nervous-system disorders, respiratory congestion, and sinus congestion. The symptoms manifest themselves during the time they spend in the building, and diminish or go away during periods when they leave the building (Raw, 1992; Palmer and Rawlings, 2002). Building-related sickness is mainly associated with office buildings, but can also be experienced in other building types. Air-conditioning is thought to be linked to the occurrence of building-related sickness, as are other building characteristics such as: fluorescent lighting and limited natural light; sources of indoor air pollution such as photocopiers, office machinery; finishes, fixtures and fittings that off-gas fumes damaging to health; excessively dry air; poor air quality resulting from insufficient air changes or dirty air filters; lack of views to the outside; and lack of the occupants' control over the temperature, humidity or lighting (Palmer and Rawlings, 2002).

Despite the effects that buildings can have on health there is relatively few regulatory control. Some regulations exist, for instance in respect of asbestos and lead. Asbestos was exploited for its incombustibility, resistance to chemical attack and other useful properties from around 1900, with time it became evident that exposure to asbestos could cause respiratory disease, lung cancer and mesothelioma, a rare tumour only associated with exposure to very fine fibre asbestos. The diagnosis of such illnesses can take place 15 to 50 years after the exposure to asbestos, and at the time of exposure the individual affected would have been oblivious to the risk placed on their health. The asbestos ban was therefore enforced only after the material had been in use for decades and many buildings still contain asbestos elements (Addison, 1990). Lead is used for roofing materials and paints, but if ingested can cause lead poisoning associated with headache, nausea and anorexia, constipation, fatigue, personality change and hearing loss and in children lead toxicity can cause developmental deficits. The use of lead for paints is now restricted (Curwell *et al.*, 1990).

A significant number of materials remain that are not regulated even though their negative effects on health are recognised. For instance, while the World Health Organisation has identified concentrations of selected indoor air pollutants which they consider to be of concern (Palmer and Rawlings, 2002), the medical profession has not reached consensus in respect of the level of risk to health associated with these pollutants and therefore no legislation has been put into place (Geiser, 2001; Institute of Medicine, 2000).

There are also materials that are damaging to health unless precautions are taken. Materials such as adhesives, concrete, mortar mixes, cleaners for stone and brickwork, treatment materials, sealants and insulants have the potential to cause allergic reactions, but can be used safely subject to adopting suitable protective measures. (Greenberg, 1990). Mineral wool, which is a recognised irritant (Curwell and March, 1986), requires the use of protective clothing and masks. Materials that produce silica dust, which can cause silicosis and may lead to developing lung cancer, require similar protective precautions to be used. That the risk to health can be reduced does not change the fact that these materials are not entirely safe.

To this group of legal but deleterious materials belong materials that offgas volatile organic compounds (VOCs), such as PVC, preservatives, sealants, adhesives, mastics, paints, solvents, carpets, furnishings. Many of the products that offgas VOCs do so mainly during the application and drying process but it can take 6 months to several years for the VOCs to be fully liberated. VOCs can cause eye, nose and throat irritation, headaches, loss of coordination, nausea, damage to liver, kidney and the central nervous system and they are being classed as known animal carcinogens but only suspected as human carcinogens. The medical profession only cautiously makes links between VOCs and asthma and building-related sickness (Institute of Medicine, 2000). Without fatal cases reported indoor air pollution remains uncontrolled by legislation. Recommendations on how to improve indoor air quality are nonetheless unequivocal: while ventilation, materials substitution, removal or sealing are all options (Curwell and March, 1986), the most effective method of controlling indoor pollutants is to remove their source and in certain cases is the only way to control pollutants (Institute of Medicine, 2000). This is the approach adopted by natural builders and in doing so the working environment is improved and health hazards for building occupants are minimised.

Two materials attract particular attention in respect of their impacts on the health of humans and the environment and are typically avoided by natural builders where possible: formaldehyde and polyvinylchloride (PVC). Formaldehyde can be found in building products such as glues or adhesives in pressed wood products, preservatives in some paints, coatings, and cosmetics, ureaformaldehyde foam insulation. Formaldehyde, which has an offgassing half life of up to six years, has been classed as a probable human carcinogen by the US Environmental Protection Agency (1994, 1995). It can cause watery eyes, burning sensations in the eyes and throat, nausea, and difficulty in breathing in some humans exposed at elevated levels (above 0.1 parts per million). High concentrations may trigger attacks in people with asthma. Formaldehyde can also cause sensitizing to other materials.

PVC is a material notoriously associated with environmental and health impacts at virtually all stages of its life-cycle, from its production through its use and to its disposal. PVC is used in buildings as flooring, panelling, windows, cladding, rainwater goods, below- and above-ground drainage pipes, and sheathing for wiring. The manufacture of PVC involves using chlorine, a highly toxic gas, to chlorinate ethylene, an oil-based and therefore scarce material, and produce ethylene dichloride. This process produces dioxins, which are persistent organic pollutants (POPs) and classified as probable carcinogens and powerful hormone disruptors. Ethylene dichloride is then converted to vinyl chloride monomer, a human carcinogen, also affecting both male and female reproductive systems. Chloride monomer is polymerised into PVC. PVC requires the addition of plasticizers, stabilisers, pigments, optical brighteners, flame retardants, biocides, fillers, foaming agents and lubricants, which can make up over 50 per cent of the final product. Many stabilisers and pigments contain heavy metals such as cadmium, tin or lead, known to affect the nervous system. Plasticizers contain phthalates and in particular di-ethyl-hexyl-phthalate, which has been identified as a hormone disruptor and possible human carcinogen (Greenpeace, 2001, 1997; Berge, 2000; US Environmental Protection Agency, 1994, 1995; Ethical Consumer Research Association, 1995). In fire PVC releases dioxins, heavy metals and chlorine gas which can form hydrogen chloride and hydrochloric acid. For this reason alone PVC products, such as halogenated cables, have been banned from construction projects for London Underground, Channel Tunnel and other underground construction projects. In use PVC is also known for leaching out phthalates, used to plasticize PVC and known hormone disruptor and possible human carcinogen, from products such as PVC flooring and children's toys. This has been recognised and the use of PVC in toys intended to be sucked by children is currently banned by the European Union. The Swedish government has initiated a move towards banning the use of PVC and some European cities have addressed the issue at a regional level. For instance Linz, in Austria, has achieved an 85 per cent phase-out of PVC in public buildings (Allsopp *et al.*, 2000; Berge, 2000; US Environmental Protection Agency, 1994, 1995; Ethical Consumer Research Association, 1995).

BUILDING MATERIALS INDIRECTLY AFFECTING BUILDING OCCUPANTS' HEALTH THROUGH MOULD GROWTH AND DUST MITES

Building materials can also have an indirect impact on human health. The occurrence of biological disease agents can be affected by the choice of materials and the indoor levels of humidity. Both moulds and dust mites thrive in humid environments. In sufficiently humid environments mould will grow on any cellulose rich material, such as wood, paper, wallboard, thermal and acoustic insulation and furnishings. Dust mites can live in carpets, beds, upholstered furniture or other material that contains human skin which can provide a food source for the mites and require 50 per cent or higher relative humidity to reproduce.

Moulds can affect people in three ways: by growing on or in a person; by producing toxins (Mycotoxins) primarily ingested with food, but that can also be inhaled; and by producing an allergic reaction, including sensitisation and immune responses such as hayfever or asthma, after inhalation of mould particles. The latter is the most common building-related effect and the typical symptoms include sneezing, watery eyes, coughing, wheezing and the like. A single high exposure to airborne mould can develop Organic Dust Toxic Syndrome. In 2002- 2003 toxic mould became the focus of much attention when a number of multimillion dollar compensation cases in the US were won by individuals who were suffering from its effects. Most of the cases were linked to ventilation systems, which had been inadequately designed or installed and allowed humidity levels to soar and Strachbotrys Chartarum to grow and affect occupants with cold-like symptoms, rashes, the aggravation of asthma, and in extreme cases pulmonary hemosiderosis (Thakrar, 2003a).

House dust mites can cause eye, nose and throat irritation, account for 50-60 per cent of asthma cases and are responsible for causing sensitisation and allergic attacks of asthma. The National Asthma Campaign warns that the number of asthmatic sufferers in the UK is growing and that currently 1 in 10 children and 1 in 12 adults suffer from asthma. 1,400 people die every year from asthma in the UK and over a third of these are people under 65 (Asthma UK, 2004). Asthma attacks occur spontaneously or as a result of a triggering agent, such as dust mites, pollen, dust from feather and animal fur, sulphur dioxide and other gases. Moreover predisposition to asthma may occur as a result of a sensitising agents, including those listed above, encountered in childhood or sometimes in adulthood (Crowther, 1994; Asthma UK, 2004).

Many of the natural building materials, such as clay, cork, timber, lime plaster, cellulose fibre insulation and natural fibres, are highly hygroscopic and have the ability to absorb and release moisture. By absorbing moisture from the air when excessive, high humidity levels are avoided, relative humidity levels are more easily maintained within the recommended 40-50 per cent levels and the risk of mould growth and dust mites is reduced, thus creating a healthier environment.

3.2.3 SECTION SUMMARY AND CONCLUSION

By focusing on materials that have not been highly manufactured the natural building approach attempts to create a meaningful relationship between the building, its occupants and nature. This reliance on nature and to a degree on historic vernacular technologies is thought to create healthier places for humans that also have lower impacts on the environment as a whole.

The principles and methods advocated (and summarised in Table 13) are easily understood and with historic examples as precedents the methods are easily implemented. However, the approach is not without weaknesses. A limitation of its focus on human health is its rejection on some of the passive low energy principles, such as building air tight (Parker-Laporte *et al.*, 2001), that are now understood as critical in achieving the level of energy efficiency necessary to address climate change. Another limitation relates to natural builder's preference for human scale building that is enhancing to the human psychology. The use of natural building technologies is compatible with such lower scale building but often inappropriate for high-rise buildings, which due to population pressures are considered by some inevitable and in addition a socially inclusive solution. An attempt at applying the principles of natural building to a holistic approach to sustainability that might prioritise high density urban centres seems missing. This deficiency of the natural building philosophy to embrace the contemporary challenges does, however, not in itself invalidate its principles.

Table 13 – **Summary of main approaches to the selection of materials in line with the natural building philosophies**

- Select / specify renewable materials
- Select / specify certified materials
- Select / specify plentiful materials
- Select / specify recycled, reused and reclaimed materials that have the above characteristics
- Select / specify materials resourced through processes that impact as little as possible on the environment
- Select / specify materials that are as close as possible to their natural state
- Select / specify materials that are associated with as little as possible manufacturing pollution
- Do not select / specify materials that are hazardous to human healthy (PVC, VOCs and all acknowledged deleterious materials)
- Avoid use of carpets and other building products that facilitate the growth of dust mites or mould.

3.3 QUANTITATIVE ASSESSMENTS SELECTION BY MEASURED IMPACTS

While the principles of natural building are clear, the decision-making relies on qualitative assessments. The limitations of such assessments are their reliance on the judgement of those who implement the principles. '[S]imple, easy-to-learn techniques based on locally available, renewable resources' and '[S]ystems [that] rely heavily on human labour and creativity instead of capital, high technology, and specialized skills' (Smith, 2002, p.6) require an interpretation. As discussed in the previous section, renewable resources may still be overharvested and there is no clear cut off between low and high technology. Making such assessments requires a relatively high level of understanding, an understanding which mainstream practitioners often do not have. To introduce sustainable material selection to mainstream construction it is necessary to provide more than principles that require interpretation; what is required is a reliable assessment system with unambiguous figures that provide a clear comparison between one material and the next. Such an assessment system needs to be reliable and therefore replicable. A clear structure has to be formulated and the assessments have to be quantifiable. However, due to the wide-ranging and complex nature of the environmental impacts associated with materials it is difficult at best and impossible at worse to make a reliable assessment of all the impacts. Nonetheless, quantitative systems have been increasingly developed and adopted, as they at least in principle appear to provide accuracy to those that rely on them.

The first attempts at measuring the environmental impacts focussed on the energy used to make materials and products: the embodied energy. With the increased understanding of environmental issues, a growing body of research work in this field, and improvements in the technologies for measuring and assessing environmental impacts, new methods of assessment were developed and continue to be developed and refined. The following sections consider a number of systems developed to measure environmental impacts, including measuring the embodied energy, life cycle impacts, materials intensity service (MIPS) and emergy.

3.3.1 EMBODIED ENERGY

The embodied energy of a material or product is the energy required to resource the material, manufacture the product including transportation to the manufacturing plants, transportation to the site and installation. The energy used to produce one year's building material's supply is estimated at 5-10 per cent of the total energy consumption in Britain (Connaughton, 1990, 1993). In principle and based on the current of energy production in the UK which relies predominantly on fossil fuels, the less energy required to manufacture a material the fewer carbon dioxide emissions and in turn a reduced global warming impact will result. Therefore, everything else being equal, materials with the lower embodied energy values should be selected in preference those with higher values. However, this generic principle has many limitations. Firstly, embodied energy only considers one of many environmental aspects, but even accepting this fundamental limitation, the embodied energy calculations suffer from a lack of a standardised measurement system (Lawson, 2002) and are too often used to assess individual materials rather than whole building constructions.

Embodied energy calculations for the same material vary depending on whether primary or delivered energy is used for the calculation; whether transport energy or the energy required to manufacture machinery is included or not (Lawson, 2002). The energy use of different manufacturing plants, fuel efficiency of transport vehicles and other manufacturer-specific contributors to the total energy associated with a material are often ignored (Borer and Harris, 1998). The unit of measure also varies: sometimes embodied energy is measured in kWh per tonne, sometimes per volume. Table 15 lists a selection of materials and their embodied energy stated in different units of measure.

Furthermore, different materials will be required in different amounts for the same purpose, for example the weight of a wall constructed in timber will be much lower than if constructed in concrete, therefore comparing the embodied energy of a kilogram of concrete with one of timber will not be an accurate representation of the embodied energy of the two wall options. Therefore using embodied energy as a measure for selecting materials should consider the construction of the building as a whole. This was done in a study by the Timber Trade Federation (Table 14) that calculates the energy needed to build a 2200m² warehouse using a selection of different building systems (Timber Trade Federation, 1995). A whole structure calculation was also undertaken for the Winter Gardens in Sheffield in which case the laminated timber structure proved to have the least embodied energy when compared to steel and concrete (HAC, 2003).

Table 14 - **US study comparing the energy needed to manufacture and build a 2200 m^2 warehouse using different construction systems**
(Timber Trade Federation, 1995)

Construction type	**Energy in GJ**	**Scale**
Timber throughout	1480	1.0
Concrete block, timber roof	2550	1.7
Prefabricated steel throughout	3150	2.1
Concrete tilt up walls, timber roof	4030	2.7
Prefabricated steel, aluminium cladding	4830	3.3

EMBODIED ENERGY AND WHOLE LIFE BUILDING ENERGY USE

The embodied energy of materials should not be considered in isolation, but rather in the context of the total energy needs of a building including its operation. The embodied energy of a building has been estimated to make up between 10 per cent and 40 per cent of the total energy consumption for a building over 50 years. For contemporary commercial buildings the embodied energy accounts for 10-20 per cent (Cole, 1996) and figures of 15-18 per cent over 60 years have also been quoted (Gorgolewski, 2000). This percentage depends on the life span of the building and the operating energy requirements. As buildings become more energy efficient to run, the embodied energy becomes a more significant percentage of the total. For the typical Swedish house the embodied energy was calculated to be 15 per cent of the whole life energy for an estimated 50 year life and for a low energy home it rises to 40 per cent (Thormark, 2001). Conversely,

Table 15 - **Embodied energy of selected materials**

((1) Talbot, 1995; (2) Berge, 2000; (3) Ethical Consumer Research Association, 1998)

Material	KWh/tonne (1)	KWh/m³ (1)	MJ/kg (2)
Fletton bricks	175	300	2
Non-fletton bricks	860	1,462	3
Engineering bricks	1,120	2,016	3.5
Clay tiles	800	1,520	8
Concrete tiles	300	630	2
Local stone tiles	200	450	0.3
Local slates	200	540	0.1
single ply membrane	45,000	47,000	70
Concrete 1:3:6	275	600	1
Concrete 1:2:4	360	800	
Lightweight blocks	500	600	4
Autoclaved blocks	1300	800	4
Natural aggregate	30	45	
Crushed granite aggregate	100	150	
Lightweight aggregate	500	300	
Cement	2,200	2,860	
Sand/ cement render	277	400	
Plaster/ plasterboard	890	900	5
Steel	13,200	103,000	25
Copper	15,000	133,000	70
Aluminium	27,000	75,600	184
imported softwood	1,450	7,540	3
Timber local airdried	200	110	
Timber local green oak	200	220	
Glass	9,200	23,000	8
Plastic	45,000	47,000	
Polyethylene (PE)			67
Polyvinylchloride (PVC)			84
Plastic insulation		1125	
Expanded polystyrene			75
Ureaformaldehyde			40
Polyurethane			110
Cork			4
Mineral wool		230	16
Cellulose insulation		133	21
Straw bale (3)			0.13-0.25
Woodwool		900	20

the longer the life span of a building, the less significant the embodied energy becomes, making up a reduced percentage of the overall energy requirements. If the embodied energy makes up 10 per cent and the running energy 90 per cent of the total energy use in the first 50 years, over 100 years the embodied energy will have dropped to 5 per cent (Thomas, 1999). According to Grammenos and Russell (1997) designing to reduce the embodied energy can at most reduce it by 30 per cent.

Furthermore, to increase energy efficiency of a building operation more material is usually required and with it an increase in embodied energy typically inevitable. When considering the insulation of buildings in cold and temperate climates, more insulation increases the building's embodied energy and lowers the building's operating energy. For example, the yearly heat loss of a dwelling with a highly insulated external envelope comprising 300mm cellulose insulation was calculated by the author to be 1090kWh/yr, which was two thirds of that of the same dwelling with only 100mm of insulation. The additional insulation was calculated to have an embodied energy of 1416kWh, which was three times the energy saved through its use, resulting in a 3-year payback period. Using insulation with a higher embodied energy would have longer payback periods, but would still be significantly advantageous considering a 50 or 100 year life span. Other calculations suggest that for domestic construction in the UK, the optimum insulation thickness in terms of energy payback is approximately 600mm (Borer and Harris, 1998).

Also to consider is that certain relatively high embodied energy materials contribute to lowering the running energy of buildings. For example, concrete is a material associated with high levels of carbon dioxide emissions, however it also can provide high thermal mass used as part of a low energy strategy to absorb internal and external heat gains and reduce cooling loads. The embodied energy of concrete is often less significant than the operating energy saved through its use, over the life time of a building. Recent research by Arup Research and Development and Bill Dunster Architects (2004) suggests that over a longer period of time and in view of rising temperatures, high thermal mass concrete buildings will prove to have a lower life time energy consumption (operating plus embodied energy) than lightweight buildings made with lower embodied energy materials, such as timber, due to the expectation that lightweight buildings will be requiring additional cooling in future. The exact amount of concrete required to provide a comfortably cool space or indeed if other materials with lower embodied energy could provide the same performance is still disputed. Cole Thompson Anders Architects have been building timber framed buildings using the INTEGER (Intelligent and green) principles and argue that 'It's about achieving the optimal level of thermal mass so you could use double layers of plasterboard, or a little solid flooring in a solar space conservatory. You can also shade the south side of a building and use shutters on the west to protect against the low evening sun, as they do in France and other parts of the Mediterranean. Combine with good through-ventilation and there shouldn't be a problem. Millions of people in the tropics living in timber buildings without air conditioning testify to that.' (Jeffree and Merrick, 2006, p13). This debate simply illustrates the lack of consensus on the matter of embodied energy in relation to whole life energy consumption.

EMBODIED ENERGY AND TRANSPORT

The transportation of materials from the manufacturer to the building site is often by road and is associated with carbon dioxide emission and air pollution. Road freight in the UK accounts for 33 per cent of all transport related carbon dioxide emissions and generated in the order of 40 million tonnes of carbon dioxide in 2007 (Department for the Environment, Food and Rural Affairs (2008a). A significant reduction in the building's total embodied energy can be made by reducing transport requirements and selecting materials manufactured close to the construction site. However, as with the total embodied energy of material the transport energy value should be considered carefully.

It is, for instance, important to consider transport energy in relation to the whole life operating energy. When building in Wales, using Welsh slates involves less transport than using slates imported from Spain or China and does not compromise the building performance. On the other hand, when it comes to certain technologically demanding building elements it may not be possible to source an appropriate quality material or technology locally. If such building products affect the energy efficiency of the building, over the life time of a building, more energy may be saved by installing a high quality, energy efficient building element sourced from further away, which therefore requires more transport energy, than a locally sourced energy inefficient building element.

The type of transport is also to be considered as the impact of different types of transport varies (Table 16). Materials from distant locations that require shipping by tanker may be associated with less energy per km of transport than materials transported by road (Clough and Mertyn, 1995). Furthermore, the same types of vehicles, for example lorries, can have efficiencies depending on the make and the accessories of the transport vehicle.

Table 16 - **Energy requirements of different means of transport** (Berge, 2000, p.17)

Type of transport	MJ/ton/km
Diesel road transport	1.6
Diesel sea transport	0.6
Diesel rail transport	0.6
Electric rail transport	0.2

CONCLUSION REGARDING EMBODIED ENERGY

The amount of energy associated with the building construction and running of a building is crucial in relation to its impact on global warming. However, the embodied energy of individual materials can only be used as an inaccurate guide to establish whether materials have high, medium or low embodied energy. Different constructions can be compared in terms of their embodied energy but such comparisons should take into account the expected life of the building and it projected operating energy. Transport energy can and should be considered but has to be considered for each project individually and accurately.

Even though the embodied energy value of a material appears accurate by virtue of it being expressed with a finite number, the above discussion has highlighted that the number is derived by making a number of assumptions (i.e. manufacturing energy, transport distances) and that it can only be used as one part of an overriding calculation of the whole life building energy consumption.

In future it is to be expected that manufacturing, resourcing and transport efficiencies will increase lowering the carbon dioxide emissions from the life cycle processes (Sturges and Lowe, 2000). Furthermore, it will become more possible to source the energy for the manufacturing processes from renewable, low and even zero carbon dioxide sources and run transport vehicles with zero carbon dioxide fuel such as hydrogen manufactured with energy from renewable sources. It is therefore conceivable that in future the resourcing, manufacturing and installing of materials be undertaken by manual means or with the aid of energy from renewable and zero carbon dioxide sources, ultimately creating buildings with very low embodied energy.

3.3.2 LIFE CYCLE ASSESSMENT

The impacts associated with materials used in buildings start at the beginning of their life as an unprocessed resource and end with their disposal at the end of the material's or the building's life. A life cycle assessment (LCA) goes beyond the calculation of the energy requirements and associated impacts alone and 'addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal' (British Standard Institution, 2006a, p.v). In relation to the building industry the 'product' can be a building material or component or a whole building.

LCAs require large amounts of data on materials and processes to make a full assessment and therefore, what some would consider, partial assessments are no uncommon. One such basic assessment is the so-called 'cradle to gate' LCA assessment, which considers the impact of the manufacture of materials only. A more complete assessment is the 'cradle to grave' LCA, which assesses the impacts of materials and element manufacture, installed in the building, their use and manufacture and finally their disposal at the end of the building's useful life. Cradle to gate LCA is more often used due to the speculative nature of the assumptions relating to the disposal of building materials. Both systems assess the following impacts:

- Resourcing and resource depletion – The availability of the material resource is assessed as well as the risk of it becoming depleted, leaving future generations without that particular resource and, therefore, at a disadvantage.
- Resourcing and resource impact on nature - The extraction or harvesting process itself can affect the surrounding environment and can be associated with pollution, the destruction of natural habitats and the reduction of biodiversity.
- Resourcing and resource impact on humans - The extraction or harvesting of resources can destroy the environments some communities rely on for their survival.
- Manufacturing process - The impacts associated with processing and preparing materials for use can include pollution to air, water and ground. Manufacturing also generally requires energy.
- Energy use – Energy is required for all processes associated with materials, including extraction, transport, manufacture, installation, use and disposal.

- Transport impacts - The transportation of materials from the resource location to the manufacturer to the building site is generally by road and is associated with carbon dioxide emission and air pollution.

A 'cradle to grave' assessment will in addition assess the following:

- Resource use while installed in a building - Maintenance of materials requires both energy and materials and is associated with similar impacts as the construction of buildings albeit at a smaller scale.
- Resources in use – the impact of materials on building occupants.
- Material disposal – At the end of the useful life of a material it may be possible to recycle, reuse or compost it. Alternatively the material may have to be incinerated or landfilled. These different methods of disposal have different environmental impacts, whereby recycling, reuse and composting have significantly less negative impact than incineration and landfilling, which are associated with the use of land, toxic materials leaching into groundwater, emissions of explosive gas and structural instability.

As discussed previously in respect of the Environmental Profile Methodology and Database and similarly to the embodied energy assessment, an LCA has its limitations. Most LCA systems assess a selection of environmental aspects, but not all. Moreover, they typically allocate weightings to the environmental issues considered. The International Standard on LCA (British Standard Institution, 2006a) identifies that weightings introduce a bias: 'Weighting steps are based on value-choices and are not scientifically based. Different individuals, organizations and societies may have different preferences; therefore it is possible that different parties will reach different weighting results based on the same indicator results or normalized indicator results.' (British Standard Institution, 2006a, p.22). This inevitably distorts the assessments and is an inherent limitation. As with the Environmental Profile weightings, the weighting are generally agreed with a broad range of interested parties, from architects to environmentalists; they are nonetheless ultimately subjective.

The European Union funded research project, PRESCO, compared nine LCA systems (Table 17) for building construction and operation and found a discrepancy of the overall assessment of ± 10 per cent. However the discrepancy in respect of the impacts of the building fabric without operation was higher between -15 and +25 per cent. This discrepancy resulted in four of the systems assessing the impacts associated with bricks to be higher than concrete and three lower (Practical Recommendations for Sustainable Construction, 2005). Despite the clear limitations of the model of a Life Cycle Assessment, it has been used as the basis to develop an increasing number of material guides and assessment software, the Environmental Profile Methodology and Database being just one of these.

Table 17- **LCA systems compared by the PRESCO research project** (Practical Recommendations for Sustainable Construction, 2005)

- ECO-QUANTUM (David Anink, W/E Sustainable Building, NL)
- OGIP (Daniel Kellenberger, EMPA, CH)
- EQUER (Bruno Peuportier, ARMINES/ ENSMP, FR)
- ENVEST (Jane Anderson, BRE, UK)
- Eco-Soft (Hildegund Mötzl, IBO, AT)
- BeCost (Sirje Vares, VTT, FI)
- SIMA-PRO (Nico Hendriks, BDA Milieu, NL)
- ESCALE (Jacques & Jean-Luc Chevalier and Sylviane Nibel, CSTB, FR)
- LEGEP (Holger König, ASCONA, DE)

One practical, as opposed to conceptual, difficulty with life cycle assessments is that related to the expense associated with carrying out such assessments, which require large amounts of data to be collected and processed. One approach to fund the research is to assess materials on request and for payment. However many of these systems are developed with industry steering groups who at the same time are requesting tests of their products. A clear potential for conflicts of interest ensues. Where the organisation is state funded such conflicts are less likely, however where the organisation is a limited company the allegiance is transferred from those that benefits from impartial knowledge to those that provide means for the company to remain in operation.

While life cycle assessments theoretically provide a means to comprehensively assess the environmental impacts of material selection, in practice this ambition is hampered by the limitations discussed. Critically it is not only the practice that impedes a comprehensive assessment but the conceptual framework of a LCA, which is intrinsically limited by the inevitably incomplete selection of issues included and the weightings adopted in the assessment.

3.3.3 EMERGY

Emergy is one of a number of less well known assessment systems that attempt to quantify the impacts of human activities that are considered critical in ensuring a healthy environment. It is a system that focuses on energy, as the discussed embodied energy assessments, but takes into account the quality of energy, in other words, its ability to do work.

Emergy is a concept of environmental measurement formulated by Howard T. Odum to account for the fact that the quality of energy may change as its nature is transformed. As energy is transformed its entropy increases decreasing the potential for that energy to do work. Emergy is described as the primary energy, which comes from the sun, before any transformations. Odum also considers the ratio of emergy to energy (the supplied energy), which he calls transformity, whereby a high transformity implies a high quality energy with high potential for doing work (Odum, 2002). Brown and Buranakarn use emergy as a means to assess the advantages of recycling different types of materials. They summarise the concept of emergy in the following manner.

> 'Emergy accounts for, and in effect, measures quality differences between forms of resources and energy. Emergy is an expression of all the energy (and resources) used in the work processes that generate a product or service in units of one type of energy. By definition, emergy is the amount of energy of one form (usually solar) that is required, directly or indirectly, to provide a given flow or storage of energy or matter.'
>
> (Brown and Buranakarn, 2003, p3)

By using the Laws of Thermodynamics Emergy accounting can convert materials and human services as well as energy into a common measure of solar emergy. The emergy of a number of materials, from lead to wool, and environmental forces, such as rain and wind, have been calculated by Brown and Ulgiati (1999), Odum (2002) and Brown and Buranakarn (2003).

3.3.4 MATERIALS INTENSITY PER SERVICE (MIPS)

Life cycle assessments aim to provide a comprehensive assessment for all impacts associated with a material life cycle. Material intensity per service (MIPS) assessment also conceptually offers a system to comprehensively assess environmental impacts by measuring the mass flows and resource use efficiencies. Developed by Friedrich Schmidt-Bleek, of the Wuppertal Institute's Division of Material Flows and Eco-Restructuring, MIPS is a measure of amount of material flows, including water and air, involved in providing a specific service, be it a material good or service such as an hours drive in a car. Manufacturing one tonne of a material may require the moving and processing of many tonnes of materials. Schmidt-Bleek refers to these materials measured in MIPS as the product's or service's Ecological Rucksack. The Ecological Rucksacks of various materials range from less than one to 350,000 for gold. As materials become scarce the material flows increase, conversely the more efficiently designed a product or building is the lower the material flows. Identifying MIPS aims to encourage higher material efficiencies also described as an increase in dematerialisation, which would result in a reduction in MIPS (Von Weizacker *et al.,* 1998).

The MIPS value is made up of the five main categories,

- abiotic (natural non-renewable) raw materials,
- biotic (naturally renewable) raw materials,
- soil,
- water and
- air.

All material is accounted for whether it is used or wasted. The water component consists of the water diverted from its natural path and the air component consists of air that is chemically or physically altered. The air component effectively accounts for carbon dioxide emissions and therefore reflects the material's impact on global warming.

Compared to a LCA assessment MIPS conceptually adds a further dimension, it aims to quantify the impact and make the assessment values explicit. Where LCA systems can in practice only be used to select between various options, MIPS provides quantified values for each of the five categories and could be used to compare products with activities. This knowledge can be used to endeavour to reduce the MIPS and in relation to building design this can be done through value engineering or dematerialisation. Bringezu (2002) sees this as a way to make theory relevant to practitioners. The concept of dematerialisation has been put into practice by Jürgen Bisch in the design of a new office building in Frankfurt where among other initiatives the structure was optimised to reduce the total amount of materials needed to support the building (Bisch, 2002).

MIPS is also, as with LCA, used to compare different option. By measuring the MIPS for different for sewage treatment solutions Reckerzügel and Bringezu were able to advise on the least material intensive option at a local authority level. (Bringezu, 2002) Such assessments require the judgement of the assessor who is given assessments for five categories. Here, similarly to LCAs, personal values will impact on the assessment, although the advantage of MIPS is that the information is available to other assessors to review.

3.3.5 ECOLOGICAL FOOTPRINT

The ecological footprint is another approach that attempts to represent the impact of diverse activities in a holistic manner. As discussed in section 2.2.2 the ecological footprint is the measure of the land and sea needed to sustain human activities in the long term, by providing food, water, energy, materials and assimilating waste.

The ecological footprint can be used to calculate the requirements of a country, building or activity, such as a football match. Sturges and Lowe (2000) believe the fact that the ecological footprint relates the impacts to an area of the earth's surface, of which there is a finite quantity, makes it an ideal method of measurement. Its structure allows for calculating equitable distribution of impacts among people.

The ecological footprint could be a quantifiable and comprehensive method of measuring the impact of materials and buildings as a whole. The detailed data required for such calculations is currently extensive and mainly unavailable but it is conceivable that in future the growing quantity of useful data will enable such calculations.

3.3.6 SECTION SUMMARY AND CONCLUSION

The quantitative systems studies aim to compile and evaluate of the inputs, outputs and the potential environmental impacts of a measurable entity, be it material, building element or whole building or indeed activity throughout its life cycle. This is in line with the concept of life cycle analysis as defined by the British Standards Institute and provides, at least in theory, a quantitative means to compare options. The focus and therefore the entity of measurement are different for each system and this difference reflects the priorities adopted.

In a paper summarising the proceedings of a conference on sustainable materials Lacasse (1999) emphasises the importance of the format of the provision of information. 'Paramount in making informed decisions about environmental issues related to sustainable construction is the manner in which information is collected, formatted and structured.' The strength of the assessment systems discussed lies in their identification of the environmental impacts to be considered and the provision of a structure and units of measure for assessment. The principles adopted by the LCA, MIPS and Ecological Footprint in particular attempt to cover comprehensively all impacts associated with materials throughout their life. The aim of the systems discussed is to provide accessible and easily usable information as advocated by Lacasse.

One weakness of the systems discussed lies in the use of generalised information, which for example does not take into account the supply chain variations that can result from good practice. Generalised information is used due to the difficulty and cost of acquiring manufacturer specific or project specific data. All three systems suffer from the difficulty in acquiring the amount of data required to make the assessment effective. In an ideal world a LCA, MIPS or Ecological footprint assessment would be carried out for each material from specific manufacturers and in relation to a specific site, taking into account as much specific information as possible. Achieving this aim does however currently appear unrealistic.

A second weakness of such systems, as discussed in relation to LCA but applicable to all systems to a degree, is the system bias. The formulation of a system carries the bias of the individuals that formulate it. Therefore, despite apparent impartiality quantitative systems have inherent biases.

3.4 INDUSTRIAL ECOLOGY

Industrial Ecology is a model applied to industrial processes that rejects conventional linear models and implements the principles of systems thinking in an industrial setting. Systems thinking advocates studying systems in their entirety and analysing the operation of the whole organism rather than dissecting systems and analysing individual parts. It represents a holistic and ecological way of thinking that is in contrast with the reductionist Cartesian thinking and has been used to study natural ecosystems as well as man-made systems. Systems thinking considers the interactions of the parts of a system to be as influential on the characteristics of the whole as the individual parts, and it therefore emphasis analysing principles of organisation. It also recognises cyclical systems and feedback loops as form-giving characteristics of systems (Capra, 1997). Industrial Ecology applies systems thinking, and in particular the principles of closed cycles, to industrial processes with the ultimate aim of creating more environmentally sustainable systems. In the last few years the principles of Industrial Ecology have been tentatively adopted by researchers such as Kibert and applied to the built environment including materials.

3.4.1 PRINCIPLES AND DRIVERS OF INDUSTRIAL ECOLOGY

Robert U. Ayres introduces Industrial Ecology by defining its focus as:

> 'to identify opportunities for reducing waste and pollution in the materials-intensive sectors by exploiting opportunities for using low-value byproducts (i.e. waste) of certain processes as raw materials for others.'
>
> (Ayres and Ayres, 1996, p.6)

Industrial Ecology's key aim is to move away from the typically applied methods to deal with waste known as end-of-pipe treatments, which involve redirecting or sequestering waste or diminishing its impact on the environment. Conventional end-of-pipe approaches, which include such approaches as landfill, incineration, sewage treatment, filtering industrial discharges and land remediation, do not eliminate waste or pollution, nor is the material cleaned up put to useful use; they simply redistribute pollution. (Ayres and Ayres, 1996; Erkman and Ramaswamy, 2006; Balkau, 2002). The movement from a linear model, which includes conventional end-of-pipe treatments, to a systems thinking compatible closed loop model is essential to achieve a waste-free system.

Ecosystems in nature are the model upon which Industrial Ecology is based. With solar energy as the only input, natural cycles are closed and balanced systems where all resources are recycled and waste from one organism becomes food for another (Frosch and Gallopoulos, 1989). For instance, nitrogen, which makes up 79 per cent of the atmosphere and is essential for plant and animal growth, is part of a natural closed cycle. Atmospheric nitrogen is transformed into ammonia and nitrate compounds by bacteria and is subsequently taken up by plants, which are in turn eaten by animals. When plants and animals die they decompose through the action of bacteria that release nitrogen gas and nitrous oxide as a by product of digestion back into the atmosphere (Mackenzie, 1998). Another natural closed cycle driven by the sun's energy is that of water, which evaporates from the seas forming clouds which eventually condense into rain. Rainfall can percolate through the earth's surface to ground water or can be diverted on its surface into rivers and other waterways, and eventually find its way back to the sea to start the cycle again.

Ayres proposes that the 'The industrial analog of an ecosystem is an industrial park (or some larger region) which captures and recycles all physical materials internally, consuming only energy from outside the system, and producing only non-material services for sale to consumers.' (Ayres and Ayres, 1996, p.279). The non-material products could include services that are provided by means of a physical element that is dismantled and reintegrated within the system at the end of their useful life.

Jelinski *et al.* (1992) characterise three system models and consider that industry is currently moving from a stage I (linear) to a stage II (quasi-cyclical) model, but must aim for the stage III cyclical model based on the cyclical and closed systems in nature. Frosch (1992) suggests that the movement from stage II to stage III requires fundamental changes and additions to the current systems in operation. The additional operators considered by Frosch to be essential to create a stage III system add to the diversity of the system, which, as in nature, creates a more resilient system. Diversity is also regarded by Korhonen and Snäkin (2005) as a fundamental requirement for implementing the principles of Industrial Ecology. According to Korhonen and Snäkin (2005) stage III systems can only operate if additional operators exist to make use of the waste still in existence in a stage II system.

To move to a stage III, cyclical and virtually closed, system Industrial Ecology adopts principles of 'cleaner production', 'pollution prevention' and 'eco-efficiencies', and aims to combine the processes of material resourcing and the manufacturing of useful products with waste byproducts into an integrated system (Frosch and Gallopoulos, 1989; Korhonen and Snäkin, 2005).

Erkman and Ramaswamy (2006) differentiate between the structure and the processes of Industrial Ecology, which they call Industrial Ecology and Industrial Metabolism respectively. The structure is concerned with the industrial supply chain and the processes of extraction, manufacture and disposal, as well as the technology and organisational structures of industry affecting them. Industrial Metabolism focuses on the material flows of industrial processes. To relate this topic to building design the concept of Industrial Ecology will be considered in respect of its material flows only, in other words: the aspect of Industrial Metabolism as defined by Erkman and Ramaswamy.

ENVIRONMENTAL IMPACTS OF END-OF-PIPE (WASTE) TREATMENTS

Industrial Ecology's concern with waste stems from the realisation that current waste treatments, such as landfill and incineration, in the context of an increasing population, and consequently increasing consumption and waste, are no longer sustainable as the associated environmental impacts can no longer be assimilated by the environment. These treatments also fundamentally fail to utilise waste in constructive ways and therefore do not contribute to reducing the impacts associated with the resourcing of raw materials, the associated transport and manufacturing.

Of particular concern are the environmental impacts of landfill and incineration. Landfill is associated with three main problems. Firstly waste disposal through landfill requires the use of land, which in many densely populated countries is becoming a scarce resource (Advisory Committee on Business & the Environment, 2001). The expected shortage of landfill sites in 30-70 years time will is expected to cause the cost of landfilling to rise significantly in future (Addis and Schouten, 2004).

Secondly, landfill sites are a source of both land and air pollution. Capping and lining landfill sites cannot ensure 100 per cent containment of the toxic materials or the site stability. The toxins leaching out of landfill sites onto land and potentially into the surface and groundwater streams include cyanide, dioxins, mercury, hydrochloric acid, sulphuric acid, lead and others. Air pollutants from landfill sites include VOCs, methane, toluene, benzene, chloroform and vinyl chloride (Enviros Consulting and University of Birmingham, 2004; Herrshkowitz, 1997; Official Journal of the European Communities, 1999a).

Thirdly landfill sites have a negative impact on global warming as decaying organic waste produces the greenhouse gasses methane and carbon dioxide, currently 65 percent to 35 per cent by volume respectively. Methane is a particularly potent greenhouse gas. While methane can be harnessed and used as fuel, such practice is not common. (Enviros Consulting and University of Birmingham, 2004).

Incineration generates toxic air pollutants including dioxins, furans, heavy metals, acid gases, particulates and also generates contaminated ash, which is generally landfilled. The residue consists of up 70 per cent of non-combustible material such as glass or metals and is generally toxic. Contemporary incinerator technology is able to filter a large percentage of these pollutants, but as with the bottom ash the filter ash is toxic and is disposed through landfill (Enviros Consulting and University of Birmingham, 2004; Official Journal of the European Communities, 1999a).

Supporters of incineration suggest it is an energy efficient disposal method, but a Natural Resources Defence Council report concluded that recycling saves more energy than that produced by incineration with energy recovery (Table 18). Furthermore, some materials, such as glass and steel, actually absorb heat and reduce the amount of energy produced by combustion (Herrshkowitz, 1997). Research from Germany supports this these conclusions (Patel *et al.*, 2000).

Table 18 – **Comparison of energy savings through recycling and energy produced by incinerating materials**
(Herrshkowitz, 1997)

Material	**Energy savings through recycling** measured in barrels of oil equivalent	**Energy produced by incinerating** measured in barrels of oil equivalent
Aluminium	37.2	-0.2
newsprint	3.97	2.24
writing paper	3.95	2.24
liner board	2.34	2.24
box board	2.43	2.24
glass recycled	0.9	-0.06
PET	11	6.8
PE	10.8	6.8
PP	10.2	7.3

At a political level waste is recognised as a problem and at the Council of the European Union there is consensus that landfill and incinerations have significant environmental impacts and that therefore alternatives such as composting and recycling should adopted instead. In 2000 the total amount of waste produced in England and Wales was estimated at 400 million tonnes (Department of the Environment, Transport and the Regions, 2000). Most waste in England and Wales is still landfilled but progress in reducing waste to landfill is being made. In the early 1990's 90 per cent of the waste is landfilled (McHarry, 1993), this has decreased to less than 80 per cent by the mid 2000's with approximately 10 per cent being incinerated (Yassin *et al.,* 2005).

Despite the progress, the total amount of waste being produced is not decreasing. In the UK between 1999-2000 and 2006-07 household waste per capita increased by 2.4 per cent (Department for Environment, Food and Rural Affairs, 2008b) and by 2004 it was 20 per cent greater than a decade earlier (Department for Environment, Food and Rural Affairs, 2004). As in other countries of the Organisation of Economic Cooperation and Development and the European Union the waste produced per capita is approximately half a tonne per annum. However the amount of waste going to landfill has decreased and in 2005/6 370kg of household waste per capita went to landfill and the rest was recycled or composted (Worldwatch Institute, 2004; Department for Environment, Food and Rural Affairs, 2008b). This improvement is the result of national and local authorities implementing the European Landfill Waste Directive 1999/31/EC (Official Journal of the European Communities, 1999) which includes targets for reducing, by 2010, municipal waste by 25 per cent compared to 1995 levels. By 2013 reductions should rise to 50 per cent and by 2020 to 65 per cent. The Landfill tax discussed earlier is one of the incentives devised to encourage recycling and diverting waste from landfill.

WASTE AND THE BUILDING INDUSTRY

Buildings are associated with waste production throughout their life, beginning with their construction, continuing through their period in use and ending with their end of life disposal. According to the Department for

Environment, Food and Rural Affairs (2007) the amount of inert construction and demolition (C&D) waste produced annually, which includes refurbishments and renovations, has remained stable for the last five years at 90 million tonnes. In addition waste arisings include 15–20 million tonnes of non-inert and mixed waste, 60 million tonnes of waste from construction-related quarrying and 1.7 million tonnes of hazardous waste. Biodegradable waste makes up less than 20 per cent of the total demolition waste and some of it, such as treated timber, is sometimes classified as special waste (Department of the Environment, Transport and the Regions, 2000). 13 million tonnes of C&D waste is material delivered to sites but never used. (Department of Trade and Industry, 2004)

15-20 million tonnes are thought to be construction waste, the rest is demolition waste. Most of the demolition waste measured by weight is concrete (making up 40 per cent) and masonry (24 per cent). The remaining demolition waste is made up of paper, cardboard, plastic (17 per cent), asphalt (15 per cent), wood based (3 per cent) and other materials (0.6 per cent) (Building Research Establishment, 2003). Construction waste measured by volume is made up of 25 per cent of packaging, 13 per cent timber waste, 11 per cent plaster and cement products, 10 per cent concrete and smaller amounts of other materials (Building Research Establishment, 2003a).

Inert C&D waste is mainly put to beneficial use such as for engineering purposes in exempt and landfill sites and 42 per cent is used as recycled aggregate. 17 to 18 million tonnes of inert C&D waste is disposed of to landfill (Adams, 2003; Department for Environment, Food and Rural Affairs, 2007). The percentage of all waste which is recycled is thought to be approximately 28 per cent, including the above figures, but according to Salvo only 3.3 million tonnes of waste is reused (Hurley *et al.,* 2001).

The UK government supports waste minimisation and recycling as part of a sustainable construction approach. The 2004 Department of Trade and Industry's 'Sustainable Construction Brief 2', suggests a number of themes for action for the construction industry (Table 19). These are directly or indirectly related to construction materials and the reuse or recycling of materials (Department of Trade and Industry, 2004).

Table 19 – **Key themes for sustainable construction from the Sustainable Construction Brief 2** (Department of Trade and Industry, 2004) **and their relation to material design**

Note: themes are shown in italics and comment in parenthesis.

Direct relation to materials	**Indirect relation to materials**
• *design for minimum waste* • *lean construction and minimise waste* • *minimise energy in construction and use* (including embodied energy of materials) • *do not pollute* (material resourcing and manufacture is to be considered) • *monitor and report* (this can apply to the impacts associated with materials as much as any other aspect of building design)	• *preserve and enhance biodiversity* (particularly the resourcing of materials can have indirect impacts on biodiversity) • *conserve water resources* (to a far lesser degree than with energy, the life cycle of materials is associated with water use) • *respect people and local environment* (material selection can affect local economies, livelihoods and local character)

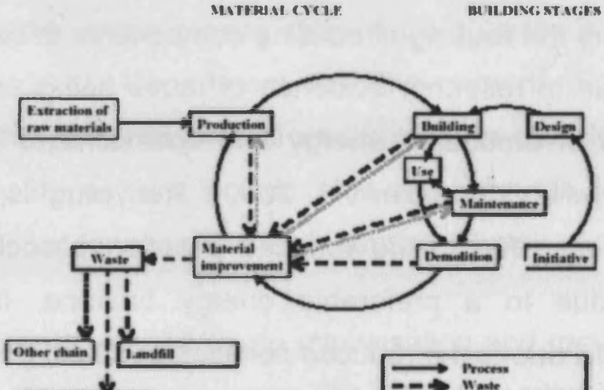
More detailed guidance is provided in the Waste Strategy 2000 for England and Wales, which sets out waste options in descending order of environmental benefit. Prevention or minimisation of waste is identified as the most preferred waste minimisation solution. This is followed by reuse; recovery, which includes recycling and composting; energy recovery from waste through incineration; and finally disposal through landfill (Department of the Environment, Transport and the Regions, 2000). The hierarchy considers the reusing of building components to be preferable to recycling them due to research evidence of reuse being associated with higher reductions of embodied energy and emissions to air and water compared to recycling (Gorgolewski, 2000). Recycling is preferable to incineration, not only due to the reduced pollution associated with the processes, but due to a preferable energy balance. Incineration is preferable to landfill due to the reduced pollution and land use.

Other concepts of waste hierarchies exist. The Dutch government formulated a waste hierarchy twenty years before the UK. The Ladder of Lansink, dating back to 1979, is similar to the UK hierarchy with prevention as the first priority followed by material reuse, then useful application, incineration with energy recovery and finally landfill. The Ladder of Lansink was updated into the Delft Ladder (Table 20), which includes a more detailed prioritisation list. The Delft Ladder is conceived as a more flexible priority list, where the order could change depending on the material's life cycle impacts (Te Dorsthorst, 2000). Furthermore, conceptually it begins to consider material cycles, which are not necessarily closed cycles but begin to suggest that the material cycle could be closed (Table 21).

Table 20 - **Delft Ladder**
(Te Dorsthorst, 2000)

1. Prevention
2. Construction reuse
3. Element reuse
4. Material reuse
5. Useful application
6. Immobilisation with useful application
7. Immobilisation
8. Incineration with energy recovery
9. Incineration
10. Landfill

Figure 21 – **Material cycle as a potentially closed cycle**
(Te Dorsthorst *et al.*, 2000, p. 128).



3.4.2 APPLYING PRINCIPLES IN PRACTICE

The principles of Industrial Ecology gained exposure through the launch of the Journal of Industrial Ecology in 1997 and the foundation in 2000 of the International Society for Industrial Ecology. Yet, examples of the principles of Industrial Ecology put into action exist from before the concept of Industrial Ecology was formulated. For instance, medieval walled cities functioned as closed systems in a symbiotic relationship with the farm land surrounding them. Food from the farmland would feed the city's inhabitants and at the same time the inhabitants' waste, including food and faecal waste, would be collected, composted and used as fertilisers on the farm land (Girardet, 1992). Ayres (2002) describes a number of historic industries that complied with the principles of Industrial Ecology such as meat packing and coke industry. However, as technologies have become more polluting and the economies and management structure have become more complex, the implementation of the principles in practice has been hampered by a number of problems (Van Leeuwen *et al.*, 2003). The organisational aspects of industry and economics mean that the '..feasibility of converting wastes into useful products often depends on two factors: (1) the scale of the waste-to-byproduct conversion process and (2) the scale of demand (i.e. the size of the local market)' (Ayres and Ayres, 1996, p.277) rather than purely technical considerations. Considering the practicalities of applying the principles of Industrial Ecology to industry, a less idealistic concept of the symbiotic relation between industrial processes has been suggested by The United States Environmental Protection Agency, which describes Industrial Ecology Parks as:

> 'A community of manufacturing and service businesses seeking enhanced environmental and economic performance by collaborating in the management of environmental and reuse issues. By working together the community of businesses seeks a collective benefit that is greater than the sum of the individual benefits each company would realise if it optimised its individual performance only.'
>
> (Martin, *et al.,* 1996, p. 11)

In line with this less ambitious definition there are a number of operating examples of Industrial Ecology. An example set up in the 1960s is the industrial park of Kalundborg in Denmark. Here a number of industrial partners exchanged materials and waste and succeeded in significantly reducing the overall waste produced. The partners include (Ehrenfeld and Gertler, 1997; Ayres and Ayres, 1996):

- an energy company that built a cogeneration plant and send the steam to a nearby oil refinery and recovered the calcium sulphate sludge and sold it to a gypsum board manufacturer;
- an oil refinery that recovered sulphur from its excess high sulphur gas and sold the clearer gas back to the energy company and to a gypsum board manufacturer and the sulphur to a sulphuric acid manufacturer;
- the town of Kalundborg that received excess heat from the energy generation plant;
- a local fish farm processed its fish waste and sold it to local farmers as fertiliser; and
- a pharmaceutical company that processed and sterilised waste sludge from a fermentation process and sold it to the local farms as fertiliser.

More recent examples of Industrial Ecology Parks can be found in Finland and include the Uimaharju forest industry park (Korhonen and Snakin, 2005), the Rauhalahti cogeneration plant set up in 1986, the Jyvaskyla industrial ecosystem, which includes a power plant, a sawmill, a forestry company, housing, a farm and the exchange of steam and woodwaste (Korhonen, 2001). Internationally there are examples in China, Denmark, Canada, Australia and India (Tudor *et al.*, 2006).

In relation to the building industry, the term 'ecology' has been used in relation to building (Graham, 2003) and construction (Kibert *et al.,* 2002).

In both cases the ultimate focus is on improving building sustainability in general, but 'Construction Ecology' is derived from Industrial Ecology principles and ultimately modelled on natural closed loop cycles. According to Kibert (2000) materials, figuratively speaking, are the nutrients of buildings. A CLMC in buildings would involve materials being used, recycled, either through natural processes as with biodegradable materials or artificially through a recycling process, and then reuse, recycled and so on. Waste produced at the end of the life a building would become a resource for new buildings or other uses.

To move from theory to practice in the building industry lessons can be learnt from the manufacturing industry and the Industrial Ecology Parks. Here a number of approaches have been implemented. To address technical issues these include: design for environment, pollution prevention, eco-efficiency, industrial symbiosis, materials flow studies, and dematerialisation. To address social economic issues these include: supply chain actions and green accounting (Lifset and Graedel, 2002; Ayres, and Ayres, 1996). These approaches share a number of methods for implementation. The next sections discuss the four main methods advocated by Ayres for raising productivity of material resources in Industrial Ecology (Ayres, and Ayres, 1996). These are divided into two groups in line with the Industrial Ecology principles of dematerialisation and rematerialisation (Bringezu, 2002).

Dematerialisation - Dematerialisation focuses on the material and product creation aspects, whereby the aim is to reduce material flows in absolute and ensure they are not polluting. This includes Ayers and Ayres' (1996) principles of:

- dematerialisation (increasing functionality per unit mass of material) and
- hazardous and scarce material substitution.

Re-materialisation – Re-materialisation focuses on the minimisation of waste by encouraging harvesting and giving a new lease of life to waste. This includes Ayers and Ayres' (1996) principles of:

- repair, reuse and recycle and
- waste mining (developing efficient recycling technologies to maximise recovery rates).

3.4.3 IMPLEMENTING DEMATERIALISATION

The aim of industrial ecology is not only to move towards cyclical material flows but also to reduce flows in absolute and ensure the materials are non-polluting. Dematerialisation describes the process of designing systems to deliver services with less resource inputs. This combined with the selection of non-polluting materials results in more sustainable products which can more easily re-materialised, as will be discussed in the next section.

Higher material efficiency can be achieved by:

- material or technology substitution to achieve the desired aim with less resource;
- material optimisation to achieve the desired aim with less of the original resource;
- design for longevity, extending the useful life of a product and increasing material productivity; and
- move towards a service society and focusing on the service and not the product.

(Ayres and Ayres, 1996; Erkman and Ramaswamy, 2006)

MATERIAL OR TECHNOLOGY SUBSTITUTION

Changes in technology can improve efficiencies (De Bruyn, 2002; Von Weizsaecker *et al.,* 1998). The miniaturisation of electronics industry is an example of new technologies associated with smaller material flows. In the building industry examples include the development of single ply membranes mechanically fixed which can be used instead of three layer felt roofing applied with asphalt; light gauge metal studs used to infill in steel or concrete frames in substitute of concrete blockwork; suspended beam and block floors that obviate the use of hardcore and sand blinding; and the composite timber studs that make use of waste timber material for the stud web in substitution for solid timber studs.

MATERIAL OPTIMISATION

Material optimisation aims to do more with less, in other words perform a task (e.g supporting a building) with less than the material used in traditional solutions. Examples in the product industry include the aluminium cans made with thinner but profiled and therefore stiffer sheets of aluminium. In the building industry material optimisation can be achieved through value engineering of design and construction. Building without excess is the aim, whether in terms of size of building or material used.

Walter Segal's approach of designing buildings on a grid that coincided with off-the-shelf material sizes in order to reduce the amount of material needing to be cut meant by default that less material was used to achieve the same aim (McKean, 1989). In a similar way architects Siegel and Strain were able to value engineer a standard timber frame house design for a housing association in Oakland, USA. The Resourceful Building Project, as it was called, resulted in a structure that was less material intensive and the savings made were invested into increased insulation and other environmental features (Sassi, 2006a).

Material efficiency can become a design criterion. A double hourglass gridshell structure was selected for the Weald and Downland gridshell due to it being the most material efficient gridshell form that exists, achieving the desired span and strength with small timber sections and relatively little material (Harris *et al.*, 2003). Jurgen Bisch, principal architect of Seegly and Bisch Architects based in Nurnberg, Germany, applies the principles of dematerialisation in a structured manner to all the architectural projects dealt within his office. The practice has successfully reduced the material used for constructing offices and other building types by value engineering the structure, omitting raised floors and suspended ceiling and accommodating services in alternative ways, and by designing for passive environmental systems, and has quantified the reduction in material used (Table 22) (Bisch, 2002).

Table 22 - **Savings realised through dematerialisation process in practice** (Bisch, 2002, p.254)

No	Description of type of reduction (units)	Quantity
1	Building height (metres)	3.5
2	Area of type B building materials (sq metres)	
3	Area of suspended ceilings (sq metres)	36,000
4	Area of double floors (sq metres)	28,000
5	Volume of type A materials – alum/glass façade (sq metres)	3,010
6	Concrete (cu metres)	230
7	Fire prevention costs – fewer fire escapes (percentage)	2
Total cost reduction as percent of building budget (percent)		**8**

Reducing materials used in a structure may, however, not always achieve the desired dematerialisation effect. Kibert warns that reducing material use in individual buildings may in fact have the effect of increasing resource use where material is used as part of an environmental strategy (e.g. concrete for cooling with thermal mass). He suggests that dematerialising the construction industry would involve a broader scope and one that is linked to the re-materialisation aspects of Industrial Ecology. 'Focusing on building longevity, durability, adaptability, deconstructability [making buildings readily able to be disassembled], recyclability, and the social/cultural impact of the building can greatly decrease the throughput of materials even if the actual mass of the building is unchanged.' (Kibert, 2000, p.178) Dematerialisation in the construction industry may involve reducing the material throughput or flows during a set period of time relative to the industry as a whole rather than reducing the materials in an individual building.

A significant contribution towards dematerialisation can also be made during the construction process. Once a project is on site, the combination of good site practice and a thought-through design can reduce the amount of offcuts, abortive work, and materials that are delivered to site, not used and then landfilled.

Considering broader aspects of dematerialisation includes considering material use per person as well as per building. In practice the building occupancy is not determined by the building design. For offices, for instance, the fit-out of the building is what determines how efficient the space is used. In housing, the design of the dwelling can affect the efficiency but so can occupancy habits. A microflat is an example of efficient use of space and materials, whether inhabited by one or two individuals. Average sized houses, such as a three bedroom terrace, could be occupied by a single individual, and therefore could be described as material wasteful, or a family of four. The efficiency is dependent on the building occupancy. At top end of the scale, assuming the average UK household size of three, an assumption could be made that dwellings with more than eight living, sleeping and working areas are unnecessarily large. Here the opportunity for dematerialisation lies in designing minimum size dwellings that feel generous.

DESIGN FOR LONGEVITY

The longer a material, product or building remains in use the lower its environmental impacts per year become. As mentioned in relation to embodied energy, if the total embodied energy or total environmental impacts of a material over 50 years are x, per year this will equate to x/50. If the material's useful life is extended to 100 years, taking into account additional maintenance impacts its yearly impact will be (x plus maintenance)/100, which could be as little as half the impact for maintenance-free materials.

In the UK, there are many buildings that remain into use for centuries. Ranging from small cottages to large public buildings, these buildings may have retained their original use or undergone one or more changes of use. Changes in a country's economy can impact on the need for different types of buildings resulting in refurbishments of, for example, Victorian warehouses into offices, 1960s offices into housing, and agricultural or industrial buildings into exhibition spaces. Even when the use of the building nominally remains the same, as with housing, the needs of users can change over the years, resulting in alterations and extensions, such as converting from cellular to open plan living and roof extensions.

Designing a building for longevity means that it must maintain its performance and its desirability while accommodating changes. For building elements and components durability and ease of maintenance can help maintain a good performance and ultimately desirability. Buildings designed for flexibility, in other words, building that allow their reconfiguration with minimal effort, can more easily accommodate change.

The office design industry is a mature industry in terms of designing for flexibility. The British Council of Offices recommends designing offices to cope with a variety of loads to allow for a change of use and extensions to existing structure. The structure may consequently be overdesigned but is likely to have a longer life (British Council for Offices, 2005). Framed structures allow for the removal of internal walls while remaining structurally intact and therefore facilitate the reconfiguration of interiors (Duffy and Henney, 1989). The ability to alter the internal layouts in offices is facilitated by a well-established industry for demountable partitions, which, at least in theory, not only can be removed but also reused.

Housing design has also been considered with the aim of creating adaptable spaces that address the requirements for change and for lifetime homes. Issues of space planning, construction and detailing have been identified as affecting the flexibility of housing design (Habraken, 1972; Friedman, 2002; Schneider and Till, 2007).

TOWARDS A SERVICE SOCIETY

The durability of building elements and materials affects the longevity of buildings and currently the responsibility for maintaining or replacing a building element is transferred from the contractor or supplier to the building owner. This creates little incentive to build or supply buildings and building element that are durable and require minimal maintenance. The concept of a service society avoids this transfer of responsibility, which therefore remains with the contractor or supplier who consequently has an interest in creating durable and easily maintained structures.

One of the first building industry related companies that implemented a service society model of business was Interface, the US based carpet manufacturer. Interface developed a carpet that could be recycled virtually one hundred per cent and rather than selling it to customers it was leased. Interface leased the service of providing a carpet finish to the customer which included maintaining and upgrading it as necessary. (Hawken and L Studio, 1997)

3.4.4 IMPLEMENTING RE-MATERIALISATION

Re-materialisation complements dematerialisation. Re-materialisation aims to put material to the best possible use after the end of its initial useful life. Making use of materials already in existence minimises the need for new materials and therefore reduces the resourcing and manufacturing impacts associated with new material production (Commission of the European Communities, 2003). Re-materialisation also prevents materials from entered the waste stream and consequently reduces the impacts associated with waste disposal.

To implement the principles of re-materialisation, Industrial Ecology promotes the repair, reuse and recycle of materials and products and the principle of waste mining. Waste mining is defined as developing systems to facilitate and maximise the efficiency with which materials are recovered for further use at the end of the product's life (Ayres and Ayres, 1996). Applied to buildings, the principle of waste mining involves designing buildings to enable their disassembly or deconstruction and the recovery of building materials and elements for reuse or recycling. Design for disassembly applied to a whole building level is rare, but, as will be discussed in Chapter Five, there are numerous building systems that have been designed for flexibility (such as demountable office partitions), ease of installations (toilet cubicles) and even reuse (temporary buildings) and these systems are easily dismantled facilitating their reuse and recycling.

While the concept of waste mining is relatively new, the principles of repair, reuse and recycle are well understood in relation to buildings and building materials, as are the associated environmental benefits (Coventry *et al.*, 1999). The greatest benefits are thought to be achieved through reusing building elements rather than recycling them (Thormark, 2000; Gorgolewski, 2000) and the reductions in embodied energy achieved through reusing and recycling have been documented (Kibert, 1999; Crowther, 1999). Reductions in embodied energy have been calculated for individual materials. For instance, aluminium manufactured from ore requires 180-250GJ/tonne (77 per cent of the energy requirements are necessary for the electrolytic reduction and 17 per cent for alumina refining), while aluminium manufactured from recycled material requires 10-18GJ/tonne (Ethical Consumer Research Association, 1995). The use of recycled glass cullet in the manufacture of glass results in a 6 per cent reduction in energy consumption compared to the use of virgin material (Dacombe *et al.,* 2005). Whole building embodied energy calculations have also been undertaken. Thormark (2000) reports on an experimental Swedish house erected at the Building Exhibition in 1997 containing a significant proportion of recycled materials, including 70 per cent of the steel from reclaimed sources, that was calculated to have 60 per cent of the embodied energy of the control house. Thormark also reported calculations based on a number of different case study buildings suggesting that the use of recycled materials can save between 37-40 per cent of the whole building embodied energy. Connaughton (1993) considered that a few materials, including steel and iron products, timber, concrete and cement and ceramic products account for up to 50 per cent of the total embodied energy of a new building, due to their embodied energy and the quantities used in construction. He then calculated that by using recycled versions of these materials the embodied energy could be reduced up to 30 per cent. Gorgolewski (2000) calculated the combined embodied and operating energy of a commercial office building over 60 years and concluded that the use of recycled materials could contribute to a reduction 3 per cent of the total energy.

The use of reclaimed and recycled materials in the building industry is also well understood and has a long tradition. Examples of reused structures range from historic examples of note, such as Crystal Palace, to small scale domestic reuse (Hudson, 1994). Historically reuse and recycling was driven by economic and not environmental considerations and today this is still largely the case. Where the economic argument proves favourable building materials and elements are reclaimed and sold for reuse. Contractors report that reclaiming asphalt, concrete, timber, metals and historic salvaging, for recycling or reuse can represent 20 to 40 per cent of some demolition companies' revenues (National Association of Demolition Contractors, 1999). The cost of scrap material has to be high enough to warrant the collection, but when it is contractors do recycle. For instance, nearly 58 per cent of scrap copper and 50 per cent of steel is recycled to produce new material and stainless steel is nearly entirely produced from recycled steel (Construction Industry Research and Information Association, 1995).

The practice of repair, and in particular, reuse and recycling has been included in building-related guidance and typically considers whole buildings, building elements and materials. The German Association of Engineers guidance on recycling in the building industry ranks three end-of-life treatments in order of environmental preference (Verein Deutscher Ingenieure, 1993). The first and most environmentally beneficial level and the second level advocate reuse, the third level advocates recycling. These priorities are the same as those set out by the waste hierarchy of the Delft Ladder and the Waste Strategy 2000 for England and Wales. Table 23 compares these with the Industrial Ecology principles of repair, reuse and recycling.

Industrial Ecology's principle of repair, in respect of buildings, can be considered equivalent to Addis and Schouten's definition of recondition (2004, p.8) , which implies a low key intervention and the retention of the original use. It also suggests an intervention in situ and therefore not involving deconstruction or dismantling.

Industrial Ecology's concept of reuse and that adopted by the German Association of Engineers and others (Herley *et al.,* 2001, Addis and Schouten, 2004) involves taking buildings or elements and putting them back into use 'without major prior reprocessing to change their physical characteristics' and '[w]hile [reuse] does not include reprocessing, it might involve some reconditioning' (Addis and Schouten, 2004, p.9). As opposed to repair, reuse of building elements implies a process of deconstruction or dismantling and the extraction of an element and more often than not a reuse in another building. Whole building reuse may involve minimal interventions, more akin to repair or reconditioning, or extensive interventions where everything except the building structure is removed and replaced.

There is some ambiguity about the Delft Ladder's use of the term reuse in relation to materials, as it refers to the reprocessing of materials through recycling. The difference between reuse and recycling according to Addis and Schouten (2004) and Hurley *et al.* (2001) is on one side the integrity of the element is retained with reuse and on the other hand the extent of work required to create a material or element ready for a second life tends to be greater with recycling, hence the environmental preference of reuse (Thormark, 2000; Gorgolewski, 2000). Interestingly, Industrial Ecology's

Table 23 - **Industrial Ecology re-materialisation principles compared to the Delft Ladder and the German Association of Engineers guidance on recycling in the building**

Industrial Ecology re-materialisation principles	**Guidance on buildings and recycling** (Verein Deutscher Ingenieure, 1993)	**Delft Ladder** (Te Dorsthorst, 2000)
Repair		1. Prevention– waste prevention in design and construction
Reuse	Level 1 - Reusing whole buildings - Buildings are refurbished, reusing the whole building or elements of the building such as its structure.	2. Construction reuse– reuse of buildings or significant parts of buildings.
	Level 2 - Reusing components of buildings - Components are salvaged from buildings and reused elsewhere, such as whole windows or timber floors by reinstating them virtually unprocessed in a new location, in particular period elements such as doors or fireplaces.	3. Element reuse– reuse of building elements or material with minimal reprocessing requirements.
Recycling	Level 3 - Reprocessing materials from buildings to produce new building materials - Components are removed and reprocessed to form new materials either identical to the source material, as when metal is recycled into new metal, or to a lower grade material, such as when concrete is reprocessed to form hard-core. The transformation of a material to a lower grade use material is known as downcycling.	4. Material reuse– material recycling 5. Useful application– material downcycling or composting
Not desirable as not part of a closed cycle.		6. Immobilisation with useful application – energy generation 7. Immobilisation 8. Incineration with energy recovery 9. Incineration 10. Landfill

principles advocate reuse even though, as will be discussed later, reuse alone does not necessarily constitute a closed cycle.

There is also ambiguity about the term recycling. Both the Delft Ladder and German Association of Engineers include downcycling as part of the recycling concept. While the processes involved in downcycling and recycling may be similar and involve a similar level of effort and energy, the end product may be very different, particularly in terms of compatibility with Industrial Ecology's principles of close cycles. The concept of a closed cycle is clearly incompatible with the end-of-life options of immobilisation, incineration (even with energy recovery) and landfill, and as will be discussed late, the concepts of downcycling and in certain instances recycling are equally incompatible.

3.4.5 SECTION SUMMARY AND CONCLUSION

Industrial Ecology's principles to achieve sustainable systems by creating closed material cycles that avoid waste and minimise pollution are not only compatible with sustainable principles related to the building industry but have also been implemented in the building industry, if not in a holistic manner at least to a certain degree.

The implementation strategies advocated by Industrial Ecology and their application in relation to construction materials include the following:

1. Dematerialisation 1 (i.e. increasing functionality per unit mass of material) through
    - Material or technology substitution to achieve the desired aim with less resource (e.g. new polymer products such as single ply waterproofing membranes).
    - Material optimisation to achieve the desired aim with less of the original resource (e.g. value engineering, designing in line with materials sizes).

- Design for longevity (e.g. extending the useful life of a building or building element and increasing material productivity by selecting durable materials and designing to allow for ease of maintenance and adaptability).
- Move towards a service society (refocusing on function of object rather that object itself and reconfigure the provision for it).

2. Dematerialisation 2 - Hazardous and scarce material substitution (this follows the principles and methods discussed in relation to natural building technologies).

3. Re-materialisation 1 - Repair, reuse and recycle through:
   - Construction reuse (e.g. reconditioning buildings for reuse of whole buildings or significant parts of buildings).
   - Element reuse (e.g. reconditioning building elements for reinstatement in existing or new building).
   - Material recycling (e.g. reprocessing of materials to form new building elements).
   - Useful application (e.g. material downcycling or composting).

4. Re-materialisation 2 - Waste mining (e.g. developing efficient technologies to maximise recovery rates).

A critical view of the methods advocated in the Industrial Ecology literature suggests that the concept of repair, reuse and recycle requires further discussion as it does not comply totally with the principle of creating closed cycles. This will be further discussed in Chapter 4.

3.5 COMBINING APPROACHES AND APPLYING TO PRACTICE

Sustainable building material design seeks to minimise the environmental impacts associated with all aspects of material use. The material philosophies discussed share this overall aim but advocate different approaches to its implementation, which reflect different priorities inherent to the philosophies. The case studies analysed in Chapter Two illustrate the opportunities for implementing sustainable material design in practice and in certain cases a clear relation to the material philosophies discussed can be seen. To comprehensively address sustainable material design, in line with a comprehensive approach to creating sustainable built environments, the three approaches and philosophies will be considered together. This concluding section to Chapter Three proposes an approach to sustainable material design that combines the three philosophies and therefore begins to create a comprehensive approach to sustainable material design. It also considers how such a comprehensive approach could be implemented in practice.

In comparing and combining the approaches and then relating them to building development practice the following aspects are considered:

- the environmental benefit of the approach or the environmental impact associated with not adopting a specific approach;
- the nature of the implementation of the approach;
- the individuals responsible in the building industry for instigating or executing the implementation and the implementation methods used.

3.5.1 ADDRESSING THE ENVIRONMENTAL IMPACTS

A comprehensive approach to sustainable material design should address, ideally, all environmental issues that are relevant to material design. To identify these issues the material philosophies studied were analysed in terms of the level of concern regarding specific environmental issues or priority give to specific issues, as evident from the literature. Using the outline of a LCA tools, a matrix was used to record and compare the foci of different philosophies. Issues that were not included in the LCA outline were added. Table 24 lists the environmental impacts that occur at the key life cycle stages of a material and identifies the priority given to the issue by the different philosophies. The table identifies issues of explicit high priority and key concern with a number 2, implied and secondary concerns with a number 1 and negligible concerns with a number 0.

The comparison shows a significant overlap of concerns and consequently approaches addressing the same impacts. However, some approaches, including Natural Building, LCA, Ecological Footprinting and Industrial Ecology, address environmental issues in a more comprehensive way; while others are one focus approaches, only concerned with other issues by implication or as of secondary importance. Certain philosophies, such as embodied energy assessments, have a very narrow focus that virtually disregard all other environmental issues.

3.5.2 THE NATURE OF THE IMPLEMENTATION

Most of the material or related philosophies advocate a number of approaches for implementation. Table 25 expands on the previous table by adding design and construction strategies advocated by the different philosophies to minimise the environmental impacts associated with each stage of the lifecycle of a material or building product. Some philosophies or assessment systems do not recommend or even suggest means of implementation beyond very broad principles. These include ecological footprinting, which is used as a measurement or monitoring tool only; and embodied energy and Emergy calculations, which mainly measure energy and only advocate a reduction in energy use but do not provide suggested means to achieve that.

Table 24 - **Comparison of priority given to environmental impacts by a selection of sustainable material approaches and philosophies**

Key: 2 = explicit high priority and key concern
1 = implied and secondary concerns
0 = negligible concerns

Processes associated with potential environ-mental impacts	**Environmental impacts**	**Natural building**	**Healthy buildings**	**Embodied energy**	**LCA**	**Emergy**	**MIPS**	**Ecological footprinting**	**Industrial ecology**
Material resourcing	Material depletion	2	0	1	2	0	2	2	1
	Pollution to air, land and water	2	1	0	2	0	1	2	2
	Energy use (resource depletion and global warming)	2	0	2	2	2	1	2	1
	Habitat destruction and loss of biodiversity	2	0	0	1	0	1	1	1
Manufacturing	Energy use (resource depletion and global warming)	2	0	2	2	2	1	2	1
	Pollution to air, land and water	2	1	0	2	0	1	2	2
Material transport	Pollution to air	1	0	0	2	0	1	2	1
	Energy use (resource depletion / global warming)	1	0	2	2	2	1	2	1
Material installation	Local noise and pollution to air and water	1	1	0	0	0	0	1	0
	Energy use (resource depletion / global warming)	1	0	2	0	2	1	2	0
	Pollution through application	2	2	0	0	0	0	1	1
Material use and maintenance	Material depletion	2	0	0	2	0	2	2	1
	Pollution to air, land, water	2	1	0	2	0	1	2	2
	Energy use (resource depletion / global warming)	2	0	2	2	2	1	2	1
	Habitat destruction and loss of biodiversity	2	0	0	1	0	1	1	1
	Indoor air pollution	2	2	0	1	0	0	0	1
Material disposal	Pollution to air, land and water	1	1	0	2	0	1	2	2
	Land depletion	1	0	0	1	0	1	2	2
	Energy use (resource depletion and global warming)	1	0	2	2	2	1	2	2
	Habitat destruction and loss of biodiversity	1	0	0	1	0	1	1	1

Each approach addresses specific environmental impacts and some approaches address more than one environmental impact. Furthermore, some approaches reduce all impacts associated with material use. For example, the use of recycled materials will circumvent the environmental impacts associated with resourcing processes altogether and it will reduce many of the environmental impacts associated with manufacturing, and reducing the amount of material use by building small, using existing buildings and value engineering, reduces the quantity of all the impacts.

The approaches listed in Table 25 affect different aspects of the building construction process and final product. They can influence:

- the quantity of material used;
- the selection of material type e.g. timber rather than steel, or recycled rather than virgin;
- the selection of material resourcing and manufacturing processes e.g. certified timber rather than uncertified timber, or air dried rather than kiln dried timber;
- the supply of a material e.g. locally resourced rather than resourced from afar;
- the installation methods e.g. screw fixed rather than glued; and
- the on-site processes e.g. hand installed rather than machine installed.

Some of these approaches fundamentally affect the planning and appearance of a building, while others, such as those concerning the supply of materials, do not affect the end product but rather the construction process. Consequently implementing the approaches advocated relies on different player in the building industry responsible for and with interests at different stages of a building development. It also relies on different tools for delivering the sustainability improvements.

Table 25 - **Design and construction strategies to minimise environmental impacts**

Processes	**Environmental impacts**	**Design and construction strategies to minimise impacts**					
		Strategies that address individual impacts		Strategies that address more than one impact		Strategies that address all impacts	
Material resourcing	Material depletion	• Use renewable materials with short regeneration cycles • Use plentiful materials and avoid scarce resources • Specify timber from managed and accreditation sources	N L M F	• Use reused / recycled materials to eliminate resourcing impacts	E L M F IE	• Build small and only if and what is required - dematerialise	IE
	Pollution to air, land and water	• Select/ specify materials associated with low levels of pollution - dematerialise • Request material supplier's environmental credential to ascertain pollution control methods	N L F IE			• Make effective use of material by value engineering and avoiding unnecessary designs - dematerialise	IE
	Energy use (resource depletion and global warming)	• Select/ specify materials with low embodied energy • Request material supplier's environmental credential to ascertain the use renewable energy, human power and energy efficiency measures	N E L F				
	Biodiversity /habitat loss	• Select/ specify materials mined, harvested or extracted with minimal impact on local and global environment and from suppliers with reinstatement plans	N			• Reuse buildings (note: reuse of buildings does not necessarily reduce the impacts associated with use and maintenance)	M F
Manufacturing	Energy use (resource depletion and global warming)	• Select/ specify materials associated with low levels of pollution • Request manufacturer's environmental credential to ascertain the use renewable energy, human power and energy efficiency measures	N E L F	• Use reused and recycled materials reduces impacts	E L M F IE		
	Pollution to air, land and water	• Specify materials associated with low manufacturing pollution - dematerialise • Request manufacturer's environmental credential to ascertain pollution controls	N L F IE			• Design for desirability to maximise the building life	IE
Material transport	Pollution to air Energy use	• Select/ specify local materials • Request manufacturer's environmental credential to ascertain the use energy efficient transport • Reuse and recycle material s on site			E L F	• Specify materials associated with low levels of carbon dioxide emissions over the life time of the building considering their impact on saving running energy	N IE
Material installation	Energy use	• Specify installation methods that use renewable energy, human power and energy efficiency measures			E L F		
	Pollution from application	• Select/ specify materials that do not constitute a hazard to health			N H		
Material use and maintenance	Material depletion Pollution to air, land, water Energy use Biodiversity /habitat loss	• Same approaches as for resourcing, manufacturing transport and installation • Design for ease of repair • Use durable materials • Use reused and recycled materials			N E L M F IE	• Consider suppliers', manufacturers' and contractors' environmental policies, track record and reporting systems – clean technologies	IE
	Indoor air pollution	• Specify materials that do not constitute a hazard to health			N H		
Material disposal	Pollution to air, land and water Land depletion Energy use Biodiversity /habitat loss	• Design for flexibility and design / develop systems for reuse and recycling or to enable the biodegrading of materials (rematerialise/waste mining) • Adopt waste prevention measures on site during construction and demolition • Adopt material recovery procedures during demolition - rematerialise			E L F IE		

Table 25 - **Design and construction strategies to minimise environmental impacts**
he design and construction strategies are set against the environmental impacts throughout the life cycle of a building and are identified in terms of the philosophies and assessments they were derived from.

Key:	E = Embodied energy and Emergy calculations
N = Natural building	M = MIPS and mass balance assessments
H = Healthy building	L = Life cycle assessments
F = Ecofootprinting	IE = Industrial Ecology

3.5.3 DRIVERS AND TOOLS OF IMPLEMENTATION

The main stakeholders influencing the decision-making include building clients, designers and contractors, each involved in different ways and with unique spheres of influence (Addis and Talbot, 2001).

- **Building clients and potential owners and users** influence building design by formulating the building brief that sets out the parameters for the project and may include specific sustainability targets and requirements. They ultimately control the budget and agree expenditure that may increase by adopting sustainable design approaches. Building owners and users are also responsible of the maintenance of the building and set the parameters for undertaking maintenance work, which as discussed, has the same environmental impacts as construction activities albeit to a lesser degree.

- **Building designers** are responsible for preparing the design and specification of the project in response to the client brief and budget. The design and specification is highly influential in respect of sustainable material use, having the potential power to affect all subsequent phases of a building life, including the construction process of the building, its maintenance and demolition. In line with the Construction (design and management) Regulations 2007 (Heath and Safety, 2007) the designer is required to consider the health and safety impacts associated with the maintenance and disposal of the building. The consideration of these future phases of a building's life is therefore a legal requirement in respect of health and safety at least. The design of a building also impacts on the ease with which maintenance is undertaken.

- **Building contractors** are responsible for the implementation of the design and specification provided by the building designer. The design and specification of a building affect but do not necessarily dictate what the construction processes are. If not stipulated in the building specification, building contractors are responsible for selecting building methods, suppliers, manufacturers, site setup and site procedures and can make contributions towards improving the sustainability of a project within these areas of influence.

The opportunities for implementing different approaches occur at different times throughout a project life and the earlier phases tend to affect the subsequent ones. There are five main phases during which different approaches can be adopted (Lupton, 2008; Office of Government Commerce, 2005):

- **The brief development phase**. (RIBA stages A and B (Preparation) and the OGC Gateway 1). Activities at this stage are largely driven by the client, with help from consultants and or building designers.

- **The design and pre-construction phases**. (RIBA stages C to H and the OGC Gateways 2 and 3 including decision points for detailed design). The main players at these stages are the building design team and the client, with sometimes the building contractor having an input depending on the contractual agreements.

- **The construction phase**. (RIBA stages J and K completing with OGC Gateway 4 Readiness for Service). The influential elements at this stage are the building design and specification and the site procedures, the latter or which are influenced by the contractor in charge on site.

- **The maintenance phase**. This phase includes the RIBA stage L Post Practical Completion but extends beyond it. The OGC Gateway 5, Benefits Evaluation, is expected to have to be repeated throughout the life of the building. This phase is affected by the client, designer and contractor in the same ways as described above, but also facilities managers.

- **The building disposal phase**. The disposal of a building is often the beginning phase of a new building and is therefore affected by the development brief and design specification for the new development. In all cases the building disposal phase is influenced by the requirements of the client and the approach to waste adopted by the contractor.

The main documents for implementation are the project brief and the project design and specifications. While sustainable site practice can be implemented voluntarily by the contracting team it is currently still dictated by these contract documents.

- **The project brief** stipulated by the client sets out the tone as well as firm targets for the project, which include those relating to sustainability. The brief therefore the key driver for all that follows, and '[to] deliver sustainable construction, it is vital that sustainability criteria form an integral part of the briefing process from the inception of the project.' (Addis and Talbot, 2001, p. 108). The brief is not necessarily a direct implementation instrument for sustainable material use, as it defines aspirations but only in rare cases elaborates how to achieve these. The implementation is left to subsequent stages.

- **The project design and specification** developed by the building designer implements the aims set out in the development brief but also independently influences the project sustainability. It defines the design, material and can stipulate the appointment of suppliers and sub-contractors (Joint Contracts Tribunal, 2007). The design and specification are critical to implementing sustainability in practice; as, while sustainable material selection can be initiated by the contractor during the building phase, unless a requirement for addressing the environmental aspects can be integrated within the contractual documentation it can not be taken for certain that such approaches will be adopted. For instance, if a product such as a dpm is specified by means of a performance specification only (i.e. gauge, vapour transmission) and not by manufacturer or product name, the on-site team can procure the dpm from a manufacturer that makes a dpm with polyethylene (PE) from primary sources or from a manufacturer who makes dpm from recycled PE. Recycled PE dpm has the same performance characteristics as the dpm produced using primary material. To be sure that the recycled dpm is installed it is necessary that the exact material specification including recycled content is specified, giving the contractor if necessary the choice of substituting the specified material with a similar and approved one (Joint Contracts Tribunal, 2007). In respect of waste minimisation the situation is similar. The contractor can choose to segregate waste and recycle it and by doing so is likely to achieve a cost saving (Building Research Establishment, 2003), but many contractors are still not taking advantage of the potential savings to be made through waste minimisation and to ensure that waste minimisation on site takes place it needs to be specified in the contract documents.

- While the bulk of a building specification is made up of material, building element and workmanship clauses, the **specification preliminary** clauses address general site procedures and processes (Joint Contracts Tribunal, 2007). A building specification can therefore stipulate site material storage, material fixing methods, site waste segregation and much more.

3.5.4 IMPLEMENTATION OPPORTUNITIES

In order to investigate how the stakeholders, building clients, designers and contractors, can operate and use the implementation documents to ensure the sustainability of a building's material design, the sustainable material design and construction strategies have to be related to the implementation documents.

The first step is to relate the implementation documents to the sustainable material strategies. Table 26 provides a structure to consider the sustainable material design strategies from the point of view of opportunities for their implementation. The environmental impacts were necessary to identify the sustainable material design strategies and can now be omitted.

The second step is to change the focus to the implementation documents. Rather than grouping the approaches by environmental impact and life cycle stage, Table 27 groups them by implementation tools including:

- The Brief
- Specification Preliminaries
- Design and Specification – LOW CARBON DIOXIDE EMISSIONS
- Design and Specification – BUILDING DESIGN
- Design and Specification - MATERIAL AND BUILDING PRODUCT SPECIFIC.

The Brief can stipulate the reuse of existing buildings and the size of the development, both aspect influence the amount of materials necessary for the development. Using existing buildings and building small helps reduce all impacts associated with materials and waste by virtue of reducing the quantity of materials used. The brief can also stipulate inclusions and exclusion in the contract documents, which are discussed in the section on specification preliminaries and design and specification sections.

Table 26 - **Sustainable material design strategies and their areas of impact of on the building design and building processes and their implementation documents.**

		Areas of impact on building design and processes						**Implementation documents**		
Life cycle stages	**Specific design and construction strategies to minimise environmental impacts at identified lifecycle stages**	Quantity of material	Material type	Lifecycle processes	Supply of a material	Installation methods	On-site processes	Design Specification	Specification preliminaries	Site procurement
All lifecycle stages	Build small and only if and what is required - dematerialise	✓						✓		
	Make effective use of material by value engineering and avoiding unnecessary designs - dematerialise	✓						✓		
	Design for desirability to maximise the building life.	✓						✓		
	Specify materials associated with low CO2 emissions over the life time of the building considering their impact on saving running energy	✓	✓	✓	✓	✓	✓	✓		
	Consider suppliers', manufacturers' and contractors' environmental policies, track record and reporting systems.		✓	✓					✓	✓
	Reuse buildings (note: reuse of buildings will not reduce maintenance impacts) - re-materialise	✓	✓					✓		
Material resourcing	Use reused / recycled materials to eliminate resourcing impacts		✓	✓				✓		✓
	Specify renewable materials with short regeneration cycles		✓					✓		
	Specify plentiful materials and avoid scarce resources		✓					✓		
	Specify timber from managed and accreditation sources			✓				✓	✓	✓
	Use materials associated with low resourcing pollution - dematerialise (clean production)		✓	✓				✓		
	Use materials with low resourcing energy consumption		✓					✓		
	Request material supplier's environmental credential to ascertain pollution control methods			✓				✓	✓	✓
	Request material supplier's environmental credential to ascertain the use renewable energy, energy efficiency measures			✓				✓	✓	✓
	Specify materials mined/ harvested with minimal local / global environment impact from suppliers with reinstatement plans			✓				✓	✓	✓
Manufacturing	Use reused and recycled materials reduces impacts - re-materialise		✓					✓		✓
	Specify materials associated with low energy consumption		✓					✓		
	Request manufacturer's environmental credential to ascertain the use renewable energy, human power, energy efficiency measures			✓				✓	✓	✓
	Specify materials associated with low manufacturing pollution – clean production		✓					✓		
	Request manufacturer's environmental credential to ascertain pollution controls – clean production			✓				✓	✓	✓
Material transport	Specify local materials				✓			✓	✓	✓
	Request manufacturer's environmental credential to ascertain the use energy efficient transport			✓				✓	✓	✓
	Reuse and recycle materials on site		✓	✓	✓		✓	✓		✓
Material installation	Specify installation methods that use renewable energy, human power and energy efficiency measures			✓			✓	✓	✓	✓
	Specify materials that do not constitute a hazard to health		✓				✓	✓		
Material use and maintenance	Design for ease of repair - re-materialise		✓	✓		✓		✓		
	Use durable materials - dematerialise		✓					✓		
	Use reused and recycled materials - re-materialise		✓					✓		
	Specify materials that do not constitute a hazard to health		✓					✓		
Material disposal	Design for flexibility and design / develop systems for reuse and recycling or to enable the biodegrading of materials (rematerialise/ waste mining)		✓	✓		✓		✓		
	Adopt construction & demolition waste prevention measures						✓		✓	✓
	Adopt construction & demolition material recovery procedures - re-materialise						✓		✓	✓

Table 27 - **Sustainable material design strategies organised by implementation documents and related to their impact of building design and processes and to the design philosophies from which they were derived.**

Key:

E = Embodied energy and Emergy calculations
M = MIPS and mass balance assessments
L = Life cycle assessments

N = Natural Building
H = Healthy building
F = Ecofootprinting
IE = Industrial Ecology

Implementation documents	Specific design and construction strategies to minimise environmental impacts in relation to implementation tools	Areas of impact on building design and processes: Quantity of material	Material type	Lifecycle processes	Supply of a material	Installation methods	On-site processes	Material philosophies
Brief	Build small and only if and what is required - dematerialise	✓						IE
	Reuse buildings (note: reuse of buildings will not reduce maintenance impacts) - re-materialise	✓	✓					E, M, F, IE
Specification preliminaries	Consider suppliers', manufacturers' and contractors' environmental policies, track record and reporting systems.		✓	✓				N, F, IE, E, M, L
	Specify materials mined/ harvested with minimal local / global environment impact from suppliers with reinstatement plans			✓				N, F, IE, M, L
	Specify timber from managed and accreditation sources			✓				
	Request material supplier's environmental credential to ascertain pollution control methods			✓				
	Request material supplier's environmental credential to ascertain use of renewable energy, energy efficiency measures			✓				F, E, M, L
	Request manufacturer's environmental credential to ascertain the use renewable energy, human power, energy efficiency measures			✓				
	Request manufacturer's environmental credential to ascertain pollution controls – clean production			✓				F, IE, M, L,
	Adopt construction & demolition waste prevention measures						✓	
	Adopt construction & demolition material recovery procedures - re-materialise						✓	
Design and specification LOW CO2	Specify materials associated with low levels of CO_2 emissions over the life time of the building considering their impact on operating energy. A whole life cost assessment is required. Approaches may include specifying local materials, low embodied energy materials (subject to whole life cost), low CO_2 emissions transport and installation systems.	✓	✓	✓	✓	✓	✓	N, F, IE, E, M, L
Design Specification BUILDING DESIGN	Design for desirability to maximise the building life.	✓						IE, M
	Make effective use of material by value engineering and avoiding unnecessary designs - dematerialise	✓						
Design Specification MATERIAL AND BUILDING PRODUCT SPECIFIC	Specify materials that do not constitute a hazard to health		✓					N,H, L
	Specify renewable materials with short regeneration cycles to avoid resource depletion		✓					N, L, M
	Specify plentiful materials and avoid scarce resources to avoid resource depletion		✓					N, M IE, L,
	Use materials associated with low resourcing pollution – clean production		✓					N, IE, L, M
	Specify materials associated with low manufacturing pollution – clean production		✓					
	Use reused / recycled materials to eliminate resourcing impacts and reduces manufacturing impacts - re-materialise		✓	✓				
	Design for ease of repair - re-materialise		✓	✓		✓		N, IE,
	Use durable materials - Dematerialise		✓					M
	Design for flexibility and design / develop systems for reuse and recycling or to enable the biodegrading of materials (rematerialise/ waste mining)		✓	✓		✓		IE, M

Specification Preliminaries – Preliminaries can be used to set overriding requirements. Strategies that apply to all aspects of building design are included in the contract preliminaries. This could include requirements that would apply to all subsequent work clauses. Building specifications can specify alternatives to materials harmful to health, but specification preliminaries can be used to exclude such materials categorically.

Similarly, some manufacturing processes are more or less sustainable depending on the technologies adopted by the manufacturer or suppliers. A brick or steel manufactured in a factory with state of the art pollution control will be associated with fewer environmental impacts than an identical type of product produced in a plant without pollution controls. Specification Preliminaries can include clauses to encourage or require suppliers and manufacturers to adopt best practice in respect of energy consumption, pollution prevention and resourcing technologies. They can specify pre-requisites for the appointment of sub-contractors and suppliers that relate to good practice in sustainability.

On-site procurement presents an opportunity for implementing sustainable material approaches, and such initiatives can also be predetermined in the contract preliminaries. For example, a requirement can be made to recycle a certain percentage of waste or integrate a certain amount of recycled materials in the building.

Design specification is subdivided to differentiate between design and specification approaches that have to be applied to individual materials and products and those that relate to the building design as a whole.

Design and Specification – LOW CARBON DIOXIDE EMISSIONS – The aim of sustainable construction is to create low carbon dioxide emissions buildings. To achieve this, the embodied energy of the building and the operational energy have to be considered together and in respect of the building design as whole. A comprehensive analysis of the whole life energy costs would involve

- calculating the embodied energy of the building structure and the operating energy of the building;
- identifying the building elements with high embodied energy and selecting alternatives to these materials; and
- repeating the calculations and amend the design accordingly.

Such an assessment would establish which of the alternatives would have the lower overall (combined embodied and operation) energy impact over a set period of time. The energy benefits gained from the use of a material could be set against its embodied energy to establish whether it would be beneficial or detrimental to the overall energy consumption of the building.

If the alternative material performs in the same way as the original material the assessment is straight forward. In such case a full energy consumption assessment may not be necessary and it may simply be possible to select the material with the lower embodied energy. Often however the performance of two materials is not identical. The durability, and therefore the number of times it needs to be replaced, may also be different and would have to be taken into account in the assessment.

Even when undertaking a full analysis, there are some complications. The full analysis includes two variables that are difficult to establish. The first variable is the estimate life of the building. The longer the life the less impact does the embodied energy have. Buildings are designed for anything from a 20 to more than 100 year service life and this is usually set at part of the building brief. However in practice, some buildings have far longer lives than intended while others are demolished before time. The second variable is the changing climate. While insulation or conversely concrete may be an appropriate response today, it may not contribute to reducing energy loads in a future where the comfort parameters have changed.

Another consideration relates to understanding what the fundamental concern is. The aim should not be not creating zero energy buildings but rather creating buildings and materials that are not resource depleting and polluting (including carbon dioxide). So while zero energy constructions are not possible, zero carbon dioxide emissions constructions could be possible. Hand-built vernacular buildings could qualify as zero carbon dioxide constructions, but in today's building industry such an approach is largely restricted to small private developments and even then the installation may be undertaken manually but the building products and tools are likely to have fossil fuel embodied energy. Furthermore, in future manufacturing plants and even city districts could run on renewable energy making concerns regarding the energy content of materials less relevant to the question of sustainability.

Design and Specification – BUILDING DESIGN – Certain aspects of the building design have a significant impact on the amount of material used. For instance, value engineering reduces the use of materials by making the most efficient use of them. Equally, designing for desirability increases the chances of the building having a long life and ultimately reduces the need for new buildings and therefore for new materials. Both approaches need to be considered at a whole building level and cannot be easily broken down into discrete elements.

Design and Specification - MATERIAL AND BUILDING PRODUCT SPECIFICATION can stipulate material selection and building design to minimise the environmental impacts associated with individual building materials and elements. These can, as opposed to the previous category, be considered element by element. This group includes: material selection relating to resourcing and manufacturing impacts and to waste impacts.

Reducing waste impacts - Using reused and recycled materials and designing for reuse, recycling and to enable the biodegrading of materials reduces primarily the environmental impacts associated with waste disposal, but they also address environmental impacts associated with resourcing of materials and to a degree the manufacturing of materials.

Reducing resourcing and manufacturing impacts - Many of the material resourcing and manufacturing impacts are linked to the processes rather than the actual material itself and good practice can be stipulated as part of the preliminaries. However some materials are intrinsically associated with more significant impacts than others and these are the impacts that can be addressed through material specification, by selecting renewable, recycled, reclaimed, plentiful and low pollution materials.

3.5.5 COMBINING APPROACHES

A comprehensive approach to sustainable materials design and selection could be said to combine all above approaches. Sustainable material design is more than just selecting materials, but involves addressing the overall building design and building procurement methods. Some approaches are independent from others while some are interlinked. Just like architectural design requires a number of reiterations to achieve the final desired product, so does sustainable materials design and selection: an initial material selection might be followed by a value engineering and energy audit, which may require a revised material selection and so on.

The above tools could be considered to present on one hand overriding principles and on the other interrelated principles. The overriding principles would include the parameters set by the development brief and the specification preliminaries, for instance the exclusion of materials that negatively affect health. These are baseline requirements that set a framework for the subsequent building and detail design. The interlinked principles would include the building design and specification in relation to carbon dioxide emissions, overall building design, and material and building product selection.

Table 28 represents a further development of the previous two tables and identifies the main sustainable materials design strategies divided into the two groups and considers the potential for setting measurable targets to assess the implementation of the strategies. A review of the case study buildings identifies that some of the approaches have been implemented in practice whereby targets were set and their implementation assessed. For instance the Beddington ZED development set a maximum distance for the resourcing of the materials and products and the development of the solarCity excluded in the development brief and contract preliminaries the use of PVC and other deleterious materials (Sassi 2006a). Furthermore there is an increased interest in implementing some approaches such as that of requesting environmental credentials from manufacturers and suppliers or assessing the lifetime energy requirements of buildings, despite the limited potential for a truly meaningful assessment.

Sustainable materials design approaches to resource depletion and disposal impacts are not currently quantified but could be. Using data on material reserves, sustainable management practice and recycled and reused materials, and in addition measuring the amount, by weight or volume, of materials used to construct a building and assessing their derivation, it would be possible to establish the percentage of a building constructed made of non-renewable, primary and scarce materials. Knowing the constitution of a building construction and the quantities of all materials and in addition how they are installed in the building would also enable an assessment of the potential waste disposal options for the building at the end of its life. By defining what constitutes a CLC in respect of building elements or materials would contribute to a comprehensive and quantifiable sustainable material approach.

Table 28 – **Framework for comprehensive sustainable material design protocol identifying potential for quantitative assessments**

Application	Aim	Approach	Potential for quantitative assessment	Potential measure for quantitative assessment or barrier to quantitative assessment.	Case studies implementing assessment
Overriding design principles					
Brief stipulations	Minimise the overall use of materials and in particular virgin materials	Build small	Medium	Values are relative to expectation. Space standards exist but occupancy cannot be dictated.	
		Reuse buildings	Good	Percentage of building volume/ weight reused.	
Specification Preliminaries	Minimise the environmental impacts associated with the processes of resourcing and manufacturing of materials and products.	Preliminaries to stipulate the appointment of subcontractors, manufacturers and suppliers to subject to submission of an environmental management system, certification systems or environmental plan that confirms the implementation by the supply chain members of environmental good or best practice.	Medium	Assessing percentage of participants with EMS or equivalent is straight forward. Limitation lies with the lack of baseline statistics relating to the quality of environmental practice adopted.	
Specification Preliminaries	Minimise risk to the health of contractors and building occupants.	Preliminaries to include list of deleterious materials excluded from the construction project.	Good	Yes/No option for implementation of exclusion list.	SolarCity
Interlinked design and material specification principles					
Design and specification BUILDING RELATED	Minimise the overall amount of materials and in particular virgin materials used	Build material efficiently through implementation of value engineering of design	Medium	Assessing the implementation of a value engineering design exercise is straight forward. Limitation lies in the difficulty in assessing effectiveness of value engineering.	Resource-ful house
		Building for long-lasting desirability	Poor	Values are relative to culture, time and economics.	
Design and specification LOW CO_2	Reduce CO_2 emissions through out the life of the building.	Select materials based on the whole building life cycle costs, i.e. materials associated with low levels of carbon dioxide emissions over the life time of the building considering their impact on saving running energy.	Medium	Assessment would have to be for whole life energy use including operation. Limitation lies in variables that are currently in a state of change.	
		Specify local materials	Good	Percentage of materials sourced from a specified distance from site.	BedZED
Design and specification MATERIAL AND BUILDING PRODUCT SPECIFIC	Minimise the environmental impacts associated with the resourcing and manufacturing of materials and products.	Specify to avoid resource depletion.	Good	Percentage of materials that are NOT renewable and sustainably managed or recycled or reused or plentiful. Limitation lies in a lack of baseline statistics.	
	Minimise the environmental impacts associated with the disposal of materials and products.	Specify to avoid waste disposal and its impacts.	Good	Percentage of materials that do not have to be disposed through methods associated with high environmental impacts. Limitation lies in a lack of baseline statistics.	

3.6 CHAPTER CONCLUSION: THE BASIS FOR A QUANTITATIVE SYSTEM

This chapter considered existing sustainable material philosophies with the aim of identifying some of the main aspects that could constitute a comprehensive approach to sustainable material selection. The study investigated the following approaches to sustainability as applied to material design:

- Natural building technologies,
- Healthy building material approaches,
- Embodied energy,
- LCA,
- Emergy,
- MIPS,
- Ecological footprinting,
- Industrial ecology.

The different material philosophies did significantly overlap but certain philosophies, including natural building, LCA, ecological footprinting and Industrial Ecology, address environmental issues in a comprehensive way; while the others were mainly if not exclusively focusing on one aspect of material design.

Some philosophies, such as the ecological footprinting, embodied energy, MIPS and Emergy highlight issues to consider, while natural building, healthy building, LCA and Industrial Ecology provide principles and guidance on how to achieve good practice.

Section 3.5 amalgamated the principles from all eight systems and distilled out a number of approaches, which are in essence shared by the different philosophies. This consolidated list was considered in terms of ability to be implemented within the construction industry. The typical building development processes was considered to identify stakeholders and tools (such as design briefs and building specifications) that could be adopted to implement the comprehensive material design approach. Approaches that already are or could be used as a means to set quantifiable targets for building designers were identified.

The consolidation of sustainable material principles and potential implementation methods concluded that building project procurement could be split into two main stages. The first introducing overriding principles of material design and the second interlinked building and material design principles (Table 28). Existing methods of design briefs and project preliminaries could be used to introduce the overriding principles and include lists of excluded materials, formulate relevant contractor's and subcontractor's qualification prerequisites, specify the reuse of buildings or building elements and so forth. The interlinked building and material design principles could be implemented through the building detail design and specification and would have to be part of an iterative process.

Three interlinked building and material design principles would be necessary to structure the issues to consider. One would address material efficiency, a second low carbon dioxide emission and a third material selection and waste minimisation.

As argued throughout this dissertation to implement good practice quantifiable targets are required and most principles included in the two stage comprehensive approach to sustainable material design have medium to good potential for developing such targets. There is therefore scope for further developing a comprehensive sustainable material design approach that incorporates quantifiable measures and targets. A CLC approach to material design would provide one of these targets and is therefore one of the fields that would have to be investigated.

The following chapter focuses on developing one component of this comprehensive sustainable materials design approach to include a quantitative assessment. Using the Industrial Ecology's model of a CLC for materials and waste, the aim is to formulate a set of criteria that define the nature of CLC in relation to building elements and materials. In conjunction with equivalent investigations and developments of the other components, it could contribute to a quantifiable comprehensive approach to sustainable material design and therefore contribute to improving the sustainability of the building industry.

4 DEFINING CRITERIA FOR CLOSED LOOP MATERIAL CYCLE CONSTRUCTION

This chapter investigates the nature of a closed loop material cycle (CLMC) in building construction in order to define criteria by which building materials and elements can be assessed in terms of forming part of a CLMC. The structure adopted for the investigation is based on Industrial Ecology's principles of waste mining and reuse and recycle to form a closed loop cycle (CLC).

Firstly, the characteristics for both concepts are examined and secondly a set of criteria is developed to form an assessment system that can be applied to the building industry, as will be discussed in Chapter Five.

(Related Appendices: 8.4-8.9)

4.1 A CLMC PRELIMINARY DEFINITION

In order to defined the scope of investigation a definition for a CLC is required from which to extract key characteristics that determine its essence. Industrial Ecology has inspired a group of researchers and practitioners (Kibert *et al.*, 2002) to consider the application of its principles, including that of closed cycles, to building construction. The term Construction Ecology was adopted to describe a system consistent with the Industrial Ecology principles. Kibert (2000) describes Construction Ecology as follows.

> 'Construction Ecology can be considered as the development and maintenance of a built environment [1] with a materials system that functions in a closed loop and is integrated with eco-industrial and natural systems; [2] that depends solely on renewable and recyclable materials, and [3] that fosters preservation of natural systems functions.'
>
> (Kibert, 2000, p. 179)

Kibert's 'materials system that functions in a closed loop and is integrated with eco-industrial and natural systems' can be expanded, taking into account his second and third point, to mean that building materials should:

- be resourced from renewable and sustainably managed sources or from recycling processes, in other words, no primary materials should to be used;
- be able to be recycled or composted, in other words, no materials that are non-biodegradable and non-recyclable should be used; and
- have no detrimental effect on the environment, in other words, materials that have a lasting polluting effect should not be used.

Kibert's description of Construction Ecology includes the main ingredients for a definition of a CLC. In addition, the concept of 'closed' applied to a cycle suggests an infinite process, which is conceptually opposed to a linear and finite process with a distinct beginning and end. To begin the investigation of CLMC characteristics, the following definition that includes the above key concepts will be examined.

A **closed loop material cycle (CLMC),** within the context of the building industry and building materials and elements, is a **resource cycle** that can operate **infinitely transforming waste material into a useful resource** for future use and producing **zero waste** and **low environmental impacts.**

This chapter considers the characteristics for conforming to the above definition of a CLMC and investigates relevant existing design guidance and assessment systems to form the basis for developing CLMC criteria.

The requirements of a CLC that require further consideration relate to the concept of [1] **infinitely transforming waste material into a useful resource** and [2] producing **zero waste** and **low environmental impacts.** Section 4.2 addresses the first concept by investigating the material recovery processes in the building industry (Industrial Ecology's waste mining) that should ensure maximum and ideally full recovery of materials to enable their subsequent useful use. Then Sections 4.3 and 4.4 address the second concept of material disposal to produce no waste nor significant pollution. Section 4.3 investigates processes of material disposal through a CLC involving industrial processes, and Section 4.4 investigates processes of material disposal through a CLC involving natural processes. Based on these investigations the definition for CLMC construction will be reconsidered in Section 4.5 and form the basis for the development of assessment criteria in Section 4.6.

4.2 WASTE MINING IN THE BUILDING INDUSTRY

Industrial Ecology describes 'waste mining' as the development of efficient technologies to maximise recovery rates (Ayres and Ayres, 1996, 2002). Applied to buildings, as already mentioned, 'waste mining' involves designing buildings to enable the extraction of materials and elements for reuse or recycling. This objective has been translated into practice in certain parts of the building industry dealing with exhibition buildings or performance stages where structures are constructed and deconstructed repeatedly (Kronenburg, 1995, 1998, 2000). However, temporary building and similar technologies have not spread to mainstream construction, and furthermore, deconstruction alone does not necessarily imply the creation of a CLC, as that is dependent on the final destination of the material recovered, which is discussed in a later section.

In the last fifteen years the fields of waste minimisation on site, designing with recycled and reused products, and designing for deconstruction and recycling have received increasing attention. Of relevance to characterising CLMCs is the research into the use of reclaimed and recycled materials and into design for deconstruction and disassembly, the latter being particularly relevant to the principles of waste mining.

4.2.1 DESIGN FOR DECONSTRUCTION: ADVANTAGES AND BARRIERS

The field of design for deconstruction, that also in effect includes design for disassembly and other related aspects, has been driven by an international research project run by the Construction Industry Board Group 39 resulting in four published reports (Chini and Kibert, 2000; Chini, 2001; Chini and Schultmann, 2002; Chini, 2003). In setting the scene in the first report Te Dorsthorst differentiates between deconstruction and demolition processes.

> Typical demolition requires balling, impact breaking, hydraulic shears, explosives, gas expansion and solid expansion. These are destructive methods that are totally inappropriate for dismantling. Mechanical cutting and grinding, thermal cutting, water jet cutting and laser cutting are a few methods appropriate for dismantling. When considering the criteria for dfd [design for deconstruction] the process of dismantling has to be considered. Dismantling is seen as the opposite of assembly and suitable precautions are necessary such as creating a supporting structure at the start of the dismantling process.
>
> (Te Dorsthorst *et al.*, 2000)

The CIB research group produced a number of derivative publications, in addition to the CIB reports, that helped to further define the research field. Hurley *et al.* (2001) differentiate between deconstruction, which enables the reuse of elements, and disassembly, that may involve some damage to the building element and therefore may not always enable the element reuse but should at least enable its recycling.

The benefits of recycling, including economic benefits, have been well understood since the 1980's (Kasai, 1988; Andra and Schneider, 1994; Pawley, 1975), but recycling, let alone design to facilitate recycling, has not been widely adopted and research has progressed slowly, even to this day. There is now a consensus that to facilitate recycling, buildings must be constructed so that they can be deconstructed rather than demolished. Chini and Kibert summarise the benefits of deconstruction:

> Deconstruction of buildings has several advantages over conventional demolition and is also faced with several challenges. The advantages are an (1) increased diversion rate of demolition waste from landfills; (2) potential reuse of building components; (3) increased ease of materials recycling; and (4) enhanced environmental protection, both locally and globally. Deconstruction preserves the invested embodied energy of materials, thus reducing the input of new embodied energy in the reprocessing or remanufacturing of materials. A significant reduction in landfill space can be a consequence. For example, in the U.S. where C&D waste represents about one third of the volume of materials entering landfills, a diversion rate of 80 per cent as is being experienced in The Netherlands would preserve increasingly scarce land for other optional uses.
>
> (Chini and Kibert, 2000, p.7)

Designing buildings so that they can easily be deconstructed makes the advantages identified by Kibert more accessible and financially attractive. Facilitating deconstruction through building design reduces the time, and therefore cost, of deconstruction and makes it possible to extract pure materials that can be reused or recycled or disposed of at cheaper disposal rates. Structures that can be easily deconstructed can also bring benefits throughout their period in use by facilitating and therefore making less costly general maintenance and the upgrading of building elements or periodic refurbishments.

Despite these advantages there is still a significant potential in the building industry for dismantling and reusing and recycling materials that remains untapped (Sassi, 2004a). In the UK, an estimated 500,000 tonnes of reclaimable timber is landfilled each year, of which 50,000 is tropical hardwood (Magin, 2002) and 3.5 billion new bricks are manufactured, 2.5 billion reclaimable bricks are landfilled and only 40 million bricks are reclaimed (Salvo, 1995). Research from the Netherlands, including detailed case studies of deconstruction and reuse of materials and buildings, identified technical and environmental issues plus economics and regulations as affecting the reuse of materials in practice (Te Dorsthorst and Kowalczyk, 2001). The industry as a whole is currently ill-equipped to support design for deconstruction and deconstruction processes. Kibert summarises the challenges faced by deconstruction as

> [1] existing buildings have not been designed for dismantling; [2] building components have not been designed for disassembly; [3]tools for deconstructing existing buildings often do not exist; [4] disposal costs for demolition waste are frequently low; [5] dismantling of buildings requires additional time; [6] re-certification of used components is not often possible; [7] building codes often do not address the reuse of building components; and [8] the economic and environmental benefits are not well-established.'
>
> (Kibert, 2000a, p.89)

These facts are interlinked: that most buildings today are not designed to facilitate the dismantling and reusing or recycling of the materials, means that the resulting excessive time for dismantling, as opposed to demolition, coupled with low disposal costs make dismantling a prohibitively expensive process (Coventry and Guthrie, 1998; Kibert, 2000a; Sassi, 2004a). This assertion is supported by research from demolition contractors who report that deconstruction can take two to ten times longer than demolition efforts putting deconstruction at a distinct economic disadvantage (National association of demolition contractors, 1999). Similar conclusions have been reached in research by Sheffield University that identified that the practical restrictions common to many demolition projects relating to time and money were the main cause for low material recovery rates. Demolition work is usually undertaken in conjunction with new building work and is often forced to take place in a very limited period of time making deconstruction impractical (Fletcher *et al.*, 2000). Fletcher *et al.* reported on interviews with 16 demolition experts who identified some of the major barriers to deconstruction. Economics linked to time featured as a key issue.

> 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 not on demolishing as speedily as it safely possible. As such demolition contracts have gone from six months to six weeks duration. If more time were 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 being due to recycling. 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 with the demolition contractor making up the difference from salvaging an many elements and materials as possible.
>
> (Fletcher *et al.,* 2000, p.12).

The labour-intensive reclaiming process and the limited market are some reasons for the cost of reclaimed materials often being higher than new material (Gorgolewski, 2000) and their uptake consequently lower. Even taking into account the additional tax burden of landfilling waste reclaimed material costs are higher than the cost of using new materials (Fletcher *et al.*, 2000; Sassi, 2004a). Some materials are difficult and even technically impossible to recycle. Composite material are often impossible to recycle even though technological advances may address such limitations in future, as has already been demonstrated by Kingspan's development of a method for recycling insulated sandwich cladding panels (Steel Construction Institute, 2006).

Other cost-related barriers to deconstruction include an increased emphasis on health and safety, which has changed demolition practice by increasing the required precautions and consequently the cost of certain material recovery processes (Fletcher *et al.*, 2000). Storey and Pedersen also identify the additional cost due to transport and storage as a further barrier (Storey and Pedersen, 2003).

Therefore, while current research into design for deconstruction identifies environmental advantages and imperatives for adopting design for deconstruction, it also highlights a number of technical, economic and legal barriers.

4.2.2 DESIGN FOR DECONSTRUCTION IN RELATION TO THE PRACTICE OF RECYCLING AND REUSE

Design for deconstruction and disassembly is related to the use of recycled and reclaimed elements: as demand of reclaimed and recycled materials rises more materials are recovered. However, the use of reclaimed and recycled materials is not without its problems.

The uptake of reclaimed and recycled materials is hampered by the need to comply with building regulations and certification systems, which do not generally deal with most reclaimed materials and elements and sometimes give preference to new materials (Te Dorsthorst *et al.,* 2000; Kibert, 2000a; Storey and Pedersen, 2003; Sassi, 2004a). This presents a problem for those wanting to use certain reclaimed materials where performance is critical e.g. weathering envelop and structure. Recycled concrete aggregate has different characteristics to natural aggregate and even though research shows that replacing up to 20 per cent of the natural aggregate with recycled does not negatively affect the concrete, widespread use of recycled aggregate has not taken place (Coventry *et al.*, 1999). The perception of many recycled materials being 'second hand' and therefore of inferior quality is reinforced by this lack of codes and standards. Te Dorsthorst *et al.* (2000) believe an independent institute would be required to certify reclaimed materials but highlight the financial implication of such assessments.

Even where performance is not an issue reclaimed materials may suffer from lack of aesthetics and commercial desirability (Fiksel, 1994; Coventry and Guthrie, 1998; Sassi, 2004a). Some building elements such as fixtures and fittings often have low resale value. Consequently even if a building material or element is capable of being dismantled from a technical and economic point of view, it still may not be reclaimed if it is perceived as having no market appeal (Kibert, 2000a).

The infrastructure for reclaiming and reusing materials is often lacking (Duran *et al.*, 2006) and the storage and transport associated helps increase the cost of reclaimed materials often above that of primary material options.

A case study from Sweden (Eklund *et al.*, 2003) involving the deconstruction of concrete housing and reuse of many elements of the original buildings in the new ones, including precast concrete wall elements, quantified the additional cost of using reused elements to be 10-15 per cent. The research reported that the 'problems encountered related to the organizational and financial aspects more than any other aspects' (Eklund *et al.*, 2003, p.257). Eklund *et al.* further identified that the increase in cost was mainly attributed to cost for labour that for the research project was double that of a conventional building development, with the increase in the cost of the reused concrete panels amounting to 80 per cent higher than if primary material had been used.

Research into the barriers to deconstruction and material reuse by Storey and Pedersen confirm many of the above-mentioned barriers. Cost is identified as a significant barrier to deconstruction and to the use of reclaimed materials. They also identify standards, technical design limitations, lack of information and the perception that the end of life of a building is in the distant future (Storey and Pedersen, 2003).

Table 29 - **Selected barriers to deconstruction and the use of recycled materials reported by Storey and Pedersen** (2003)

Barriers to use of recycled materials	**Barriers to deconstruct**
• Standards specification giving preference to new mats, lack of standards for recycled mats, lack of warranties and guarantees • Technical limitations of possible uses of certain reclaimed mats • Cost of reclaimed materials is high due to storage, transport and often procurement difficulties (quantities and quality uncertainty) associated with additional time.	• Lack of information relating to methods of deconstruction and to the types of materials included in buildings. • Building methods increasingly make it difficult to deconstruct and many existing buildings are not designed for deconstruction. • Cost associated with more H&S regulations, increased time requirements and skilled workforce for deconstruction. Furthermore there are few financial incentives to deconstruction • Benefits of deconstruction are long term

The last point listed, 'benefits of deconstruction are long term', is shared by Coventry *et al.*, (1999), who suggest that the concept of designing for deconstruction and recycling, in other words designing to enable the dismantling and reuse or recycling of material in future, requires a visionary approach, quite distant from the practicalities and immediate concerns of the typical building designer and is therefore unlikely to be taken up in the near future.

The financial context may however become more favourable towards the use of recycled and reclaimed products. Gorgolewski (2000) suggests that while the cost and the sometimes erratic availability of recycled and reclaimed materials are detrimental to the development of the industry, as the market for recycled materials becomes more mature and stable these discrepancies are expected to disappear. Bradley reports on a case study of a six deconstruction projects in Florida that proved to be economically viable, proving to be 37 per cent cheaper to deconstruct taking into account the revenue from the reclaimed materials (Bradley, 2000). The economic benchmark is to be considered in flux.

4.2.3 DESIGN FOR DECONSTRUCTION REQUIREMENTS

As a fundamental stage in the CLMC process, the deconstruction or dismantling of a building is designed to recover elements or materials in a state that can be reused or recycled either through natural or industrial process. Currently the barriers to deconstruction include:

- technical (buildings, building elements and materials not designed to be deconstructed) (Te Dorsthorst *et al.,* 2000; Kibert, 2000a), and
- economic (time requirements for deconstruction and labour costs are too high while disposal costs are too low) (Kibert, 2000a).

Additional barriers result from the interdependence of deconstruction and the reuse and recycling of materials, which include:

- legal (dismantling relies on the use of recycled materials which is hampered by lack of certification) (Coventry and Guthrie, 1998; Te Dorsthorst *et al.*, 2000; Kibert, 2000a; Storey and Pedersen, 2003); and

- customer expectations (recycled materials suffer from prejudice against second hand materials and aesthetic limitations)(Coventry and Guthrie, 1998; Sassi, 2004a).

The fundamental requirements for design to enable deconstruction or dismantling must address the above barriers and enable building elements to be removed from a building

- quickly (which would involve information and guidance being available, access being direct, few larger elements in preference to many small elements) and
- easily removed from the building (which would involve standard tools being suitable, deconstruction aides being available).

The elements removed from the building would also have to be designed to ensure compliance with future requirements, including legislation and user requirements, to be reused and or should be designed to enable their transport to be recycled through industrial or natural processes. How these outline requirements can be satisfied in detailed will be discussed in section 4.6.

4.3 CLOSED LOOP CYCLES THROUGH INDUSTRIAL PROCESSES

Once recovered from a building, materials can be reused, recycled, downcycled, composted or disposed of through incineration or landfill. As discussed in section 3.4 incineration and landfill are linear processes and incompatible with CLCs. This section considers what constitutes a CLC in respect of recycling, reuse and downcycling through industrial processes. As suggested in section 3.4, reuse and downcycling and indeed certain types of recycling have to be examined carefully for their compatibility with CLCs. The main issues have to be considered include:

1. the boundaries of the recycling cycle
2. the loss of material in a CLC;
3. the ability to recycle infinitely;
4. the differences between recycling and downcycling; and
5. the status of reuse in relation to CLCs.

4.3.1 THE BOUNDARIES OF THE RECYCLING CYCLE

In considering Industrial Ecology Korhonen and Snäkin suggest:

> [t]he system boundary definition is crucial for IE. The chosen geographic scope, e.g., local vs. regional vs. national vs. global, must be decided upon, as well as the studied dimensions, e.g., ecological, social, cultural or economic dimensions of [Sustainable Development], and the studied flows, e.g., matter, energy or information.
>
> (Korhonen and Snäkin, 2005, p.170).

Applied to building materials the flows Korhonen and Snakin regard as important to define are the materials themselves. (In a comprehensive approach to sustainable building materials the flows of energy and water would be considered as part of the materials manufacturing processes).

One system boundary could be the building industry itself. However, the aim of a CLMC is to minimise environmental impacts, the importance of a cycle is its closed nature that minimises waste and resource consumption and not its realm of operation. Restricting the boundary to include the building industry only has no environmental advantage. In fact, it may be beneficial to extend the operation of the cycle to facilitate its implementation and include cycles outside the building industry. For instance the steel industry recycles steel from many different industries very successfully with recycling rates of 60 per cent in the UK (Environmental Resources Management for the Department of Trade and Industry, 2002).

The geographical boundary has to be considered. The common building industry practice of resourcing building materials from distant locations and the limited numbers of recycling facilities suggest large geographic boundaries have to be applied. However, as opposed to opening the cycle to other industries, which potentially reduces environmental impacts, expanding the cycle geographically increases the environmental impacts associated with transport of materials. Sustainable materials should ideally be associated with minimal transport impacts, either through reducing transport or and using sustainable means of transport. As with the flows of water and energy, the transport implications are addressed as part of other elements of the comprehensive protocol for sustainable material design and therefore should not be considered again as part of the material cycle.

The boundaries of the CLC can therefore be said to consider the material flows only and not be limited to the building industry nor to a defined geographical location.

4.3.2 THE INFINITE CYCLE

A material has specific characteristics that dictate its final disposal options. For example, the final disposal options for timber include composting, incineration and landfilling. A solid timber beam can have been used and reused several times, then shredded and formed into hardboard and then finally composted. Its life as a beam could last over 200 years and be extended another ten or twenty years as a hardboard and finally become a resource for growth of new timber. In principle, timber is an example of a CLC material linked to the natural carbon cycle, as will be discussed in section 4.4. Steel's final disposal options are recycling, landfill and incineration. Like timber, steel beams also can remain in use over centuries and then be smelted down to form new steel. Steel is also in principle an example of a CLC material, but linked to an industrial cycle rather than a natural cycle.

The critical aspect is that the recycling process whether industrial or natural can continue indefinitely. The fact that a material is recyclable per se may not be enough to qualify it as a CLC material. The recycling of expanded polystyrene illustrates this point. Thermoplastics can be chemically recycled, a process that involves separating and recombining the chemical elements and can be carried out an infinite number of times; or they can be recycled mechanically, which slowly changes the chemical structure limiting the number of times the material can be reprocessed without loss of quality. Expanded polystyrene (EPS) can be shredded, melted down and extruded to form trims, skirting boards, external furniture. Once extruded the recycled material can only be further recycled into the same material with the addition of polystyrene from primary sources (Tukker *et al.*, 1999), without which the recycled EPS product would not achieve the desired quality. This suggests EPS cannot be considered part of a CLC. However, chemical recycling does enable repeated recycling, which would qualify EPS as a CLC material.

Achieving an infinite loop, therefore, depends on the material characteristics and adopting recycling methods that retain both the quality and mass of the material.

4.3.3 MATERIAL LOSS

In addition to the theoretical ability to be recycled infinitely, there is also a practical limitation. In practice recycling processes are not 100 per cent efficient due to the waste occurring through handling and the need to add primary material to avoid loss of quality or reintroduce a constituent material lost through the recycling process (Quinkertz *et al.*, 2001).

For instance aluminium recycling involves some loss of material through oxidation. In addition, the inefficiencies at pre-processing stages can result in recycling efficiency as low as 85.7 per cent (Quinkertz *et al.*, 2001).

Concrete could be said to be recycled into concrete by crushing the concrete to form aggregate and combining the recycled aggregate with cement and sand, but the ratio of recycled content would only be 40-60 per cent and the effective loss of material would therefore also be 40-60 per cent. Gypsum can be recycled, but new gypsum boards can be formed with a maximum ratio of 20 per cent recycled 80 per cent primary gypsum material (Beck and SCS Engineers, 2003).

A CLC material has to incur minimal material losses. The definition of 'minimal' has to be set but there are currently no parameters that directly relate and could be used for this purpose. A parallel could be drawn with composting. As will be discussed in section 4.4, packaging materials that are defined as biodegradable have to comply with the BS EN 13432:2000 Packaging. Requirements for packaging recoverable through composting and biodegradation (British Standards Institution, 2000). This sets out a maximum residue from the composting process of 10 per cent. In other words 90 per cent of the material is biodegraded. A similar limit could be used for industrial recycling processes. Losses occurring through transport and collection of materials are not included in the 10 per cent. This omission is in line with previous deliberations relating to transport and carbon dioxide emissions. Transport and collection efficiencies can vary and are not inextricably linked to the material properties and their recycling processes and therefore should not form part of the assessment of material loss through recycling.

Consequently, for the purpose of this thesis, a material loss in line with BS EN 13432:2000 of 10 per cent will be taken as the acceptable limit for qualifying as a CLC material. Further research involving industry deliberation would be requiring to confirm or change this proposed limit.

4.3.4 THE DIFFERENCES BETWEEN RECYCLING AND DOWNCYCLING

Recycling and downcycling are clearly distinguished from the concept of reuse. Recycling and downcycling refer to materials rather than building elements and involve reprocessing material, often but not always, destroying their current state and creating a new one. Reuse, on the other hand, refers to building elements, which while they may be reused for different uses from their original use, do not require reprocessing, only repair, refurbishment or minor adjustments. Hurley *et al.* expand:

> Some components may be cut into new sizes and reused but not reprocessed in any way; for example a timber floor joist may be cut to length to suit a different size building. Other components such as timber studs may be reprocessed (cut) into slate batons or recycled (chipped, washed and manufactured) into chipboard. Only when a reclaimed material or component is reprocessed and manufactured into a different form is it classed as recycled material.
>
> (Hurley *et al.* p.2)

The difference between recycling and downcycling lies primarily in the value of the end product after the reprocessing. Recycling is defined as a process that retains the value, while downcycling suggests the material after reprocessing has an inferior value to its original value. This is critical to the concept of CLC. If a loop is to be closed the value of a material needs to be maintained. If the value of a material were allowed to deteriorate the material would reach a stage where the material is no longer useable, ultimately forming part of a linear not a cyclical process.

Considering the statistics for reuse and recycling in the UK it becomes clear that the term recycling often includes downcycling, and that a significant percentage of waste which is said to be recycled is in fact downcycled. Statistics relating to the year 2000 suggest that 50 per cent of construction and demolition inert waste was used as fill materials in landscaping and road building (McGrath *et al.*, 2000). 2001 figures suggest that of the 75 per cent construction and demolition waste in the UK being recovered, 41 per cent was being disposed of in exempt sites and used for landfill engineering and only 35 per cent was being recycled into new uses (Hobbs and Hurley, 2001). What these statistics refer to includes mainly concrete and masonry, originally structural and finishing materials, being crushed and used as fill. Once a material such as concrete is downcycled into fill material, it can not be reformed into concrete without significant cleaning processes and the addition of 40-60 per cent of new material (Based on the typical mixes for concrete ranging from 1:2½:5 to 1:2½:3 (cement:sand:aggregate) (Everett, 1994, p.133)). This deterioration of the value of the material compromises the CLC.

For a material to qualify as a CLC material through industrial processes, it must be able to be recycled in the way steel is recycled into new steel with no loss of quality and not downcycled as with masonry into fill or hardcore.

4.3.5 REUSE IN THE CONTEXT OF CLC

The UK Waste Strategy 2000 for England and Wales (Department of the Environment, Transport and the Regions, 2000) supports a waste hierarchy that prioritises reuse over recycling. This prioritisation is shared by a number of researchers who suggest reusing elements provides greater environmental benefits than recycling them (Gorgolewski, 2000; Thormark, 2000). The main aim of the strategy is to reduce waste going to landfill and being incinerated, and at first sight both reuse and recycling contribute towards this aim. However, while materials and products that can be recycled can potentially be kept out of the waste stream indefinitely, being able to reuse a material or product may only prolong its useful life before entering the waste stream (Sassi, 2004).

In considering reuse the context of CLC materials, it is questionable whether a material that can be reused but not recycled or recovered naturally can be considered to form part of a CLC.

Examples of products that can be reused, but not recycled, and which will therefore eventually enter the waste stream include composite acoustic matting, ceramic sanitary ware, composite laminated boards, plugs, concrete tiles, structural insulated timber roof panels and many more (Sassi, 2004a). With such building components the environmental advantages of reuse will depend on the total length of the useful life of the component.

An example supporting the inclusion of reused materials within the definition of a CLMC is a stone block. A stone block reclaimed from a historic castle to build another building still in use today could be in excess of 400 years old (Sassi, 2004a). At the other end of the scale are finishing elements with a life expectation of as low as five years for internal finishes and twenty-five years for external finishes (Anderson *et al.*, 2002; Coventry *et al.*, 1999). For such elements reuse may only provide a nominal environmental advantage. The same argument applies to products made of recycled materials that cannot however be recycled again, such as composite recycled plastic and timber fibre panels (Sassi, 2004a). If an element can be reused but not recycled, it will eventually have to be landfilled or incinerated. For instance, a composite timber and PVC door can be reused and has a typical lifespan of 40 years, after which it has to be incinerated or landfilled as it cannot be recycled.

The deciding factor is the lifespan of the building element in question. It could therefore be argued that reusable long life span building elements should be considered to comply with the principles of a CLMC construction as they potentially could remain in use indefinitely. However, the lifespan of buildings and elements is not only dependent on technical aspects.

SERVICE LIFE SPAN VERSUS ECONOMIC LIFESPAN

The life span of buildings has been defined in BS 7543:1992 Guide to durability of buildings and building elements, products and components. (British Standards Institution, 1992), which sets out five building design life categories (Table 30). The life of a building element may not coincide with that of the building into which it is initially installed. The BS 7543:1992 categorises the predicted element life in relation to the building as a whole (Table 31). The British Standard categories describe the potential life span, not necessarily the typical life span. Nienhuis *et al.*, (2003) differentiate between the predicted service life of building elements and the actual life in situ by defining the predicted service life span as the technical lifespan, defined as 'the time span in which this product complies with the demands concerning the functioning of this product' (Nienhuis *et al.*, 2003, p.325), while the actual lifespan, described as the economical lifespan, 'is the time span in which someone needs this product.' (Nienhuis *et al.*, 2003, p.324)

Table 30 - **Categories of design life for buildings according to BS7543:1992**

(British Standards Institution, 1992, p.2.)

Category	Description	Building life for category	Examples
1	Temporary	Agreed period up to 10 years	Non-permanent site huts and temporary exhibition buildings
2	Short life	Minimum period 10 years	Temporary classrooms; buildings for short life industrial processes; office internal refurbishments, retail and warehouse buildings
3	Medium life	Minimum period 30 years	Most industrial buildings; housing refurbishment
4	Normal life	Minimum period 60 years	New health and educational buildings; new housing and high quality refurbishment of public buildings
5	Long life	Minimum period 120 years	Civic and other high quality buildings

The predicted service life span and the economic lifespan of building elements are often different. This can be seen by comparing the data from the 'HAPM component life manual' (Housing Association Property Mutual Publications Ltd., 1992) and the 'Green guide to specification' (Anderson *et al.*, 2002). The 'HAPM component life manual' provides predicted component lives based on assessments for insurance purposes and therefore consider the service life. 'The Green Guide to Specification' states replacement intervals for building elements that take into account durability but also changes in fashion and needs, reflecting the economic and the service life. The economic life can be shorter than the service life.

Table 31 - **Categories of design life for building element according to BS7543:1992**

(British Standards Institution, 1992, p.2)

Category	Description	Life	Typical examples
1	Replaceable	Shorter life than the building life and replacement can be envisaged at design stage	Most floor finishes and service installation components
2	Maintainable	Will last, with periodic treatment, for the life of the building	Most external cladding, doors and windows
3	Lifelong	Will last for the life of the building	Foundations and main structural elements

Such differences are the result of different motivations for undertaking work to buildings as shown by a survey that identified 25 per cent of building work being undertaken was driven by a need for maintenance and upgrading to current technology, and 75 per cent was motivated by the wish to enhance the appearance, increase space or improve the economic value of the building (Sassi, 2000). Duffy and Henney (1989, p. 31) identified the drivers for change in commercial office environments as including:

- 'Information technology;
- Accelerating organisational changes;
- Increasing staff demands for better working environments;
- Their [the company's] desire for a better image;
- Rising occupancy costs.'

Duffy and Henney's research identified that issues related to the economic life of building components are as influential as, if not more influential than, those relating to their service life. The potential life of a building element cannot be taken to be a realist prognosis for its life in use and the implications are that some building elements are removed from buildings before their service life is over.

Based on these lifespan considerations Durmisevic and van Iersel consider in what circumstances reuse or recycling would be recommended (Table 32) (Durmisevic and van Iersel, 2003). Where the predicted service lifespan is longer than the economic lifespan they consider it desirable to be able to deconstruct the structure or element and reuse the element elsewhere. Demountable partitions are an example of a building element that can be reused and repositioned a number of times within the life span of a building.

Table 32 - **Relation between service life and economic life of a building element.** Adapted from Durmisevic and van Iersel (2003).

Note: Durmisevic and van Iersel originally use the terms 'use life cycle' to mean economic lifespan and 'technical life' cycle to mean service life.

Relation between service life and economic life of the building element	**Environmentally recommended approach.** Such building elements should be:
Economic lifespan of building element < service lifespan of building element	reusable or recyclable.
Economic lifespan of building element > service lifespan of building element	replaceable and recyclable.
Economic lifespan of building element = service lifespan of building element	recyclable.

Where the economic lifespan is longer than the predicted service lifespan Durmisevic and van Iersel consider it desirable to be able to replace and recycle the redundant building element. The redundancy may result from a break down of the element or the introduction of stringent regulations may require the replacement of elements before they cease functioning. Services, which are typically replaced more than three times in a building's life, are mainly removed due to their technological obsolescence and could not be reused but should be dismantled and the materials recycled (Thomas, 2003). Also the performance of building elements such as windows have improved significantly in the last twenty years and older versions, some of which may still be in perfect functioning state, are replaced to improve the whole building performance. Skretteberg (2003) reports on windows in Norway installed in 1945 being replaced to improve the building performance but still being in good and workable condition. These too should be recycled.

A pattern of relationships becomes evident when Durmisevic and van Iersel's priorities are analysed in relation to estimated life expectations of building elements and expected life span of the buildings into which they are integrated (Table 33, 34 and Appendix 4). Buildings with short design lives tend to incorporate elements whose service life is longer than their economic life. Buildings with long design lives tend to incorporate elements whose service life is shorter than their economic life. For buildings with medium to normal design lives the relationship varies according to the service life of a building element. It also becomes clear that some building elements integrated in buildings with a long (i.e. over 120 years) design life, which have an economic lifespan equal to their service lifespan and equal to the building's design life, would benefit from also being designed for durability to ensure the longest life possible.

Reuse is therefore beneficial where the service life is longer than the economic life. This typically includes virtually all elements integrated in temporary buildings and those with short design lives and building structures in all cases. However, the service life of most building elements except the building structure is less than 120 years, which means that to avoid such building elements being landfilled or incinerated they need to be able to be recycled or composted. For these elements, reuse alone will not extend the building service life beyond 120 years and cannot therefore be considered compliant with the principles of CLMC.

In respect of the building structure the question remains as to whether the reuse of a structure can indefinitely avoid its disposal through a linear system. Two arguments suggest that in also this case reuse alone is not sufficient.

Table 33 - **Environmentally preferred building element design approach in relation to expected economic and service lives**

Key:			References:
Typical work affecting building elements show in italics e.g. *Decorations, Replacement of services*	**Environmentally preferred building element design approach** D=Durability RU= reuse RC= recycle / compost 2nd priority=(xx)	**Relation between economic and service life assuming a maximum economic life** E= economic life S= service life	[1] (Sassi, 2000) [2] (British Standards Institution, 1992, pp. 37-38) [3] (Duffy and Henney, 1989) [4] (Yates, 2003)

Definition of durability of buildings and elements and expected service life as per BS 7543:1992			Building elements				
Description of life	Building and element life	Types of buildings categorised by typical lifespan	Structure	Roof and wall cladding	Secondary elements (ext. doors, windows)	Services	Finishes and fit-out elements
Temporary	Agreed period up to 10 years	Temporary exhibition buildings	E<S D + RU(RC)	E<S D + RU(RC)	E<S D + RU(RC)	E<S D + RU(RC)	E>=<S D + RU/RC *Decorations every 5-7 yrs [1] [3]*
Short life	Minimum period 10 years	Temporary classrooms, short life industrial, retail and warehouse buildings	E<S D + RU(RC)	E<S D + RU(RC)	E<S D + RU(RC)	E>=S RC *Replacement of services every 10-15 yrs [1][3]* *Major plant replaced every 15-20 yrs[4]*	E>=<S D + RU/RC *Major commercial office refurbishment every 20yrs [2]*
Medium life	Minimum period 30 years	Most industrial buildings, commercial buildings	E<S D + RU(RC) *The 'Shell' (structure) of commercial offices with a 50 yr lifespan [3]*	E<=S D + RU(RC) *Replacement of external non-structural elements every 25-30yrs [1]*	E>=S RC *Replacement of external non-structural elements every 25-30yrs [1]*	E>=S RC *Housing refurbishments [2]*	E>=<S D + RU/RC *Housing refurbishments [2]*
Normal life	Minimum period 60 years	Housing, health and education buildings	E<=S D + RU(RC)	E>=S RC *High quality refurbishments of public buildings [2]*	E>S RC *High quality refurbishments of public buildings[2]*	E>S RC *High quality refurbishments of public buildings[2]*	E>=<S D + RU/RC *High quality refurbishments of public buildings[2]*
Long life	Minimum period 120 years	Civic and other high quality buildings	E<=S D + RU/RC	E>S RC	E>S RC	E>S RC	E>=<S D + RU/RC

Table 34 - **Environmentally preferred building element design approach in relation to building types**

Definition of durability of buildings and elements and expected service life as per BS 7543:1992			**Examples of building work**		**Environ-mentally preferred building element design approach**
Description of life	*Building and element life*	*Types of buildings categorised by typical lifespan*	*as per BS 7543:1992*	*as per Sassi, 2000*	
Temporary	Agreed period up to 10 years	Temporary exhibition buildings		Decoration Work to retail and bar and restaurants	Design for deconstruction and reuse, recycling or composting.
Short life	Minimum period 10 years	Temporary classrooms, short life industrial, retail buildings, warehouse buildings	Office refurbish-ments	Internal remodelling Replacement of services Work to housing, offices, community buildings and leisure buildings	
Medium life	Minimum period 30 years	Most industrial buildings	Housing refurbishments	Replacement of external non-structural elements Structural alterations	
Normal life	Minimum period 60 years	Health, education and housing	High quality refurbish-ments public buildings	Work to existing churches	
Long life	Minimum period 120 years	Civic and other high quality buildings		Main structures left untouched	Design for durability and recycling

Firstly, there is difference between theoretical expectations and practice. As discussed in relation to building elements, design expectations and the economic realities vary and this also applies to whole buildings. Even buildings with long design lives are sometimes prematurely redeveloped. Furthermore, in practice the reuse of building structures involves a certain amount of wastage to adapt the structure to new building configurations. Where the structural material is recyclable or biodegradable this waste could be recycled or composted but where it is not it would have to be landfilled or incinerated.

Secondly, building structures are typically made with steel, concrete, masonry or timber and these do include some recyclable and biodegradable options. Therefore, when essentially proposing a radically different approach to building design there is no advantage in compromising the ideal to accommodate existing technologies as the required change will in any case be significant.

Therefore, the logical conclusion is that reuse cannot, despite its indisputable advantages, be considered a CLC process. This conclusion remains somewhat unsatisfactory when considering the history of building reuse and may suggest there is further scope for considering this principle; even though the unease may again come from the difficulty in thinking outside the realms of convention.

4.3.6 SUMMARY OF INDUSTRIAL CLC PRINCIPLES

In summary, for a material to be considered a CLC material through industrial processes it needs to

- be able to be reprocessed infinitely through industrial processes,
- without loss of material quality that would preclude its continuous recycling, and
- without the loss of more than 10 per cent of its mass through the recycling process.

Materials that can be reused but not recycled cannot be considered closed loop cycle materials.

4.4 CLC THROUGH NATURAL PROCESSES

The concept of a CLC, as advocate by Industrial Ecology, is modelled on closed loop natural cycles, such as the carbon cycle where 'plants consume carbon dioxide and produce oxygen as a waste. Animals consume oxygen and produce carbon dioxide as a waste.' (Ayres, 2004, p. 427) In the construction industry there is the opportunity to dispose of waste by linking into such processes in nature as well as other natural means of material disintegration such as erosion.

To consider a material as a candidate for inclusion in a natural CLC it is necessary to consider:

- which materials qualify as biodegradable materials;
- which materials qualify as materials that disintegrate naturally and sustainably through means other than composting;
- the time span and efficiency of material disintegration; and
- the quality of resulting material.

4.4.1 BIODEGRADABLE MATERIALS

The British Standard ENBS 13432 (2000) on the requirements for packaging recoverable through composting and biodegradation defines biodegradability as the

> 'breakdown of an organic chemical compound by micro-organisms in the presence of oxygen to carbon dioxide, water and mineral salts of any other elements present (mineralization) and new biomass or in the absence of oxygen to carbon dioxide, methane, mineral salts and new biomass'
>
> (British Standards Institution, 2000, p.6)

While biodegradability is often associated with natural materials man-made materials can also be manufactured to biodegrade. Natural biodegradable building materials have a very long history, but with the advent of synthetic and contemporary materials, biodegradable materials have progressively lost their share of the building industry market. Today, increasing environmental concerns have again brought natural materials to the fore as well as pushed the plastics industry to develop biodegradable plastics (Cripps *et al.,* 2004).

Biodegradable materials can be grouped in four categories: natural materials that can be used following minimal processing (e.g. timber, bamboo); natural materials bonded with a resin or mesh (e.g. sisal carpet, soy boards); natural compounds used in manufacturing products including adhesives and other polymers (e.g. natural protein to manufacture biodegradable plastics); and biodegradable synthetic materials (biodegradable plastics).

MINIMAL PROCESSING NATURAL BIODEGRADABLE MATERIALS

In contemporary construction, natural biodegradable materials that need minimal processing include timber, straw and bamboo used for structural purposes; straw, cork, flax, hemp and sheep's wool insulation; cork floor and wall finishing; bamboo and timber rigid floor finishes; timber and thatch timber roofing finishes; and timber fixtures and fittings, including bathtubs and sinks. Subject to these materials being shredded into small enough pieces, existing composting technologies are able to decompose them in a period of less than six months (Hobbs *et al.,* 2005).

BONDED BIODEGRADABLE MATERIALS

Examples of bonded biodegradable materials include mixtures of hemp or straw and clay used to infill external wall frames; straw bonded between two layers of kraft paper to form non-loadbearing internal partitions; timber, straw and soy finishing or structural boards; jute carpet backing and wall coverings; seagrass, sisal, coir, cotton, paper and wool carpeting; cork mixed with wood flour, powdered limestone, linseed oil and natural resin to make linoleum. Natural fibres have been shown to have equivalent performance characteristic to synthetic fibres (Wambua *et al.*, 2003) and their use in concrete and cement products has generated great interest in the research community (Sorbal, 1990). However, bonding a biodegradable material with a non-biodegradable material, such as concrete or cement will compromise overall biodegradability. Similarly effects may occur when including additives to improve the performance of building products. For example some insulation products made with natural and polyester fibre mixed can be unsuitable for composting, but equally inappropriate for landfilling due to the large percentage of organic matter (Cripps *et al.,* 2004). Some bonding mediums, such as the kraft paper in straw walls or the natural resins in hardboards are themselves biodegradable, others are not. To maximising the biodegradability of building products natural fibres should be bonded with the biodegradable high performance plastic resins, as discussed in the next paragraph. Where the bonding agent is added in minimal amounts and is non-toxic the preferred disposal option will still be composting, even though the use of the compost may have to be restricted in its potential uses.

NATURAL BIODEGRADABLE PLASTICS

Biodegradable plastics, which include adhesives and resins, can be made from naturally occurring polymers such as cellulose, starch, protein, and sugar molasses extracted from plants. Historically natural adhesives, such as potato and rye flour starch, soya protein and natural rubber have been used very successfully, and while still in use are now largely superseded by higher performance synthetic glues (Berge, 2000). Research is now focusing on manufacturing natural and biodegradable plastics with performance characteristics equivalent to synthetic options. Corn zein, wheat gluten, soy protein, and peanut protein have been investigated for potential uses. New building products made in this way are not yet available, but industries such as the paper and colouring industry are beginning to replace synthetic polymers with natural ones (Swain, *et al.*, 2004). The packaging industry is also making use of natural plastics for food packaging and protective mouldings. The use of expanded starch packaging is already relatively widespread and could be introduced to building industry (Cripps *et al.,* 2004).

SYNTHETIC BIODEGRADABLE PLASTICS

Petroleum-based plastics, mainly polyolefins such as LDPE in, LLDPE, can now be modified with additives to be made biodegradable and able to be converted through digestive activity of microorganisms into water and carbon dioxide (Swain *et al.*, 2004) Current uses include biodegradable waste bags. Building products made with synthetic biodegradable plastics are unlikely to be developed for the time being, due to the higher manufacturing costs, but could be developed in future.

4.4.2 MATERIALS THAT DISINTEGRATE SUSTAINABLY

Biodegradation is a chemical process which takes place at a relatively fast speed, as will be discussed in the next section. Natural disintegration of materials also takes place through natural mechanical processes such as erosion and compression. Plant material is fossilised under pressure to form oil, gas or coal. Stone is eroded by water. However these processes are slow geological processes that take millennia and in certain cases the natural environment that supported the processes no longer exists (Mackenzie, 1998).

Some materials do disintegrate mechanically much faster and some of these materials, such as unfired earth and sand, are used for building. Such materials can be returned to their original natural state without loss of quality and mass within a short period of time. Unfired earth products such as rammed earth without cement additives can be completely recovered. Easton (2000, p.160) states that '[t]he earth from which [the rammed earth walls] were built is complete reusable'. The same applies to unfired clay bricks and cob walls (Smith, 2000), which can all be allowed to disintegrate naturally within the timeframe of the standard for biodegradation discussed in the next section. Sand used in hemp bags to form domed and other small structures can equally be made to return to its natural state. Once a structure made of such materials has been allowed to disintegrate, the materials can be reused to build new structures demonstrating the retention of the material quality (Keefe, 2005).

The natural disintegration of materials can therefore be accepted as a CLMC subject to it occurring within the timeframe set out in the next section, without loss of material quality and without negative impacts on the environment akin to those associated with landfilling.

4.4.3 TIME SPAN AND EFFICIENCY OF NATURAL CLC PROCESSES

Composting is recognised as a viable disposal option for biodegradable construction and demolition waste, and considered to have significant environmental advantages and the potential to contribute to reduce biodegradable waste sent to landfill over the next 20 years as required by the EU Landfill Directive (Building Research Establishment Centre for Resource Management, 2003).

The British Standard 13432:2000 (2000) on the requirements for packaging recoverable through composting and biodegradation has been developed to define biodegradability particularly in relation to packaging. Petroleum-based plastics, mainly polyolefins such as LDPE and LLDPE which can now be modified with additives to be made biodegradable and able to be converted through digestive activity of microorganisms into water and carbon dioxide (Swain *et al.,* 2004), have to comply with the BSEN 13432:2000 to be able to be considered biodegradable.

The standard test methods set out of in the BSEN 13432:2000 consider aerobic degradability in water, anaerobic degradability in water and aerobic composting, and stipulate the rate and efficiency of the biodegrading process and the quality of the resulting compost with particular attention to phytotoxicity and heavy metal content. It requires the biodegrading process to take place within a semi-industrial composting environment without adverse impacts. It states that biodegradability in watery medium must convert at least 90 per cent of the organic material into carbon dioxide within six months and disintegration into compost must achieve no more than 10 per cent residue after three months' composting and subsequent sifting through a 2 mm sieve (British Standards Institution, 2000). Research by the Building Research Establishment into the potential of composting and bioremediation as a means to divert construction and demolition waste from landfill tested the composting of treated and untreated timber plus various timber building boards and the results showed adequate results within six months (Hobbs *et al.,* 2005).

In respect of natural CLCs other than through composting, the same standards can be adapted to form suitable criteria that relate to the same aims. The rate of natural disintegration should ensure a full disintegration within six months and the percentage of waste should not exceed 10 per cent and the quality of the resulting material should be equivalent to that used to form the original product.

4.4.4 POTENTIAL SOURCES OF CONTAMINANTS

Biodegradable materials integrated into buildings often have to be treated in order to avoid premature degrading and insect attack. When composting these materials such treatments could result in higher than acceptable toxicity of the resulting compost. The BSEN 13432:2000 standard sets limits of the content of heavy metals and the compost's phytotoxicity has to be tested to the British Standards Institute's Publicly Available Specification (PAS) 100:2005 which requires the compost to achieve growth performance equivalent to 80 per cent of the control compost (British Standards Institution, 2000).

Research by the Building Research Establishment has shown that composting was suitable to dispose of untreated and painted timber;

formwork with releasing agent and concrete contamination; chipboard; glue laminated timber; hardboard; OSB; MDF and similar boards bonded together with between 2 and 12 per cent by mass of isococyanates; melamine urea formaldehyde; and phenol formaldehyde or urea formaldehyde binders without negatively affecting the phytotoxicity of the compost. The research also showed that where toxicity was excessive as with CCA treated timber, the composting process could be followed by a second phase of bioremediation to reduce toxins to safe levels. This suggests that composting with bioremediation can successfully be used to divert a significant amount of biodegradable material for landfill and incineration, including materials that are considered toxic (Hobbs *et al.*, 2005).

Natural materials that can be made to disintegrate are generally free from chemical contaminants and therefore do not present a problem in relation to chemical toxicity, but would nonetheless have to be tested to confirm this.

4.4.5 SUMMARY OF NATURAL CLC PRINCIPLES

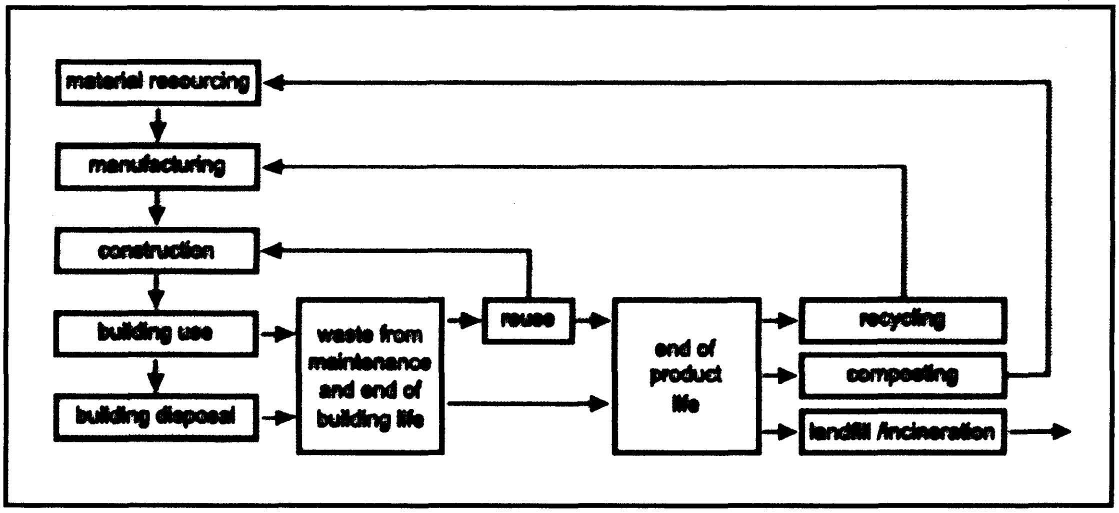
In summary, for a material to be considered a CLC material through natural processes it, therefore, needs to biodegrade or disintegrate and if necessary be treated to result in

- less than 10 per cent of waste (material left over after composting or cannot be made to disintegrate) in line with the ENBS 13432:2000 standard, and
- a material with low toxicity in line with ENBS 13432:2000 standard and the BSI's PAS 100:2005 which can safely be used as compost or reused as a building material.

4.5 CLC MATERIALS AND CLMC CONSTRUCTION DEFINITIONS

In conclusion, for a building element or material to qualify as part of a CLMC it has to be able to be recovered and enter a CLC either through industrial processes of recycling, subject to recycling being possible infinitely, or through natural processes of composting or natural disintegration. Elements and materials that eventually have to be landfilled or incinerated are part of a linear process (Figure 35).

Figure 35 - **Material flows within CLC and linear processes**



The key feature that could characterise a CLMC construction is the ability to be deconstructed without precluding the ability of the material to entre a CLC. The key features of a CLC material include the ability of the material to be reprocessed:

- infinitely through industrial or natural recovery (including biodegradation and natural disintegration);
- without significant loss of material quality and mass;
- within a limited timeframe; and
- without uncontrolled or significant pollution emissions.

Considering the above characteristics, the definition of a CLMC proposed in section 4.1 can be expanded to address CLC materials and CLMC building elements (Table 36).

Table 36 – **Definitions for CLMC, CLC materials and CLMC construction**

closed loop material cycle
: a closed loop material cycle, within the context of the building industry and building materials and elements, is a resource cycle that can operate infinitely transforming waste material into a useful resource for future use and producing zero waste and low environmental impacts.

closed loop cycle material
: a material that retains a use infinitely while potentially changing its application and material state through industrial or natural processes associated with minimal waste and pollution.

closed loop material cycle construction
: a construction made of materials and elements that qualify as closed loop cycle materials and are integrated within the building so as to enable their removal and introduction into a closed loop material cycle process.

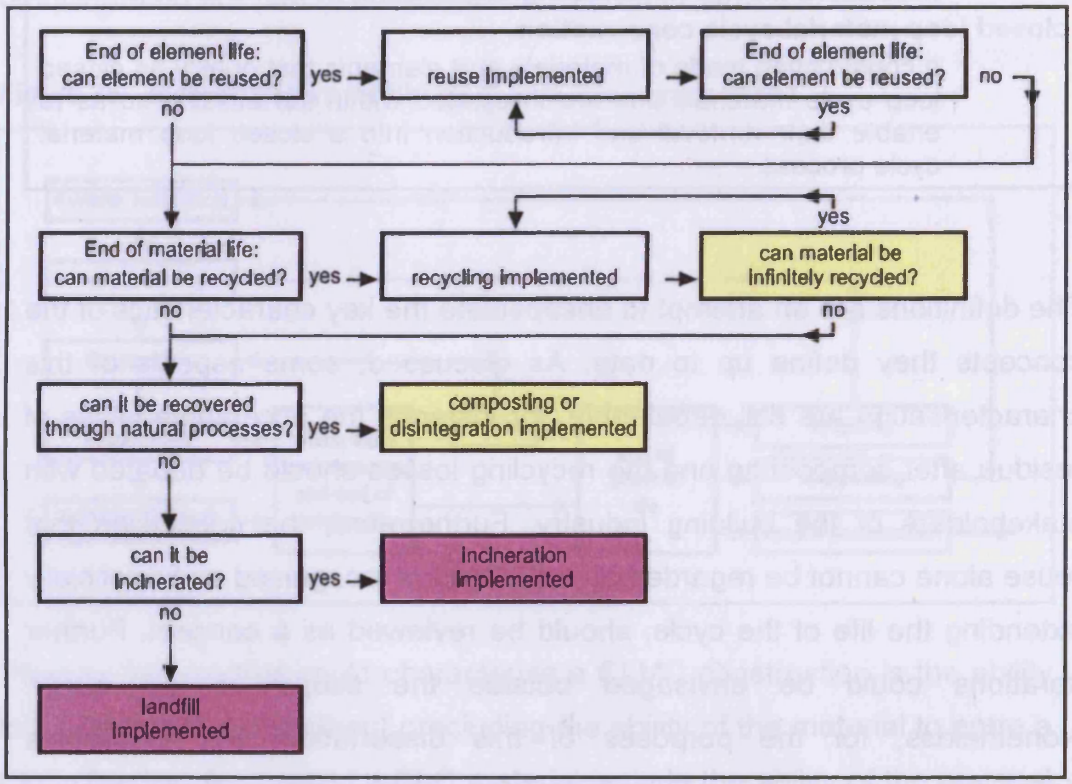
The definitions are an attempt to encapsulate the key characteristics of the concepts they define up to date. As discussed, some aspects of this characterisation are still debateable, for instance the acceptable levels of residue after composting and the recycling losses should be debated with stakeholders of the building industry. Furthermore, the conclusion that reuse alone cannot be regarded as a CLC but is recognised as beneficially extending the life of the cycle, should be reviewed as a concept. Further iterations could be envisaged outside the scope of this study. Nonetheless, for the purposes of this dissertation, the arguments developed support the characterisations above that will be further investigated in the next section to develop a set of quantifiable criteria to assess the compliance with the principles of CLMC construction.

These criteria would not only allow a building to be assessed in respect of its compliance with the principles of CLMC construction, but would also enable designers to understand and foresee the end-of-life options and design accordingly. Figure 37 identifies the decision-making process required to select environmentally sound end-of-life disposal options for building elements and materials. CLMC compliant solutions will result in an approach identified with the yellow boxes, while a non-CLMC-compliant option will result in an approach identified with the purple boxes.

Each decision identified in the flow chart requires making an assessment on the suitability of the options available. The criteria would provide the assessment tools to support these decisions.

Figure 37 – **Decision-making flow chart for selecting disposal options for building elements and materials.**

Key:
Purple boxes = the end-of-life options that constitute a linear process
Yellow boxes = the end-of-life options that constitute a closed loop material cycle.



The criteria will be divided into two groups: one relating to the element design and installation into the building and assessing its ability to be deconstructed or dismantled (Industrial Ecology's waste mining); and the second relating to the characteristics of the materials and their ability to comply with a CLC as defined in the previous section.

4.6 ASSESSMENT CRITERIA FOR CLMC

In considering the potential benefits of deconstruction, recycling and reuse researchers have not only investigated the barriers to design for deconstruction, recycling and reuse, but have also attempted to address the gap between the potential for deconstruction and its implementation in practice by developing guidance for building designers.

This section analyses the existing guidance, which includes criteria for deconstruction, reuse and recycling, and considers its relevance to the concept of CLMC construction and the characteristics identified in the previous section. Existing criteria are considered for inclusion in the CLMC concept and additional criteria are developed based on existing research as required to form a comprehensive set of criteria to assess buildings for their compliance with CLMC principles.

As mentioned earlier the criteria will relate to technical and practical issues only and not economic issues that are liable to change over time. The following documents, listed in chronological order, were studied to form the basis for the development of CLMC criteria. Appendix 8.9 includes the analytical tool used to compare and assess the different systems. Table 38 includes a comprehensive and rationalised list of criteria and guidance for deconstruction, reuse and recycling derived from existing literature and expanded to address natural recovery. The reference numbers preceding the authors are used to reference the guidance in Table 38.

[1] Sassi, P. and Thompson, M. (1998) - Summary of a study on the potential of recycling in the building industry and the development of an indexing system to assess the suitability of materials for recycling and the benefits from recycling. *Proceedings of Building a New Century, 5th Conference on Solar Architecture and Design, Bonn.* pp.344-349.

This paper summarises a system developed to assessment the ability of building elements to be dismantled and reused or recycled. It considered technical and economic issues and uses a weighting system to emphasise the technical aspects while considering the economic factors. The criteria regarding the preparation, toxic content and design of the elements were given the highest weighting as they affect the ability to recycle the elements. The criteria regarding the accessibility, tool requirements, time involvement and sturdiness are given a medium weighting, as they affect cost, but not the ability to recycle. The criterion regarding the market availability was given the lowest weighting due to its changing nature. The result is a system that reflected the importance of speed in the construction industry. Elements that are easily and quickly removed and dismantled attained a high suitability index. Elements that are difficult to recycled or have toxic components attained a low suitability index.

[2] Crowther, P. (2000) - Developing Guidelines for Designing for Deconstruction. *Deconstruction - Closing the loop. Workshop held at the Building Research Establishment, Watford, UK. May 2000.*

The guidelines presented in this paper are the result of research into designing for deconstruction and is aimed at designers wishing to design buildings that can be deconstructed in future. It groups the guidance in relation to the final use of the building product, i.e. whether it is to be deconstructed and reused or reconditioned or recycled. It also offers guidance on designing for deconstruction to facilitate building adaptability and relocation. The focus is on facilitating the process therefore economic aspects are considered as well as provision of information, health and safety and other practical deconstruction aspects.

[3] Fletcher, S.L., Plank, R. , Popovic, O. (2000) - Designing for future reuse and recycling. *Deconstruction - Closing the loop. Workshop held at the Building Research Establishment, Watford, UK. May 2000.*

This paper reports on research undertaken as part of a doctorate of research that included an analysis of the attitudes of demolition experts to deconstruction and demolition. It summarises the guidance offered by the demolition experts in response to the question of how to make buildings more easily demountable. The study groups the guidance into three main groups including system's level (the building), product level (building component) and material level. All aspects of dismantling, including technical and practical, are considered and listed under the headings of design, information, market, disassembly [process], construction [deconstruction process], pre-cast and pre-assembly. The reported views are not categorised, but the demolition experts appear to put equal emphasis on issues of cost, including time and health and safety, as on designing buildings to facilitate their dismantling and in doing so highlight the interrelated nature of the technical and practical aspects.

[4] Thormark C. (2001) - *Recycling Potential and Design for Disassembly in Building. TABK— 01/1021.* Sweden, Lund: Lund Institute of Technology.

This doctoral dissertation considers the recycling potential of buildings by measuring the amount of material and energy that could be recovered once the building comes to the end of its life. In order to measure this potential the dissertation devises a means of assessing the dismantleability of a structure and in doing so develops guidelines for design for dismantling. The guidelines include economic and technical aspects and are divided into three main groups dealing with choice of materials, design of construction and choice of joints and connections. Each guidance item is justified with relevant evidence.

[5] Sassi, P. (2002) - Study of current building methods that enable the dismantling of building structures and their classifications according to their ability to be reused, recycled or downcycled. *Proceedings of Sustainable Building 2002: 3rd International Conference on Sustainable Building. 23-25 Sep.2002. Oslo, Norway.*

This paper reports on a study of 60 building products that were analysed to establish their most suitable end-of-life treatments. A system was developed to assess building products and materials and identify their deconstruction, reuse, recycling and downcycling potential. This could be used to classify products and materials and provide guidance to facilitate the design of recyclable and reusable building systems. The system comprised two sets of criteria, the first assessed the ability of building products to be dismantled and a second set of criteria assessed their ability to be reused, recycled or downcycled. The criteria considered economic and technical aspects and were used to assess.

[6] Addis, W. and Schouten, J. (2004) - *Principles of design for deconstruction to facilitate reuse and recycling CIRIA C607* London: Construction Industry Research and Information Association.

This Construction Industry Research and Information Association publication provides guidance mainly for designers in respect of deconstruction. It also reviews examples of good practice that relate to deconstruction. The publication includes guidance in a number of different formats. The principle guidance relates to and is structured by building element, and incorporates the guidance developed by Sassi (2002) but expands it to include more building element types. This document presents evaluations of building elements in relation to three options: designing for deconstruction, deconstruction for reuse and deconstruction for recycling. Economic and technical issues are considered. Additional guidance is provided for designing temporary buildings.

[7] Morgan, C. and Stevenson, F. (2005) - *Design for Deconstruction. A SEDA Design Guides for Scotland.* Scottish Ecological Design Association. Available online http://www.seda2.org/dfd/index.htm.

This guide proposes five wall, floor and roof details that are designed to maximise the potential for the reuse and recycling of the constituent components and materials. The construction types selected are standard construction systems adopted in Scotland that have been altered as necessary to achieve a deconstructable, reusable and recyclable construction. Ten detailed drawings, five original constructions and five deconstructable constructions, are provided with specification notes and guidance on cost. The introduction to the guide provides general principles and background to the research field of design for deconstruction. The principles put forward consider economic as well as technical aspects.

DISCUSSION OF CRITERIA

Table 38 represents a rationalisation of the guidance and criteria for design for deconstruction, reuse and recycling developed by the above researchers. Appendix 8.9 includes the full set of data and illustrates the rationalisation process. Table 38 is divided into four sections addressing:

- deconstruction process,
- processing for reuse,
- processing for recycling, and
- processing for natural recovery.

Principles shared by the researchers are identifying and grouped together.

The concept of CLMC construction is a further development of the concepts of deconstruction, reuse and recycling combined. Many of the guidance that applies to the combined concepts will apply to the CLMC concept. However, the latter is more demanding in respect of the recycling, which is required to be infinite, and in respect of the addition of recovery through natural processes. Therefore, new criteria, particularly in relation to recovery through natural processes, are required. The analysis of the existing criteria differentiates between criteria related to economic and technical aspects in order to exclude economic criteria. It also considered the following issues.

Most of the researchers consider dismantling and reuse and recycling together. Lutzendorf (2000) states that the specific requirements for deconstruction will vary depending on whether the material or element will be ultimately reused and recycled (Lutzendorf considers the requirements for an assessment of the recycling potential of materials). Some differentiation is made by Sassi (2002) between the requirements for dismantling, reuse and recycling and Addis and Schouten (2004) provide different guidance specific to reuse and recycling and other guidance specific to designing temporary buildings. Differentiating between requirements is useful in avoiding designing elements to a superior standard than the one required to achieve the final goal.

CLCs through natural recovery processes are not considered by any of the researchers. The systems either simply considers disassembly or disassembly with reuse and recycling, but do not consider composting or other natural recovery processes of returning material to a useful use. New set of criteria area required to address these additional options.

The systems consider technical and economic aspects, including market desirability. In selecting and developing criteria for CLMC only those criteria that are fundamentally linked to the material and building element characteristics can be considered constant. Aspects that affect the economics of dismantling may vary for the following reasons.

- The financial impact of the development time, labour costs and material costs vary depending on the type of project. On a self-build development labour costs may not be considered, while in commercial project loss of time is associated with loss of money, typically through interest payments.
- Fluctuations in energy costs affect the cost of transport, manufacturing and installation and will change in a future relevant to the lifespan of buildings.

There is a consensus among researchers that as deconstruction becomes more commonplace the economics of it will become more favourable (Eklund *et al.,* 2003). An economic assessment therefore, is likely to be valid for a relatively short period of time and should not be considered as part of this assessment.

Weightings for the different criteria are used in some of the assessment systems (Sassi, 1998, 2002). Weightings are appropriate where a series of unrelated assessments are combined to deliver one single overall assessment value. Weightings are used, for instance as part of the Building Research Establishment Material Profiles and were used in Sassi and Thompson's research (1998) where economic and technical assessments were both considered. The use of weightings in a CLMC assessment system is inappropriate as partial compliance with the principles would results in non-compliance overall. A CLC materials must be technically able to be dismantled and disposed of through recycling or natural disintegration. Furthermore, the sub-requirements for those main requirements are also all mandatory and only achieved if 100 per cent achieved. A material and building element either is part of a closed loop cycle or not, only partially forming part of a CLC is equivalent to not forming part of it at all.

SELECTING THE CRITERIA

The ultimate aim of such as assessment system is to encourage more sustainable building practice and consequently the potential for a widespread application is essential. The purpose of the assessment criteria is to provide a tool to assess the ability of a building methods or system to form part of a CLC but should also be able to be used as a means to guide designers through the material selection and detailing process. Taking into account the dual aim, the criteria should be explicit but allow for problem-solving relating to specific situations. In relation to the criteria's role in providing guidance for designers, the criteria should reflect the design process. Therefore, the CLMC criteria need to consider the deconstruction followed by the processing of reclaimed elements and materials. A basic understanding of construction may be a prerequisite to using the criteria.

As discussed above economic-related criteria will not be included and the inclusion of criteria will depend purely on their technical ability of forming part of a CLC. Table 38 consists of a comprehensive list of the criteria for deconstruction, reuse, recycling and natural recovery. The criteria are rationalised from the different assessment systems reviewed and derived from the same to be applied to the concept of natural recovery. Appendix 8.9 shows the analysis of the existing assessment and guidance systems that underpins the selection of criteria included in Table 38. Sections 4.6.1 to 4.6.4 discuss the relevance of the criteria listed in Table 38 and their potential for adoption as part of the CLMC criteria.

Table 38 – Comprehensive and rationalised list of criteria and guidance for deconstruction, reuse and recycling from existing literature

The development work for this table is included in Appendix 8.9

Key:

[1] Sassi and Thompson (1998).

[2] Crowther, P. (2000).

[3] Fletcher *et al.*, (2000).

[4] Thormark C. (2001).

[5] Sassi, P. (2002).

[6] Addis and Schouten (2004).

[7] Morgan and Stevenson (2005).

DECONSTRUCTION PROCESS	type of criteria and comments
Ability to access Ensure all components can be readily accessed[7][3]	*technical* Ability to access elements to allow for dismantling
Ease of accessibility Consider people, methods, plant for deconstruction, in particular, safe and adequate access and appropriate speed of deconstruction. [1] [2] [6]	*economics* Ease of access impacts on the speed and involvement of deconstruction
Order of accessibility Hierarchy of disassembly relevant to component life span[2] [7]	*economics* The ability to directly access sections to be removed without the removal of others reduces time and cost.
Accessibility of fixings Ensure interface/connection points are identifiable and accessible[6] [5]	*technical* Fixings need to be accessible
Parallel disassembly Design for parallel disassembly [2] [5] [7]	*economics* The ability to dismantle different area in parallel increases speed of deconstruction and reduces costs
Number of components minimise number and variety of components [6]	*economics* Few large components can be handled quicker than many small ones
Tools for dismantling Simplify fixing systems and enable removal by means of small hand tools and handheld electrical tools avoiding specialist plant. [5] [1] [2]	*economics* Non-specialist assembly and the use of common tools results in lower costs.
Types of fixings Fixings have to be (a) weaker than the bonded element, (b) reversible fixings ie mechanical reversible fixings or soluble adhesives. [1] [2] [3] [4] [5] [6] [7]	*technical* The type of fixing is critical in respect of the ability to dismantle. Certain fixings preclude dismantling.
Durability of fixings Design joints to withstand dismantling process. [5]	*technical* Fixings need to be durable enough to be used after a long time and, if the element is reused, also reused
Sturdiness of components Design components to withstand dismantling process. [5]	*technical* Sturdiness helps prevent disintegration when dismantled and any damage to the material should not compromise the ability to contain it and transported it
Number of fixings and parts Minimise number and variety of components [6] [5]	*economic* Minimising parts and fixings makes the process simpler, quicker and cheaper
Ease of handling Make components sized and of a weight to suit the means of handling and provide means of handling and locating [5] [2] [3] [6]	*technical* The ability to handle elements is essential to recover them from a building
Tolerances Provide realistic tolerances for assembly and disassembly. [5] [2]	*technical* Insufficient tolerances can compromise element being removed and compromise subsequent processes.
Hazard Eliminate use of toxic or contaminated materials [6] [5]	*economic* Removal of toxic material is very costly e.g. asbestos
Time requirements The time required to dismantle the building elements should be a short as possible. Modularity can help in terms of speed of dismantling. [4] [1] [3]	*economic* The quicker the deconstruction the cheaper the process
Information Provide As Built drawings and Maintenance Log including identification of points of disassembly, component and material and identify materials and points of disassembly on elements[5] [3]	*technical* While some building elements can be dismantled without guidance the dismantling of others can be subject to the provision of information and instructions.

PROCESSING FOR REUSE	
Reprocessing Use materials that require minimal reworking [5] [1] [3] [7]	*economic* The less reprocessing required the more economic the reuse. The amount of processing may be dictated by the aesthetic expectations of the market.
Durability of material Use only durable components which can be reused. [7] [1] [2] [5]	*technical* Sufficiently damaged elements will not be reused.
Durability of fixing Joints and components to withstand repeated use[5][2]	*technical* Damaged joints will not be reused.
Flexibility of reuse Use modular design to facilitate interchange of elements. [2] [5] [6]	*economic* Standardised/ modular elements facilitate interchange of elements. Unit size encourages reuse by reducing its effect on the building design.
Hazards Minimise toxic content, if toxic content is unavoidable ensure the ability to release it in a controlled manner[5] [1] [2] [3] [4]	*technical* Toxic materials found in building elements can either be handled with precautions without excessively elevating risk to health or are not suitable for reuse.
Information Provide product details and installation instructions. [5] [4]	*Technical* If the methods for reuse are not self-evident information is a prerequisite for reuse.
PROCESSING FOR INDUSTRIAL RECYCLING	
Multiple reprocessing Materials have to be recyclable into their original state	*Technical* Unless the material can be indefinitely recycled it cannot be considered part of a closed loop
Reprocessing Avoid non-recyclable materials such as composite materials and treatments and secondary finishes to materials that complicate reprocessing. [5] [1] [3] [6] [7]	*Economic* Technologies now exist to separate composite structures therefore bonded elements can be separated at a cost.
Material purity Use monomeric components. [7] Make inseparable subassemblies in same material. Minimise number of different materials. Avoid applied finishes [2]. Materials should be a 'clean' as possible. [4] [5] [6]	*Technical* Material impurities that compromise recycling constitute a technical barrier.
Hazards Information on hazardous materials is required [4] [1] [3]	*technical* Toxic materials found in building elements can be handled without excessively elevating risk to health but precautions could be costly.
Material damage Sturdiness of elements affecting recycling[1] [4]	*economic* Fragile or loose materials may require additional precautions to compromising the ability to contain it and transported it to recycling facilities.
Material loss/ degradation The recycling process should minimise material loss	*technical* Most recycling processes undergo some material loss which can be regarded as acceptable.
Information Provide identification of material and component types. [5] [2] [4] [6]	*economic* Identifying materials would make segregation of materials quick and avoid the need of specialist assessments.
PROCESSING FOR NATURAL RECOVERY (BIODEGRADATION AND RETURN TO NATURAL STATE)	
Pre-processing Minimal preparation of material to enable composting is desirable	*economic*
Material purity	*technical* Impurities that compromise a full biodegradation
Rate of biodegradability / erosion the material has to biodegrade at a rate that meets the criteria set out in BSEN 13432.	*technical* the rate of biodegradation
Hazards Avoid hazards that could contaminate the ground	*economic* Hazardous treatments that would leach out in the ground and contaminate it compromise the ability to compost safely without additional clean-up costs.
Material damage Sturdiness of elements affecting composting	*technical* Damage to the material should not compromise the ability to contain & transport it to composting facilities.
Information Provide identification of material and component types.	*economic* identification of material would make segregation of materials quick / avoids specialist assessments.

4.6.1 CRITERIA FOR DECONSTRUCTION

The dismantling of building elements and materials relies on the ability to access, handle, detach, collect and contain the element or material. The criteria discussed are divided into three groups including: component accessibility, connections and deconstruction process. The reference numbers refer to the seven guidance documents listed above and in Table 38. The short discussion for each criterion will conclude whether the criterion is essential or non-essential for the CLMC criteria.

4.6.1.1 COMPONENT ACCESSIBILITY

ABILITY TO ACCESS - Ensure all components can be readily accessed and removed [3] [7]

Essential criterion

Building elements and components have to be able to be accessed to allow for them to be detached from other elements. Direct accessibility is preferable to indirect accessibility, but essential is the ability and not the ease of access. The advantage of direct access in terms of facilitating maintenance and building upgrades, particularly as the servicing of buildings becomes increasingly complex, is well understood. Notable examples such as the Richard Rogers Architects' Lloyds Building in London (Powell, 1994) and the Pompidou Centre have addressed this issue by exposing the services and making them directly accessible. Where accessibility is complex but possible, the cost of access will rise. As the CLMC criteria do not consider economic aspects, as long as access is possible this criterion would be satisfied. Difficulty per se does not preclude access.

Where building element are embedded or encased in another element it may be impossible to separate them without destroying one or the other or accessed with great difficulty, the ability to access it remai fundamental requirement.

EASE OF ACCESSIBILITY - Ensure the people, methods and used for deconstruction have been considered, in particular, and adequate access and appropriate speed of deconstruction. [[6]

Non-essential crit

Having established that an element can be accessed, the consideration is how easily it can be accessed and what if any supp precautions should be taken. Ease of access is achieved by prov direct access without requirements for additional aides and with suff space to manoeuvre. The ease of access to elements determines the and therefore cost, for dismantling (Dowie, 1994).

Where access is not easily possible it may be necessary to pr scaffolding or mechanical or other equipment, which are typ associated with additional costs. In addition, if access is complex, fo planning may be necessary and that too is associated with time and c

Ease of access is purely an economic criterion and therefore non-ess for the CLMC assessment. Furthermore as deconstruction becomes common the cost of planning and common deconstruction method decrease. Also new approaches to dismantling are being develope make access for dismantling easier or irrelevant and can help spee the process of dismantling (Gregory *et al.*, 2004).

ORDER OF ACCESSIBILITY - Hierarchy of disassembly relevant to component life span [2] [7]

non-essential criterion

Order of accessibility is related to the Ease of Access (previous criterion). The order in which activities on site take place has been the focus of research into buildability and maintenance of buildings. Buildability is related to the ability to dismantle structures in the same way deconstruction is the reverse of construction. Guidance on buildability by the Construction Industry Research and Information Association (1983, p.9) lists seven recommendations three of which, recommendations 2, 3 and 4 listed below, are related to the order in which activities take place.

> '2 - Plan for essential site production requirements - The layout of a building or buildings on site and the programming of phased completions should recognise the requirements of site access, materials handling, and construction sequences.
>
> 3 - Plan for a practical sequence of building operations and early enclosure - The method of construction of a project should encourage the most effective sequence of building operations, and it should recognise the advantages of an early enclosure of the building.
>
> 4 - Plan for simplicity of assembly and logical trade sequences - The construction and setting out of a building should encourage simplicity of assembly, recognise trade sequences, and minimise requirements for return visits.'

This guidance advocates simplicity and considering site access and materials handling within the constraints of the site to ensure a logical and effective sequence of work. Guidance that is as relevant to deconstruction as construction.

When dismantling a building, the order in which building elements are accessible dictates the order of dismantling activities. The order of accessibility may have little significance if the whole building is dismantled, but is relevant to maintenance and upgrading activities during the building's life. These may involve accessing building elements, such as services, installed behind other elements that are due to be retained.

Good practice in building design has long supported the grouping of building elements. Alexander *et al.'s* (1977, p.1077) recommends to 'make ducts to carry hot air conduits, plumbing, gas, and other services in the triangular space, within the vault, around the upper edge of every room.' Grouping of elements should be according to their predicted lifespan and organised services would make access and future changes and additions easier. Duffy and Henney (1989) considered, among other issues, the construction and maintenance of commercial offices and identified how different layers of such buildings were installed and maintained independently from each other. Duffy and Henney (1989) identify four layers of building in descending order of longevity: the 'Shell', the 'Services', the 'Scenery', and the 'Sets'. The 'Shell' includes 'Lifelong Elements' as described in BS 7543:1992 (British Standards Institute, 1992), such as foundations and building structure. These elements 'with an life of up to 50 years, should be designed as a framework onto which mechanical, electrical and data services can be readily attached and detached' (Duffy and Henney, 1989, p.60). The 'Services' include mechanical, electrical and information technologies with a lifespan of 10-15 years. The Scenery includes the partitions, finishes and furniture with a life span of 5-7 years and the Sets is described as 'the rearrangement of the scenery by office workers to meet the daily and weekly exigencies of office life' (Duffy and Henney, 1989, p.62). The different layers are made accessible and able to be maintained independently through the use of demountable building elements such as demountable partitions, accessible service shafts, suspended ceilings and access floors, which all together form a loose fit flexible building. By making the whole building flexible the order of accessibility became less important.

The concept of building in layers is also discussed by Brand (1994) who develops a concept of layers as a means to achieve better architecture that is able to respond to the needs of users. Brand's build-up of layers is similar to that proposed by Duffy and as suggested in BS 7543:1992, but expands the concept in character and relevance making it applicable to different building types.

Brand's layers include:

- the Site;
- the Structure, expected to last from 30 to 300 years;
- the Skin, which encompasses all elements to create a weather-tight envelop, is expected to last twenty years and is affected by fashion and technology;
- the Services, have an expected life of from seven to fifteen years;
- the Space Plan, which includes partitions, ceilings, floors and doors, has an expected life of three years in commercial buildings and up to thirty years in housing;
- the Stuff, which includes loose furniture, appliances and objects, is expected to change daily to monthly.

Brand (1994) discusses how design for disassembly can be applied with the principles of layering to create flexibility that will allow users to adapt the building to their needs. He also offers a helpful, if inaccurate, image of the layers being one within the other, with the least accessible layers with the longest lives hidden behind the more accessible layers with shorter lives. In practice the requirement to replace layers does not necessarily occur in the neat sequence that Brand's image suggests, for instance services may have to be accessed at times when the Space Plan elements do not need to be disturbed. Therefore, while considering the access sequence appears of importance, the actual sequence is difficult to predict and it is often necessary to access a hidden layer.

The critical aspect of layered design is not the order of accessibility but the ability to access at all and if necessary access an element by first removing another and subsequently replacing it. If elements are directly accessible this will reduce the time required to remove or replace them. If they are hidden under another layer, accessing them will require removing the first layer costing time and money but not making the accessibility impossible. Whether in relation to deconstruction or maintenance the order of accessibility remains a non-essential economic criterion.

PARALLEL DISASSEMBLY - Design for parallel disassembly [2] [5] [7]

non-essential criterion

The ability to disassemble building elements in parallel is related to the principles of building in layers and order of accessibility. Parallel disassembly has the same advantages as layering elements in the order they need to be accessed, which is economic.

Studies of deconstruction and demolition cost and time showed a time saving of nearly 50 per cent where parallel deconstruction could take place (Schultmann and Rentz, 2002). It is clearly desirable in relation to deconstruction to have easily accessible elements, configured in layers and able to be deconstructed in parallel. Nonetheless, as with the previous two criteria, not being able to disassemble in parallel will not negate the ability to disassemble in absolute.

4.6.1.2 CONNECTIONS

ACCESSIBILITY OF FIXINGS - Ensure interface/connection points are identifiable and accessible [5] [6]

essential criterion

In relation to connections parallels can be drawn with product design that has benefitted since the 1980's from an interest in design for environment, which incorporates principles of design for disassembly and recycling. In summarising guidance on design for disassembly in relation to product design Desai and Mital (2005) recommend ensuring fixings can be accessed with ease and not requiring force. In relation to buildings, being able to access fixings and operate them is critical to being able to remove elements from buildings. The concept of not applying force is also valid as force could damage the fixing and make it inoperable or damage the element to the extent that it is difficult to transport it off site. The ease of accessibility, once more as with the previous discussion, affects the economics of the recovery process only, but accessibility per se is essential.

Completely non-accessible fixings are relatively uncommon, an example being any fixing cast within concrete. In many cases some scope for access may remain, as with screw fastenings for plasterboard which are plastered over, thus hiding the fixing and making them difficult, but not impossible, to use if identified. Fixings may be visually covered in which case information about their location would be required and would make the fixings essentially accessible. In certain cases the fixings may be covered with a removable element and it may be possible to remove the barrier to the fixings and use the fixings. On the other hand, damage to a fixing can make it impossible to use, thus making disassembly impossible.

The assessment should consider whether the fixing is or can be made accessible. Making a fixing accessible may be done through the provision of information or other means.

TYPES OF CONNECTIONS - Fixings have to be (a) weaker than the bonded element, (b) reversible fixings i.e. mechanical reversible fixings or soluble adhesives. [1] [2] [3] [4] [5][6] [7]

essential criterion

Research into design for deconstruction and product design for disassembly has focused on the connection of elements as a critical factor in enabling elements to be separated and disposed of sustainably. The aim is to be able to detach elements and preferably quickly and the connection type used is pivotal in achieving this aim.

The guidance in respect of fixings and connections, including the seven core guidance documents studied, typically aggregates the requirements to allow for reuse and those to allow for recycling, although these can be fundamentally different. The requirements for connections to enable reuse of elements are more demanding than those for recycling in that they need to enable the removal of the element without damaging it. The requirements for fixings to enable recycling have to ensure that excessive contamination and deterioration of the element that would preclude recycling is avoided.

Table 39 lists different methods for connecting building elements and their impact on the potential of dismantling and recycling (through industrial or natural means) and reuse of the building element. The table is divided into four main methods of connecting building elements, which include:

- mechanical fixings (e.g. screws);
- chemical fixings (e.g. adhesives);
- friction fixings (e.g. rubber profiles to take inserts); and
- loose connections that rely on interlocking elements (e.g. terracotta tiles supported within profiled metal channels).

Connections can be ranked from most demountable to least demountable with loose and friction fixings being inherently demountable followed by mechanical fixings, with relatively high demountability, and finally chemical fixings as the least demountable (Crowther, 2000; Sassi, 2002; Addis and Schouten, 2004; Morgan and Stevenson 2005).

Loose interlocking connections and friction connections enable elements to be reused and recycled and are primarily subject to limitations due to the durability of the fixing system, which is discussed as the next criterion.

Mechanical fixings should be reversible, such as screws which can be unscrewed. Examples of effectively reversible fixing systems abound in the temporary and exhibition building industry (Kronenburg, 2000). Recommendations are for the use of bolts in preference to rivets, and for sprung clips, wing nuts (Addis and Schouten, 2004). However, elements fixed with non-reversible fixing systems, such as nails, may still be able to be recycled (if not necessarily reused). Also riveted steel can be cut and

Table 39 - **Building element connections and their impact on the potential for dismantling, reuse and recycling thought industrial or natural means**

Fixing / jointing type	Ability to enable deconstruction of elements connected	Ability to be recycled / composted	Ability to maintain recycling (through industrial or natural cycles) potential of elements connected	Ability to be reused	Ability to maintain reuse potential of the elements connected
MECHANICAL					
nail	good if accessible and the elements are stronger than the fixing	good	Poor - May damage material, but might not compromise potential for recycling and composting	poor	poor – removal of nail fixings usually damages element
screw fixing	good – may rust over time	good	good	limited – reuse is possible for a limited number of times	good
bolt fixing	good – may rust over time	good	good	good -	good
riveted fixing	poor	good – if collected the rivets can be melted down	Is likely to damage material	poor	poor
ADHESIVES					
Same material jointing medium	poor	good – included within building element recycling process	adequate - a loss a material is possible	poor	poor
compatible material adhesives (silicon fixed glass)	adequate - time consuming to remove	poor	minimal – bonding medium does not compromise the recycling of building element	poor	poor
incompatible material adhesives weaker than element (lime mortar)	good	poor	minimal	poor	good
incompatible material adhesives stronger than element (cement mortar, resin anchors into weak materials)	generally poor but depends on the recycling process.	generally poor	generally poor but depends on the recycling process.	poor	poor
FRICTION					
Push-fit connections	good	good	good	good	good
LOOSE INTERLOCKING CONNECTIONS					
Elements held in place through self-weight (paving slabs)	good	good	good	good	good
Elements held in place through interlocking fixing system (terracotta cladding)	good	good	good	good	good

recycled, but there may be a resulting waste of material that cannot be recovered. Whether a fixing is reversible or not cannot be the fundamental requirement for a fixing, instead an essential requirement is to be able to remove the fixing. Two other aspects of mechanical fixings are critical to deconstruction and CLMCs, and they are interlinked. Mechanical fixings (1) should remain operational over time and (2) should not result in a level of contamination of the element that precludes its recycling. For instance, a rusted metal fixing in timber may break in the process of dismantling and remain embedded in the timber ultimately constituting a contaminant, albeit small.

Chemical fixings are considered the least demountable of the connection options. These can be divided into four groups to be considered in sequence.

Same material bonding medium - Chemical fixings which consist of a bonding medium that is identical to the element to be bonded, such as steel welding or hot air welded PVC roofing ply, cannot be separated at the connection point. Reuse of the building element in its original state is therefore not possible, but in an altered state may be possible (cutting welded steel beams is possible and the newly cut sections can be used in new locations). If the material is recyclable then the same material bonding medium does not present a problem to the recycling process. However, the deconstruction may not be as efficient in terms of percentage of material removed, separated and sent for recycling. Same material bonding medium may allow for dismantling for recycling (subject to material characteristics) notwithstanding a potential loss of material.

Recycling-compatible bonding medium – Some chemical adhesives can be introduced into the recycling process of the element they connect without compromising the quality of the recycled material. Recycling processes that involve high temperatures can burn off organic polymer adhesives without affecting material quality (Onusseit, 2006). Lightweight metal sections bonded with an organic chemical adhesive can be melted down into new steel without affecting the steel quality.

Recycling-incompatible bonding medium stronger than building element and recycling-incompatible bonding medium weaker than building element – Where the bonding medium cannot be recycled with the building element, it must be separated from it. Recommendations in this respect call for the fixing medium to be weaker than the bonded element. This relates particularly to the potential for reuse of elements as reuse is dependent on the recovery of an element intact. For instance, bricks bedded in cement mortar, which is stronger than the bricks, are likely to break during the deconstruction of a wall, while if bedded in lime mortar, which is weaker than the bricks, they are likely to remain intact (Ethical Consumer Research Association, 1995a). Where the adhesive is weaker than the element and a water-based adhesive it can be dissolved in water either as part of the element removal process or and in the process of cleaning the material before reuse or recycling. However, research into recycling in the product industry suggests that the relation between strength of bonding medium and element to be connected depends on the recycling process. Where the recycling process involves shredding a material, such as with rubber, an adhesive medium that remains intact can be removed more easily (Onusseit, 2006).

In conclusion the essential criteria for the fixing method suitable for a closed loop material cycle have to include

- the ability to be removed (mechanically or with solvents) from the element or alternatively integrated within the recycling process;
- the ability to ensure a high percent of recovery of the material;
- the ability to ensure a high quality of the material recycled without contaminants and
- the ability to remain operational long term.

DURABILITY OF FIXINGS - Design joints and components to withstand dismantling process. [5]

essential criterion

As mentioned above the fixing system needs to remain operational long term to ensure deconstruction and recycling or reuse can take place at a future point in time. This is particularly relevant for mechanical and friction fixings that can rust and seize up and rubber gaskets that can dry out or stick to the element. Fixings need to be durable enough to be used after a long periods of inaction and may also require some protection from weathering agents. Fixings may have to be overdesigned to withstand the additional pressures of repeated use. To ensure a CLMC construction the fixings used have to remain operational long term and consideration has to be given to it typical operational life and circumstances that might reduce it.

NUMBER OF FIXINGS - Minimise number [5] [6]

non-essential criterion

Research into product design strongly supports the reduction of the number of fixings that need to be removed to recondition or recover a material (Dowie, 1994; Desai and Mital, 2005). The concept of minimising fixings can also be seen implemented in temporary buildings such as tent structures (Kronenburg, 1995, 2000) and through more sophisticated design processes in exhibition buildings such as, the British Expo building in Seville by Nicholas Grimshaw and Partners (Davies, 1992).

Minimising the number of fixings makes the process quicker and therefore creates an economic advantage that can encourage deconstruction but does not affect the fundamental ability to deconstruct.

4.6.1.3 DECONSTRUCTION PROCESS

TOOLS FOR DISMANTLING - Simplify fixing systems and enable removal by means of small hand tools and handheld electrical tools avoiding specialist plant. [1] [2] [5]

non-essential criterion

In respect of product design Desai and Mital (2005, p.717) suggest that 'Ideally, disassembly should take place without the use of tools'. In building construction deconstruction without tools is very limited, but advantages of using non-specialist and common tools have been identified and include:

- reduced preparation costs (specialist tools may have to be purchased or hired);
- lower equipment costs (same reason as above) ; and
- no training requirements (the use of specialist tools may need an induction or training).

These advantages have driven companies such as Weatherhaven Resources that build temporary shelters in remote locations to design systems that require no specialist tools (Kronenburg, 2000), but the advantages would apply also when building and deconstructing in any context. Furthermore, the use of complex, mechanised and specialist plant may be more energy-intensive to use and therefore combined with the reasons listed above the use of specialist dismantling tools is more costly than the use of standard tools. However, as technologies for recycling and dismantling are explored and developed, the use of specialised plant may not only become more affordable, but elements that might currently not be cost-effective to dismantle might become more economically viable to dismantle (Gregory *et al.*, 2004).

Despite the advantages of simple tools this criterion remains an essentially economic criterion and therefore non-essential for the CLMC assessment.

NUMBER OF COMPONENTS - Minimise number and variety of components[6] [5]

non-essential criterion

As with minimising the number of fixings, minimising the number of components makes the process of deconstruction quicker and therefore cheaper (Dowie, 1994; Desai and Mital, 2005). A simple example is removing paving slabs compared to cobble stones sufficient to cover the same area, which involves handling (prising, lifting, moving) between 4 and 20 times fewer elements resulting in a significant time saving. As with the number of fixings the number of components does not affect the fundamental ability to dismantle a construction.

STURDINESS OF COMPONENTS - Design components to withstand dismantling process. [5]

non-essential criterion

As discussed in relation to the potential damage resulting from the removal of fixings, damage to building elements destined for reuse is of greater concern that damage to building elements destined for recycling. Handling components is easier if they are sturdy enough not to disintegrate when dismantled. Fragile components, such as acoustic tiles, may break apart in the process of dismantling and handling and material can be lost in the process. Nonetheless, while sturdiness will facilitate the dismantling process fragile materials can be recovered subject to higher levels of care being taken, which will result in higher costs. Any loss of material experienced as a result of building elements breaking would be considered as part of the criterion for material loss as part of the recycling or natural recovery process.

EASE OF HANDLING - Make components sized and of a weight to suit the means of handling and provide means of handling and locating [2] [3] [5] [6]

non–essential criterion

This criterion addresses two points, one focusing on the economics of dismantling the other on health and safety of the dismantling procedure. Small components, such as bricks or paving slabs, can be easily picked up by one person; don't need special handling equipment (e.g. crane); and present minimal hazards to health when handled. At the other end of the spectrum steel structures often require the lifting capacity of a crane and to minimise health and safety risks should be provided with lifting points. Modern construction requires the construction process to be considered and aspects such as providing means of handling all building elements safely is now a requirement under The Construction (Design and Management) Regulations 2007 (Heath and Safety, 2007). Existing structures that do not benefit from having, for instance, integrated handling points would require additional work being done before the deconstruction could take place. This would involve additional effort and therefore cost but would not make the deconstruction impossible.

TOLERANCES - Provide realistic tolerances for assembly and disassembly. [2] [5]

non–essential criterion

As with the assembly process the disassembly process depends on sufficient tolerances to move elements. Where a series of elements are installed one after the other, the risk is that the installation of the latter elements reduces the tolerances available to the earlier elements installed, making it impossible for these to be removed. In that situation the element would be considered as inaccessible and therefore not comply with the accessibility criterion. A lack of tolerances that does not preclude access will not preclude dismantling ether and simply result in more time being needed.

HAZARD - Eliminate use of toxic or contaminated materials [5] [6]

non-essential criterion

Building construction and deconstruction has to consider a number of different hazards associated with these processes. These can be broadly classified in two groups: physical-mechanical hazards and chemical-physical hazards.

Physical-mechanical hazards relate to activities at heights, moving vehicles and other objects and physically straining activities. Precautions to reduce the risk associated with these hazards are well understood and part of on-site construction routines and are regulated through the Construction (Design and Management) Regulations 2007 (Heath and Safety, 2007). Deconstruction has additional hazards associated with instable structures and the potential for collapse. These risks may be inherent in some construction type (for instance pre-stressed concrete) but can be addressed by adopting appropriate means of deconstruction.

In addition deconstruction has to address chemical-physical hazards typically associated with materials and toxins (Strufe, 2005). The hazardous wastes European Council Directive 91/689/EEC & 94/904/EC requires the safe management of hazardous waste including its collecting, transport and storage (Official Journal of the European Communities, 1991). Materials that constitute hazardous waste include pigments, paints, resins, and plasticizers, and materials that can leach out toxins into the natural environment or that are corrosive or carcinogenic or harmful in other ways (McDonough and Braungart, 2002; Strufe, 2005; Giudice *et al.*, 2006). Materials in buildings can be hazardous due to their material characteristics or can become hazardous through additives (treatments and finishes) (Table 40).

The process of removal of such pollutants is controlled and has to present minimal risk to the operatives. The removal of certain toxic materials is very much in line with the principles of deconstruction. Asbestos, for instance, has to be removed carefully and with minimal breakages that would form hazardous dust and the removal has to take place in a controlled environment (Health and Safety Commission, 2006). While costly, the removal of asbestos is in essence a common process, which effectively involves deconstruction.

Table 40 - **Potential pollutant sources in buildings and building sites** (Schultmann, and Rentz, 2000, p. 53).

Origin	**Relevant Pollutants**
natural stone	heavy metals
gypsum	sulphate, heavy metals
asbestos	Asbestos
treated wood	heavy metals, lime, phenol, PCP
plastics	phenol, CHx, organic components
sealant	PCB
roofing felt	CHx, PAH, phenol
tech. installation	PCB, Hg, Cd
soot	heavy metals, PAH
dust	heavy metals
fire	PAH, PCDD/PCDF
Accidents (use)	includes oil, alkalis, acid

While the existence of hazards has an economic impact on deconstruction, the absence of hazardous materials or physical-mechanical hazards cannot be considered a pre-requisite for deconstruction as long as these can be addressed with suitable precautions.

TIME REQUIREMENTS - The time required to dismantle the building elements should be a short as possible [1] [3] [4]

non-essential criterion

One of the barriers to deconstruction has been identified as the time required for deconstruction and the resulting additional cost associated with it (Kibert, 2000, 2000a). Many of the guidance recommendations studied suggest ways of minimising the time required to dismantle a building including modularity, reduced number of components, independent layers and fixings and reversible fixings. Several have been discussed in previous criteria. While identified as an important issue for the widespread uptake of deconstruction in the current building industry context, the context for deconstruction is changing and, similarly to all other economic factors, the impact of time on the uptake of deconstruction approaches is volatile.

INFORMATION - Provide As Built drawings and maintenance log including identification of points of disassembly, component and material and identify materials and points of disassembly on elements [5] [3]

essential criterion

While some building elements can be dismantled without guidance, the dismantling of others can be dependent on the provision of information and instructions. Furthermore considering the building as a whole, information on its constituent parts may be critical to ensure an effective and hazard-free deconstruction. Some materials may be self-evidently dangerous to handle while other hazardous substances may be difficult to recognise. The requirement for asbestos surveys in public buildings and identification programmes are a case in point (Health and Safety Commission, 2006). Often buildings contain only a small amount of hazardous substances, which can nonetheless constitute a hazard to human health and, if not isolated, may contaminate and preclude the recycling of a large amount of other materials (Schultmann, and Rentz, 2002).

Recommendations for the provision of adequate information to allow for deconstruction include the use of Log Books (Morgan and Stevenson, 2005) and Material Recovery Notes (MRNs) (Hurley, 2003). The provision of information is generally viewed as invaluable for maximising reclaimed materials (Guy and Ohlsen, 2003). This is also in line with the requirements of the Construction (Design and Management) Regulations 2007 (Heath and Safety, 2007) and BS 7543:1992 Guide to durability of buildings and building elements, products and components (British Standards Institution, 1992) which suggests the use of a design life data sheet.

Morgan and Stevenson suggest a Deconstruction Plan should be devised at the construction phase of a project and include information on all materials included in the building and their best option for reuse, recycling or incineration and instructions on how to deconstruct elements including sequential processes and equipment required (Morgan and Stevenson, 2005).

Te Dorsthorst *et al.* (2000) highlight the importance of keeping such deconstruction plans up to date. A project studied by the group involved the dismantling of some apartments that had been built differently to the original drawings. A plan for the dismantling had been formulated, but as deconstruction began and the discrepancy became apparent a new plan had to be formulated, causing loss of time and increased costs.

Where such information is not available a building audit may provide much of the information required to deconstruct safely and efficiently. Despite the cost of formulating a deconstruction plan, and if necessary undertaking a building audit, overall deconstruction plans have been show to save time, and therefore money, as a result of more efficient use of manpower and equipment regardless of the demolition or deconstruction methods applied (Schultmann, and Rentz, 2002).

Particularly the economic advantages of having deconstruction information and the ability to undertake a pre-demolition audit would suggest that the provision of information is a non-essential criterion that affects economics of deconstruction but the absence of which can be overcome. This is only true of construction that can be recognised through a pre-demolition audit, which is essentially a visual inspection (Hurley, 2003). Where this is not possible information becomes critical. Therefore the criterion should not be the provision of information per se but the provision of information in respect of elements that cannot be assessed through visual or other simple means. The essential criterion could be defined as the provision of information where deconstruction would be impossible without it.

4.6.2 CRITERIA FOR REUSE

Despite having established that the ability of a building element to be reused does not by itself qualify it as a CLC material, the criteria that relate to the reuse of elements will be discussed briefly before focusing on those for recycling.

MULTIPLE USE MATERIAL – The element can be reused

essential reuse criterion

This essential criterion identifies the difference between a single use material, such as paint, that can only be used once and a material with the potential for multiple use such as timber cladding, windows, doors and more.

DURABILITY OF MATERIAL - Use only durable components [1] [2] [5] [7]

essential reuse criterion

If materials become damaged then they lose the ability (and value) to be reused (Guy and Ohlsen, 2000). The primary consideration in terms of the ability for a material to be reused is its durability overtime and its ability to withstand the deconstruction process.

DURABILITY OF FIXING - Design joints and components to withstand repeated use [2] [5]

non-essential reuse criterion

If the fixing is to be reused as well as the building element, it too should be durable enough to withstand the deconstruction process and even repeated use. Fixings are only a small percentage of a building element and if standard fixings are used they can be easily replaced and therefore their recovery becomes non-essential.

REPROCESSING - Use materials that require minimal reworking [1] [3] [5] [7]

non-essential reuse criterion

The less reprocessing that is required to bring a reclaimed material to a standard appropriate for re-installation in a building, the lower the cost associated with its reuse. At one end of the scale are roof tiles that need no reprocessing and minimal cleaning, and at the other end of the scale are windows that may need re-glazing, stripping and painting and even new ironmongery. Another aspect of reprocessing is the fragility of the building element that, if fragile, would require more care when handled and therefore require more time for processing. More extensive reprocessing requirements are not however a fundamental barrier to reuse.

HAZARDS - Minimise toxic content, if toxic content is unavoidable ensure the ability to release it in a controlled manner [1] [2] [3] [4] [5]

essential reuse criterion

As discussed in relation to the hazards related to deconstruction, this criterion is satisfied if the hazards associated with the reprocessing of elements to enable their reuse can be controlled. A total absence of hazards is not required to satisfy this criterion.

INFORMATION Provide product details and installation instructions. [5] [4]

essential reuse criterion

Information is only required if the reuse of a building element is not self-evident. At one end of the scale would be the reuse of bricks that requires general trade knowledge and building skills, and at the other end of the scale would be mechanical plant equipment which would require detailed installation manuals. As with deconstruction information for reuse is essential only for elements that require more than common knowledge.

FLEXIBILITY OF REUSE - Use modular design to facilitate interchange of elements. [2] [5] [6]

non-essential reuse criterion

Flexibility of reuse refers to the options available for reuse of an element and the ease and likelihood of it being reused. It considers market acceptability. Recommendations for flexible reuse include the use of modular and standardised construction, which allows for materials to be exchanged, and small unit size, which reduces the impact on the building design. Elements that can be reused without affecting the building design include bricks, wall boards and ceiling, wall and floor tiles.

> 'Standardisation in window dimensions and doors has provided untold ease in replacement. It hasn't reduced individuality to a point that is unacceptable, but the advantages for glaziers, furniture manufacturers and many other businesses can be easily recognised. '
>
> (Thomas, 2003, p.22)

Market acceptability can also be affected by aesthetics and connotations of 'second hand products'. There is often a prejudice against second-hand products without historic appeal. While a Victorian fireplace will attract a respectable resale price, second-hand modern sanitary ware is very difficult to resell at all. To overcome this barrier the ability to reapply a finish to a product to be reused could prove invaluable. Being able to reapply a finish would also address the issue of design fashion, enabling building elements to be upgraded to the current fashion requirements. Walter Stahel, considered as one of the pioneers of durability thinking, suggested that building in layers and separating the structural elements and visible elements of furniture would increase their life expectancy. By marketing substitute visible elements and complete take-back schemes by manufacturers the expected life could be extended indefinitely (Von Weizacker *et al.,* 1998).

Market appeal is not considered an essential criterion as it will vary with the changing economic and social context and is not a technical issue, despite the potential technical solutions suggested.

CERTIFICATION AND PERFORMANCE
essential reuse criterion

Reuse is affected by performance requirements and certification (Coventry and Guthrie, 1998). Reuse of such products as roof membranes, structural elements or insulation material can be hindered by the lack of certification of the elements' performance. Provision of information on the building products may partially eradicate the problem, but in certain cases testing will still be necessary adding to the cost of reusing the products. Guidance on testing and assessment services is available for the reuse of steel and timber structural members, but for certain products, such as roof membranes which require a warranty, reuse is limited. Furthermore, elements that are used to comply with regulations, such as acoustic or thermal regulations, may not be able to be reused as they fail to comply with upgraded standards (Eklund *et al.*, 2003). The ability to comply with legal requirements is a fundamental criterion for the reuse of a building element.

4.6.3 CRITERIA FOR RECYCLING

The following criteria relate to the assessment of the potential for recycling through industrial processes. Some considerations are identical to those that relate to deconstruction and will not be repeated.

MULTIPLE / INFINITE RECYCLING / MATERIAL DEGRADATION

essential criterion

The difference between existing criteria for dismantling and reuse and recycling and the criteria for CLMC is that the ability to be recycled once only does not qualify a materials as CLC material. The material properties of the constituent part of a building element have to be able to be recycled infinitely. The classic example of an infinitely recyclable material is steel, while an example of a material with limited recyclability is thermo-setting plastic. Thermo-setting plastics lose their physicochemical properties permanently during the manufacturing and may be able to be shredded and reformed into a product with different material characteristic but not recycled to regain their original physicochemical properties (Mellor *et al.* 2002).

Materials that can be recycled infinitely may nonetheless require the addition of a certain amount of virgin feedstock to the manufacturing process in order to maintain the material quality required for specific uses. While a small addition of virgin material may be acceptable within the concept of CLMC, a limit to the amount added needs to be established to achieve the ultimate environmental aims of minimal waste production and virgin material use. A precedent for setting such limits can be found in the standards for biodegradable material discussed in section 4.4. The same requirements can be applied to recycling through industrial methods, which would set a limit for the maximum additional virgin material added to recyclate at 10 per cent. This limit should be reviewed in the light of further research within the wider industry consultation, which is outside the scope of this study.

MATERIAL LOSS

essential criterion

In addition to having to add virgin feedstock to recycled materials to ensure adequate material quality, additional feedstock may be necessary to make up a loss of material mass associated with the recycling process. Pre-processing stages of recycling, which include the collection and transport of the materials are not fundamental characteristics of the recycling process, while losses such as the oxidation of aluminium are (Quinkertz *et al.*, 2001) and should be considered. Losses of mass have to be kept to a minimum and a limit of what would be acceptable for a CLMC assessment could be set as with the previous criterion at 10 per cent.

MATERIAL PURITY - Try to use monomeric components. [7] Make inseparable subassemblies in same material. Minimise number of different materials. Avoid applied finishes [2] Materials should be a 'clean' as possible. [4] [5] [6]

essential criterion included in criterion for multiple recycling

One of the main problems with recycling any material is the contamination from bonded materials, additives, finishes or treatments (Onusseit, 2006). For instance, gypsum plaster contamination of concrete can cause a decrease in the strength of concrete achieved (Sturges and Lowe, 2000a). On the other hand small amounts of different materials may not compromise the quality of the recyclate. As discussed in relation to adhesives, organic coatings and additives used in conjunction with materials that require high temperatures for recycling will burn off in the process and not contaminate the end product (Onusseit, 2006).

It is therefore not necessary for the material to be monomeric, but rather for any bonded materials, additives and finishes not be of a nature or included in such quantities to compromise the quality of the recyclate. This criterion is directly linked to the first criterion for infinite recycling, which as discussed may require an addition of virgin feedstock to maintain the required quality standards. Ultimately if the material purity compromises recycling the first criterion is not achieved. The material purity criterion must therefore be seen as part of the criterion for multiple and infinite recycling.

REPROCESSING - Avoid non-recyclable materials such as composite materials and treatments and secondary finishes to materials that complicate reprocessing. [1] [3] [5] [6] [7]

non-essential criterion

Some composite elements or elements with particular finishes can be treated prior to the recycling process to separate the constituent parts and recycle them separately. Technologies to separate certain composite materials include 'kryotechnology' (cooling materials) which can be used to separate composite materials such as gypsum and extruded insulation or bitumen covered expanded polystyrene and pressure water jets have been used to remove plaster and render from blockwork (Andra and Schneider, 1994). Cardiff University has researched recycling methods to clean bricks that use vibrating elements to separate the reclaimed bricks from the mortar (Gregory *et al.*, 2004). Composite steel and insulation panels by Kingspan are also separated and recycled (Steel Construction Institute, 2006). These separating techniques, can be a resource-intensive and would add to the cost of reprocessing and recycling. However, the fact that a building element is a composite material cannot per se be considered a hindrance to the recycling.

If the composite nature of the material means that the purity of the recyclate is compromised or the ability to infinitely recycle is compromised (see previous criteria) then the element can be considered not to comply with the CLC requirements. However, if purity and the ability to infinitely be recycled are maintained subject to a 10 per cent additional feedstock or material loss then, regardless the recycling process necessary, the element can be deemed to have satisfied the criteria for CLMC construction.

HAZARDS - Information on hazardous materials is required [1] [3] [4]

essential criterion

As with deconstruction and reuse the risks associated with recycling hazardous materials may require taking precautionary measures. Some of these measures would be integrated within the recycling facility and indistinguishable from those in place for manufacturing the primary material, as with steel. Other measures may be particular to the recycling process. If the hazard cannot be contained and a hazard to health remains then the materials cannot be considered part of a CLC process. This criterion is therefore not assessing the existence of hazards, but rather the residual hazard after precautionary measures are taken.

MATERIAL DAMAGE - Sturdiness of elements affecting recycling[1] [4]

non-essential criterion

Material damage that can affect the recyclability of a material might occur during the transport or collection process and must be such that a significant amount of contamination or loss of material occurs. The recycling process of materials typically involves shredding or melting materials and the physical integrity is therefore irrelevant. To collect and transport a material it has to be able to be handled and contained and the fragility of a material could affect these processes. Nonetheless, in practice even very fragile and loose materials, such as glass and loose insulation, are recycled (Morgan and Stevenson, 2005) suggesting that material damage is irrelevant to the recycling process subject to sufficient time and effort being invested in the process.

Material damage is therefore a non-essential criterion affecting primarily economic aspect of the recycling process.

INFORMATION - Provide identification of material and components. [2] [4] [5] [6]

non-essential criterion

As opposed to the dismantling or reuse of materials where specific installation and dismantling configurations may be unique to a building and cannot be extrapolated from other information, the nature of materials can be tested as is common with automated sorting of different plastics (Shent *et al.*, 1999; Patel *et al.*, 2000). Materials that are not readily identifiable can be tested to establish their constituent substance. The lack of identification of materials on the materials themselves can result in a time-consuming testing regime, but would not preclude the ability to recycle the material.

4.6.4 CRITERIA FOR NATURAL RECOVERY

The criteria for natural recovery, including biodegradability and erosion, have been based on those for industrial recycling and expanded and adapted as required.

RATE OF BIODEGRADABILITY / EROSION (derived from MULTIPLE RECYCLING AND MATERIAL DEGRADATION and MATERIAL LOSS criteria for Recycling)

essential criterion

A fundamental criterion for a CLC material through natural recovery relates to the rate of disintegration. All materials will eventually disintegrate, even stone over millennia will dissolve, but only if a material can be recovered quickly will it avoid becoming associated with environmental impacts associated with waste. Therefore, for a material to qualify as recoverable through natural processes the speed of the process should be relevant to a human life.

In respect of biodegradable materials standards that relate to the time required to disintegrate have already been set. The 'BSEN 13432:2000 Packaging. Requirements for packaging recoverable through composting and biodegradation. Test scheme and evaluation criteria for the final acceptance of packaging' (British Standards Institution, 2000) defines the requirements for packaging to be considered recoverable through organic recovery. It is one of the standards used to implement the 'Directive on packaging and packaging waste' (94/62/EC). Other standards include BS EN 13427:2000, which provides a general framework and BS EN 13429, BS EN 13430 and BS EN 13431 (British Standards Institution, 2000a).

Organic recovery includes aerobic composting and anaerobic biogasification, which can take place in municipal or other biological waste treatment plants. BS EN 13432:2000 stipulates the characteristics of compostable material by considering four characteristics including:

- biodegradability;
- disintegration during biological treatment;
- the effect on the biological treatment process; and
- the effect on the quality of the resulting compost with particular attention to phytotoxicity and heavy metal content. (British Standards Institution, 2000).

As discussed in section 4.4 BSEN 13432:2000 stipulates that the rate and efficiency of the process of biodegradability in watery medium must convert at least 90 per cent of the organic material into carbon dioxide within six months. It also stipulates that the disintegration in compost must achieve no more than 10 per cent residue after three months' composting and subsequent sifting through a 2 mm sieve (British Standards Institution, 2000). The BSEN 13432:2000 further considers the effect of the treatment on the end product which will be discussed under the heading of Hazards.

The rate and efficiency of the process of natural recovery set out in the BSEN 13432:2000 can equally be applied to other means of natural disintegration, such as those that would act on a cob structure.

In conclusion, the criterion for the rate and efficiency of natural recovery can be considered to have been satisfied if from the natural recovery process a maximum 10 per cent residue results after sieving through a 2mm sieve in a period shorter than six months for composting and three months for natural disintegration.

HAZARDS - Avoid hazards that could contaminate the ground
(derived from HAZARDS criterion for Recycling)

essential criterion

Materials, which have been treated or finished with toxic materials, can be recovered through natural processes but may result in a contaminated residue. Hazardous treatments may also leach out into the ground, but this is typically prevented by controlling the process. The BSEN 13432:2000 and the BSI's PAS 100:2005 set limits for the toxicity of the compost resulting from organic recovery by stipulating a maximum level of heavy metals, including cadmium, chromium, copper, lead, mercury, nickel and zinc, and setting a standard for phytotoxicity. The phytotoxicity is to be tested to the PAS 100:2005, and it requires the recovered compost to achieve growth performance equivalent to 80 per cent of the control compost (British Standards Institution, 2005). The same toxicity tests applied to the compost could be applied to the material resulting from natural biodegradation.

Research by the Building Research Establishment showed that even highly toxic biodegradable materials, such as creosote treated timber, can be made to biodegrade into safe compost in two stages that comprise a biodegrading stage and a bioremediation stage (Hobbs *et al.*, 2005).

In conclusion, this criterion adopts the requirements in respect of health hazards of the BSEN 13432:2000 and requires the recovery process, whether biodegradation or natural disintegration, to result in a safe product. One or more processes may be necessary and would be acceptable in terms of satisfying the criterion.

MATERIAL PURITY - Material impurities that compromise the ability to fully biodegrade a building element. (derived from MATERIAL PURITY criterion for Recycling)

essential criterion included in Hazards and Rate of biodegradability/erosion criteria

Some biodegradable materials include additives, finishes or are treated with non-biodegradable materials and if composted would form a residue. Such materials include hemp insulation that includes a polyester binder, painted timber and timber and plastic boards. The material purity is critical to achieve the both the rate of biodegradation and hazard criteria, but does not need to be assessed independently and can be assessed as part of the criterion for the rate and efficiency of natural recovery.

MATERIAL DAMAGE - Sturdiness of elements affecting composting (derived from MATERIAL DAMAGE criterion for Recycling)

non-essential criterion

The effects of material damage on the ability to recover materials naturally are similar to those of industrial recycling. The potential loss of material as a result of the collection and transport of damaged material is separate from the calculation of the material loss through natural recovery.

INFORMATION - Provide identification of material and component types (derived from INFORMATION criterion for Recycling)

non-essential criterion

Information regarding the materials to be composted would provide information about constituent parts and treatments that would compromise the quality of the material recovered. The quality of the compost has to be tested to comply with the criteria anyway, therefore the knowledge of a potential contaminate in advance would not change the recovery process and cannot be regarded as an essential criterion.

PRE-PROCESSING - Minimal preparation of material to enable composting is desirable (derived from REPROCESSING criterion for Recycling)

non-essential criterion

Materials that can be recovered naturally may have to be separated from other materials prior to the recovery process. For instance, timber may have to have fixing plates removed. Materials may also need to be sorted by separating materials that can be recovered naturally from those that cannot, for instance timber from plastic building components (Environmental Resources Management for the Department of Trade and Industry, 2002a). These pre-processing requirements may be time-consuming and require manpower and would therefore increase the cost of the processing, however they do not constitute a unsurpassable barrier to recovering the material.

4.6.5 SUMMARY OF CRITERIA FOR CLOSED LOOP MATERIAL CYCLES

The aim of this section was to formulate a set of criteria for CLMC that considers only the essential technical aspects of CLMC principle. As discussed previously, economic aspects were not considered. Each existing criterion related to CLMC principles was considered for inclusion as part of the CLMC criteria and additional criteria were formulated to address aspects not covered by existing systems.

Table 41 summarises the selected criteria, whereby the criteria for reuse are listed but will not be part of the final assessment system. It could be envisaged that a separate system would also include the criteria for reuse to provide a system that encourages reuse as well as CLMC construction.

Table 41 - **Summary of technical criteria for design for deconstruction, reuse and recovery through natural and industrial processes**

PROCESS	REQUIREMENT	compliant example	non-compliant example
DECONSTRUCTION PROCESS – included in final criteria			
Ability to access	All components are readily accessible and removable.	door	service duct embedded in concrete
Accessibility of fixings	All interface/connection points, fixings are identifiable and accessible.	screw-fixed timber cladding	plasterboard fixings under full coat of plaster
Types of fixings	Fixings have • the ability to be removed (mechanically or with solvents) from the element or alternatively integrated within the recycling process; • the ability to ensure a high percent of recovery of the material; • the ability to ensure a high quality of the material recycled without contaminants and • the ability to remain operational long term.	water-based/ soft adhesive screw,/bolts	insoluble adhesive rivet
Durability of fixings	Design joints will remain operational and do not compromise removal of element over time.	stainless steel fixing	steel fixing that may rust
Information	Sufficient information is provided OR no information is required to enable dismantling.	brick wall	proprietary temporary building
RECYCLING THROUGH INDUSTRIAL PROCESSES – included in final criteria			
multiple recycling / materials degradation	Material have the ability to be recycled multiple times.	steel	thermosetting plastics
Hazards	There are no residual hazards after precautions are taken.	thermoplastics	
Material loss	Material recycling efficiency is higher than 90 per cent.	aluminium	asphalt
RECOVERY THROUGH NATURAL PROCESSES – included in final criteria			
Rate and efficiency of biodegradability / erosion	Material recovery is a minimum of 90 per cent efficient and occurs within a period shorter than six months if through composting and three months for natural disintegration.	straw	Non-biodegradable plastic
Hazards	There are no residual hazards after precautions are taken.	Biodegradable thermoplastics	PVC
PROCESSING FOR REUSE – not included in final criteria			
Single use elements	Element can be used more than once.	cladding	paint
Durability of material	Components are durable enough for reuse.	tiles	shingles
Hazards	There are no residual hazards after precautions are taken.	treated timber	asbestos
Information	Sufficient information is provided OR no information is required for reinstallation	brick	Boiler without installation guidance
legal compliance or certification	The reuse of material should not contravene legal requirements.	door	waterproof membrane

4.7 CHAPTER CONCLUSION: CRITERIA FOR CLMC CONSTRUCTION

This chapter developed a set of criteria for CLMC construction that would enable a quantitative assessment. The characteristics of building elements that can be deconstructed were identified, as well as the characteristics of materials that can be recycled or recovered through natural processes. The latter, which includes composting and natural disintegration, were modelled on characteristics formulated for industries other than the building industry.

The sources of information used to characterise the CLMC concepts and subsequently formulate the assessment criteria included guidance on design for deconstruction, recycling and reuse and some assessment criteria of the same, as well as British Standards documents relating to natural recovery. In considering which characteristics and criteria to include in the assessment system a critical difference became apparent between the design guidance, which when applied would result in a building that is more easily able to be deconstructed and the elements reused and recycled or naturally recovered, and a set of criteria that can be measured. Guidance can be imprecise, for example recommendations for mechanical fixings would sanction CLMC non-compliant and compliant fixings, for instance screws that corrode in a few years' time and high quality stainless steel durable screws. Instead the assessment criteria should assess the potential outcome: in the case of the fixings, it has to assess whether the fixing will still be operable in ten or fifty years' time. Mechanical fixings are more likely to satisfy this requirement but do not necessarily do so. Guidance sets out broad principles that require interpretation, while a quantified assessment has to assess a specific outcome. The criteria have to assess performance in the same way a performance specification dictates performance.

The investigation of the BSEN 13432:2000 (British Standards Institution, 2000) highlighted how guidance, such as avoiding treatment and binders on organic products, can be translated into a performance requirement, in this case the requirements for maximum residue and processing time. The same performance specification had to be attempted in relation to design for deconstruction and the recycling criteria. The success of this attempt will be tested to some degree in Chapter Five by using the criteria to assess materials and construction systems.

The exclusion of reuse as a CLMC compliant process was reconfirmed by using the criteria formulated in a pilot assessment of selected materials (Table 42). Reuse can extend the life of a building element but not create a CLC and therefore cannot be included in the CLMC assessment.

Table 42 - **Illustration of the irrelevance of reuse as part of a CLMC assessment**

Product first life	**End of life option**	**2nd life**	**End of life option**	**3rd life**	**End of life option**	**4th life**	**End of life option**	**reuse**	**recycling**	**downcycling**	**composting**	**landfill/ incineration**	**closed loop cycle**	**linear cycle**	**example**
Use 1	reuse	Use 1	recycling	Use 1	reuse	Use 1	recycling	✓	✓				✓		steel
Use 1	Recycling	Use 1	recycling						✓				✓		Solenium carpet by Interface
Use 1	reuse	Use 1	downcycle	Use 2	reuse	Use 2	composting	✓		✓	✓		✓		Timber floor / chipboard
Use 1	reuse	Use 1	composting					✓			✓		✓		Flax insulation batts
Use 1	reuse	Use 1	downcycle	Use 2	reuse	Use 2	landfill	✓		✓		✓		✓	Bricks / hardcore
Use 1	reuse	Use 1	Incineration /landfill					✓				✓		✓	Timber windows with PVC coatings
Use 1	downcycle	Use 2	landfill							✓		✓		✓	Glass to concrete paving slabs
Use 1	Incineration /landfill											✓		✓	Composite timber and plastic board / Plaster

The resulting criteria that are included in the assessment (Table 41) have to be satisfied in their entirety or else the assessment result is negative. This approach, which results in two possible assessment answers only, either compliant or not compliant, is adopted from the BSEN 13432:2000

(British Standards Institution, 2000). The standard acknowledges that test results will vary and puts a minimum compliance level. While some of the criteria as currently formulated require 100 per cent compliance, for instance 100 per cent of the fixings have to be accessible, it could be envisaged that a reiteration of the assessment system would vary the minimum level of compliance. Such adjustments would have to be justified through empirical evidence that, in this example, a certain percentage of inaccessible fixings would not compromise the deconstruction process. Confirmation of the levels set within the criteria would be desirable, but is beyond the scope of this study.

The assessment of pollution impacts adopted in this research requires no additional impact to be produced through recycling compared to manufacturing with virgin materials. These assessment parameters have been considered acceptable for this research, however if the ultimate aim is to improve environmental performance then requirements for reducing pollution would be preferable. This would necessitate a detailed comparison of the emissions from manufacturing and from recycling processes to assess the acceptability of each. In 2008 McDonough Braungart Design Chemistry has began offering a product design assessment service in relation to their cradle to cradle concept that includes an assessment of the pollution impacts (MBDC, 2008). To date a limited number of products have been assessed. Their assessment effectively expands the definition of waste from material matter only to include chemical pollution. Adopting this broader definition and assessing for the pollution impacts as part of the CLMC assessment instead of, as suggested by the comprehensive approach to sustainable material design proposed in this research, as a prerequisite, is an alternative method of assessing and reducing the pollution impacts.

The next stage of the research aims to test the application of the criteria in order consider how it could be possible to set targets for CLMC content in buildings and also to consider how the criteria might be further developed.

5 TESTING FOR COMPLIANCE WITH THE CLMC CRITERIA AND FORMULATING TARGETS

Using case studies this chapter demonstrates the use of the assessment system developed in Chapter 4. Three assessments were undertaken including:

- a selection of construction materials were assessed for their ability to be recycled industrially or recovered naturally;
- a selection of building elements were assessed for their compliance with the CLMC criteria; and
- three building constructions were compared in terms of their content of CLC materials.

The method adopted for these empirical tests is described in the Chapter One and Chapter Five summarises and discusses the results and reviews the assessment system.

(Related Appendices: 8.10-8.14)

5.1 MATERIAL ASSESSMENTS

The first assessment undertaken with the CLMC criteria was a material assessment which considered the material alone and not its installation in a building. The materials analysed included a selection of materials that would be ultimately be part of the assess the whole building design in section 5.3. The assessments were based on information on material characteristics gained through a literature review of construction material texts and journal papers related in particular to end-of-life options for materials. The materials assessed (Table 43) were classified according to Maguire's Construction Materials (Maguire, 1981) material groups including cementing and masonry materials, plastics and oil-based materials, metals and materials of wood and other natural products.

Table 43 - **List of materials assessed for CLMC construction compliance**

Cementing and masonry materials	Plastics / oil-based materials	Metals	Materials of wood and other natural sources
fired clay gypsum cement concrete ballast mineral insulation	thermoplastics PE/EPS thermoplastics PVC thermosetting plastics PU glass	steel	timber recycled cellulose fibre cork

For a material to form part of a CLC it must be able to be recycled infinitely with processing rates and efficiencies that are adequately high. For a material to comply with the CLC criteria three criteria have to be satisfied for recycling through industrial processes and two for recovery through natural processes (Table 44). Appendix 8.10 includes the material characteristic sheets created through a study of material characteristics and used to make the assessment.

An assessment form was devised to use as a checklist and record the results of the material assessments. The form sections shaded in grey provide prompts and are not to be changed by the assessor, while the sections in white are those to be completed. Compliance with a criterion is marked with a '✓' and failure to comply with a 'x'. Table 45 shows an example of a completed CLC material assessment table for concrete.

Table 44 – **Assessment table for material assessment showing criteria for CLC**

Recycling through industrial processes		**Recycling through natural processes**	
Criterion	**Description of requirement**	**Criterion**	**Description of requirement**
Infinite recycling	Material has the ability to be recycled multiple times.	Rate and efficiency	Material recovery is a minimum of 90 per cent efficient and occurs within a period shorter than six months if through composting and three months for natural disintegration.
Processing efficiency	Material recycling efficiency is higher than 90 per cent.		
Hazards	There are no residual hazards after precautions are taken.	Hazards and quality	There are no residual hazards after precautions are taken.

Table 45 – **Example of completed CLC material assessment sheet: Concrete**

Key: compliant = ✓
non-compliant = x

Concrete	**Recycling through industrial processes**	x	**Recycling through natural processes**	x
	Infinite recycling	x	Rate and efficiency	x
	Processing efficiency	x	Hazards and quality	x
	Hazards	✓		x

5.1.1 MATERIAL ASSESSMENT RESULTS

The selection of materials tested, which was limited to those required for the following tests, was unrepresentative of the materials currently available in the building industry. Consequently generalised patterns and rules cannot be extracted. However, the limited results suggest that there are sufficient materials that comply with the CLC criteria to build buildings that in turn could to a great extent comply with the CLMC construction principles.

Of the materials assessed metals and natural materials all complied with CLC principles by conforming to the requirements for natural recovery through biodegradation or through industrial recycling. Two of the materials in the cementing and masonry category complied. Ballast and mineral wool insulation were able to be recycled through industrial processes with sufficiently high processing efficiencies to comply. The remainder of this category did not comply. The plastics investigated were not able to biodegrade sufficiently quickly but some could be recycled through industrial processes.

It is interesting to note is that recycling techniques are increasingly being developed and some new systems, particularly in relation to the chemical recycling of plastics, could mean that in future more materials could be recycled through industrial processes.

The assessments also suggested that the system of criteria is reasonably straight forward to use and appears to address the necessary material characteristics to make a reliable assessment. The model of assessment constituting a limited number of performance requirements appears to create a workable system.

5.2 BUILDING ELEMENT ASSESSMENT

While individual materials may be part of a CLC, once integrated within a building element and then further integrated within a building it may become impossible to remove them and compost or recycle them. The element and installation design are therefore as critical as the material composition itself to establish whether a construction can be considered to constitute a CLMC construction. This second assessment considered building elements integrated within a typical construction.

The building elements selected for this assessment using the criteria developed, included those that would be required to undertake the whole building assessment in the next section.

The assessment criteria used to analyse the selected building elements and their integration in a building include the full set of criteria for CLMC. Table 46 lists the criteria required for deconstruction, which together with the criteria to assess materials for their compliance with CLC principles, constitute a complete CLMC assessment. Again an assessment form was devised to be used as a checklist and to record results, including grey boxes providing assessment prompts and white boxes for the assessor to complete. Table 47 shows the deconstruction assessment table completed for a beam and block floor and Table 48 shows the full assessment table used in this section completed for a beam and block floor.

The assessment table allows for the inclusion of material quantities which would be necessary to assess the amount of different types of waste a building would result in at the end of their life. Appendix 11 lists the tables used to assess the elements for the whole building assessment of house type 1 including the quantities of materials integrated into the building.

Table 46 – **Assessment criteria for deconstruction**

Criterion	Description of requirement
Ability to access	All components are readily accessible and removable
Accessibility of fixings	All interface/connection points, fixings are identifiable and accessible
Types of connections	fixings have • the ability to be removed (mechanically or with solvents) from the element or alternatively integrated within the recycling process; • the ability to ensure a high percent of recovery of the material; • the ability to ensure a high quality of the material recycled without contaminants and the ability to remain operational long term.
Durability of fixings	Design joints will remain operational and do not compromise removal of element over time
Information	Sufficient information is provided OR no information is required to enable dismantling

Table 47 - **Example of completed deconstruction assessment table: Beam and block floor with a screed finish.**

Key: compliant = ✓
non-compliant = x

Deconstruction process	x	notes
Ability to access	✓	fully accessible
Accessibility of fixings	x	screed bonded to substrate
Types of connections	x	screed bonding impedes damage-free separation
Durability of fixings		n/a
Information	✓	standard construction

Table 48 - **Example of completed table for full assessment of CLMC compliance: Beam and block floor with a screed finish**

Beam and block floor with a screed finish				**Overall compliance with closed loop material cycle criteria**	x
Constituent part compliance				Key: compliant = ✓ non-compliant = x Disposal options: RI = Industrial recycling RN = Natural recycling L = Landfill or incineration	
Constituent part description				Quantity	RI/RN/L
Cement screed layer					L
Concrete beams and blocks					L
Deconstruction process	x	notes			
Ability to access	✓	fully accessible			
Accessibility of fixings	x	screed bonded to substrate			
Types of connections	x	screed bonding impedes damage-free separation			
Durability of fixings		n/a			
Information	✓	standard construction			
Recycling process					
Cement screed		**Recycling through industrial processes**	x	**Recycling through natural processes**	x
		Infinite recycling	x	Rate and efficiency	
		Processing efficiency	x	Hazards and quality	
		Hazards	✓		
Concrete beams and blocks		**Recycling through industrial processes**	x	**Recycling through natural processes**	x
		Infinite recycling	x	Rate and efficiency	
		Processing efficiency	x	Hazards and quality	
		Hazards	✓		

5.2.1 REVIEW OF BUILDING ELEMENT ASSESSMENT CRITERIA

While undertaking the assessments each stage of the process was reflected upon critically. This review identified that the combined criteria for CLMC were reasonably reliable and comprehensive in terms of reflecting the practice in the building industry and addressing all the significant detailed requirements, but it also identified a number of deficiencies of the system.

Firstly, the system suffers from a lack of clarity in relation to the definition of an element. While certain elements, such as a roofing slate, are clearly defined, others, such as a wall construction or even a window, are not so clearly defined. A building is an assembly of different elements that are delivered to site as individual entities, but some these elements may also themselves be assemblies. A window is an assembly of the frame and the glass. What is critical for this assessment is to include an assessment of all sub-assemblies. While this lack of definition does not compromise the assessment it is conceptually unsatisfactory as it requires the assessor to define the units to assess and therefore introduces a potential for error.

Secondly, in respect of the ease of using the assessment system there is significant scope for improvement. The tables identify the process of assessment, but are in practice unnecessarily complex. For instance the individual material assessments do not need to be included and could simply be referred to. The deconstruction notes do not appear to have any use in terms of the assessment and only really have the role of justifying the assessment. This may be useful in relation to ensuring that the assessment has been done correctly, but if that is its purpose more detail is required. Taking into consideration the previous comment regarding the lack of definition between building elements, a construction tree that could identify the assemblies and their subassemblies down to the inseparable element or material would be useful to bring clarity to the process and avoid omitting elements from the assessment; and this construction tree could be linked to the assessment sheets.

In conclusion, while the assessment reliability appears satisfactory, the tools related to the assessment process should be improved.

5.2.2 BUILDING ELEMENT ASSESSMENT RESULTS

As with the material assessment, the limited range of construction elements tested for compliance with CLMC criteria precludes making generalised conclusions. However, some trends can be identified.

The study suggests that elements made of minimally processed material (e.g. timber) and homogeneous material (e.g. steel); and building elements that are fixed mechanically (screwed ply or metal cladding) or with a material compatible with the main building element are likely to qualify as a CLMC elements. While composite elements (e.g. external insulation with render finish) and compound materials (e.g. concrete) and elements that are fixed with adhesives or have applied coatings are unlikely to comply. These points are in line with the existing research which informed the characterisation of the CLMC concept: and while a close relationship between the characterisation of CLMC construction and the assessment results is to be expected, it reiterates the importance of an accurate characterisation.

A few of the elements assessed could be deconstructed but not recycled, bricks and tiles being examples. Research referred to in Chapter Four suggest that in practice more building elements would fall in this category. Furthermore, installation methods affect the ability of an element to be deconstructed and if, for example, the carpet assessed in this research were fixed with carpet grippers rather than adhesive that too would be able to be deconstructed but could nonetheless not be recycled. These elements together with elements that cannot be deconstructed nor recycled, such as concrete, plasterboard and thermosetting plastics, constitute a significant percentage of common building elements that cannot be considered CLMC compliant elements. From a sustainable material design point of view this suggests technical improvements are required to ensure that more mainstream elements are CLMC compliant.

Table 49 – **Results of assessment of selected building elements for compliance with CLMC criteria**

Key: compliant = ✓
non-compliant = x

Building element type	Assessment of element regarding compliance with requirements for			
	Decon-struction	industrial recycling	composting / natural erosion	CLMC construc-tion
Concrete trench foundations	X	X	X	X
Timber pile foundations	✓	✓	✓	✓
Concrete ground bearing slab (with insulation below ground)	X	X	X	X
EPS insulation below ground	✓	✓	X	✓
PU foundation perimeter insulation	✓	X	X	X
PE DPM below ground	✓	✓	X	✓
Suspended timber ground floor	✓	X	✓	✓
Recycled cellulose insulation between joists	✓	X	✓	✓
Timber frame with hardboard linings	✓	X	✓	✓
PE vapour control layer	✓	✓	X	✓
PU external insulation	✓	X	X	X
Timber fibre external insulation	✓	X	✓	✓
Rockwool insulation between studs	✓	✓	X	✓
Cellulose insulation between studs	✓	X	✓	✓
Brick cladding to external envelop	✓	X	X	X
Timber cladding screwed to timber battens to external envelop	✓	X	✓	✓
Render on external insulation	X	X	X	X
Plasterboard lining to timber frame	X	X	X	X
Ply lining to timber frame	✓	X	✓	✓
Roof concrete tiles	✓	X	X	X
Roof slates	✓	X	X	X
Roof timber cladding	✓	X	✓	✓
Rainwater good in PVC	✓	✓	X	✓
Rainwater good in metal	✓	✓	X	✓
Rainwater good in timber	✓	X	✓	✓
Chipboard floor panels	✓	X	✓	✓
Solid timber floor panels	✓	X	✓	✓
Vinyl floor finish fixed with adhesive	X	X	X	X
Cork floor finish in rolls loose laid	✓	✓	✓	✓
Timber flooring mechanically fixed	✓	X	✓	✓
Synthetic carpet fixed with adhesive	X	X	X	X
Timber windows (and doors) frames only	✓	X	✓	✓
Timber windows (and doors) glass only	✓	X	X	X

5.3 WHOLE BUILDING ASSESSMENTS

Knowing which building elements are CLMC compliant is not sufficient information to establish a model of good practice and relevant targets to encourage good practice. For this an understanding is needed of the types of elements and the quantities of material contained in a typical building. The whole building assessment undertaken as part of this fourth objective compares different types of building construction in terms of their content of CLMC construction.

As described in the methodology section, one building design was detailed (Appendix 8.13) using three construction types: a mainstream option based on the 21st Century homes (Figure 50); a contemporary option based on the Toll House Gardens (Figure 51); and an alternative option developed for this study to have maximum biodegradable materials. The quantities of materials necessary to build the three alternatives were measured. Services were excluded from the assessment as their contribution to the total quantity of waste is limited and minimal variation was envisaged between the three construction options.

Figure 50 - **21st Century homes in Aylesbury by Briffa Phillips Architects for Hightown Preatorian Housing Association**

Figure 51 - **Toll House Gardens in the Fairfield estate, Perth, Scotland, by Gaia Architects for Fairfield Housing Co-operative**

Based on the building elements assessments made in section 5.2 (Table 49) and the measured quantities of building materials included in each building, it was possible to establish the amount of materials in the three design options that conformed to the CLMC concept and whether this compliance was achieved through industrial recycling or through natural recovery processes (Table 52). For each of the three construction options the quantities of materials were divided into three categories according to their end-of-life disposal including:

- non-recyclable materials either to be landfilled or incinerated;
- industrially recyclable materials (CLMC compliant); and
- naturally recyclable materials through composting or natural disintegration (CLMC compliant).

This information considered in relation to whether the house construction was mainstream or not was used to propose a level of CLMC construction content in a building that could be considered good practice.

Table 52 – **Building elements of three housing types divided by material end-of-life disposal options**

House 1 = ① House 2 = ② House 3 = ③

Building elements	Non-recyclable	Industrially recyclable	Naturally recyclable
Foundations	Concrete ①②		Timber③
Frame windows doors			Timber①②③
Insulation below grd		EPS①	
Insulation btw studs		Rockwool①	Recycled cellulose fibre ②③
External insulation	Polyurethane①		Wood fibre insulation ②
Wall panel lining			Hardboard ②③ OSB ①
Vapour control		PE① ②	
External cladding	Brick① Render②		Timber①②③
Roof finishes	Concrete tiles① Slates②		Timber③
Rainwater goods		PVC① / Metal②	Timber ③
Floor panel lining			Timber ②③ Chipboard ①
Wall /ceiling finishes	Plasterboard①②		Ply with natural glues ③
Floor finishes	Carpet① vinyl① ② fixed with adhesive		Timber③② Cork③

5.3.1 WHOLE BUILDING ASSESSMENT RESULTS

House 1, the most mainstream timber framed construction with external brick cladding and concrete ground bearing slab, contained 97 tonnes (63 cubic metres) of non-CLC waste. House 2, a contemporary timber framed construction with a suspended timber ground floor instead of a concrete ground floor and a rendered external wall finish instead of a brick cladding, resulted in a reduction of 85 and 86 per cent in non-CLC waste compared to House 1 by weight and by volume respectively. House 3, a radically alternative construction with timber cladding throughout including to internal walls and timber piles, included virtually no non-CLC waste at all (Figures 53-56).

These results suggested that radically reducing waste destined for landfill is possible within a contemporary construction. The results are in line with related research, such as an early study of the recycling of a timber frame in Germany, which resulted in only 6 per cent of the building by weight destined for landfill (Ruch *et al.*, 1994).

Achieving a totally CLMC compliant construction would however have to adopt radical alternatives. House 3 achieves virtually 100 percent CLMC content by employing non-conventional construction systems, in particular timber piled foundations and timber panelling for the interior wall lining. Such construction is uncommon and would seldom be adopted and almost certainly not be adopted in mainstream construction.

House 2 fails to achieve as high a CLMC content due to its adoption of a few very typical and equally problematic materials: concrete and gypsum boards. Concrete, perhaps the most ubiquitous material in the current building industry, is the preferred material for foundations, alternatives are seldom used particularly in housing. Another problematic material is plasterboard. Its relatively low recyclability and problems with its demountability excludes it as a CLC material, yet it is commonly used for all internal finishes and provides the aesthetic finish expected by most people. Alternatives to plasterboard are as rare as concrete foundation substitutes.

Figure 53 - **Waste arisings from three building constructions measured in tonnes**

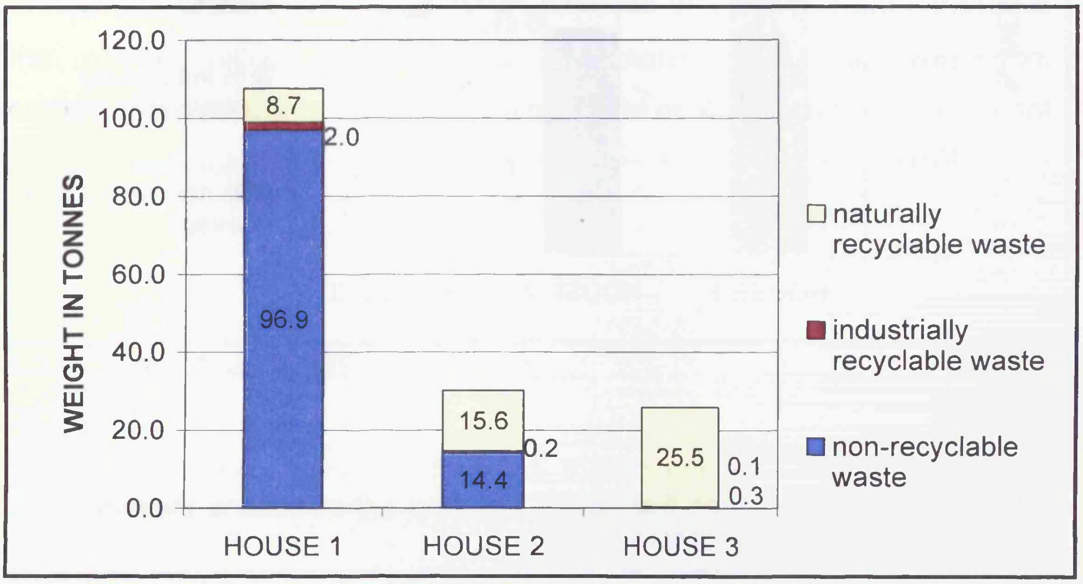


Figure 54 - **Waste arisings from three building constructions measured in cubic metres**

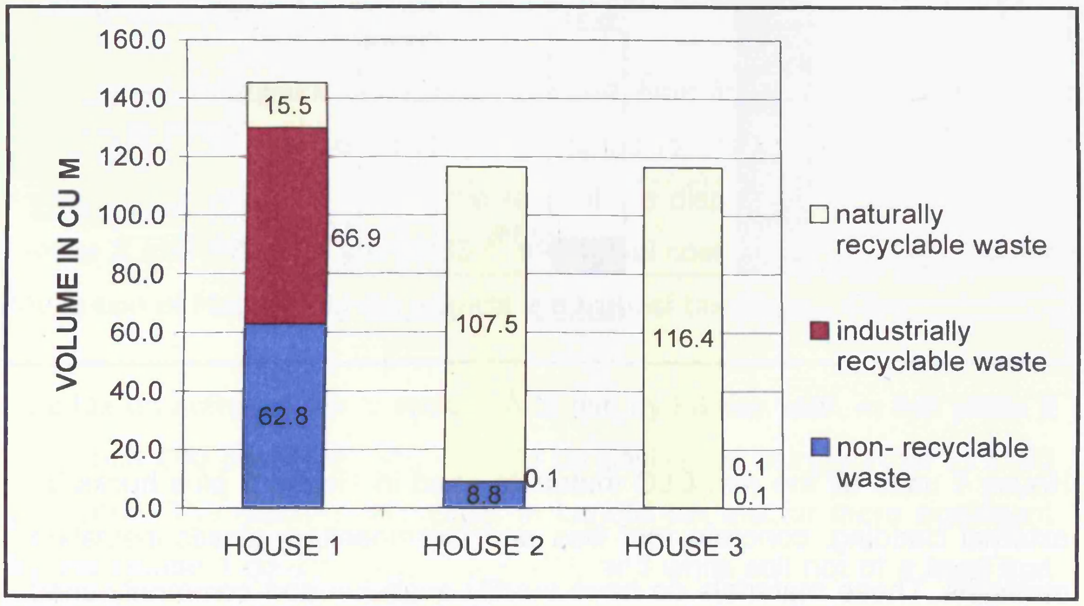


Figure 55 - **Waste arisings from three building constructions measured by weight as a percentage of total weight**

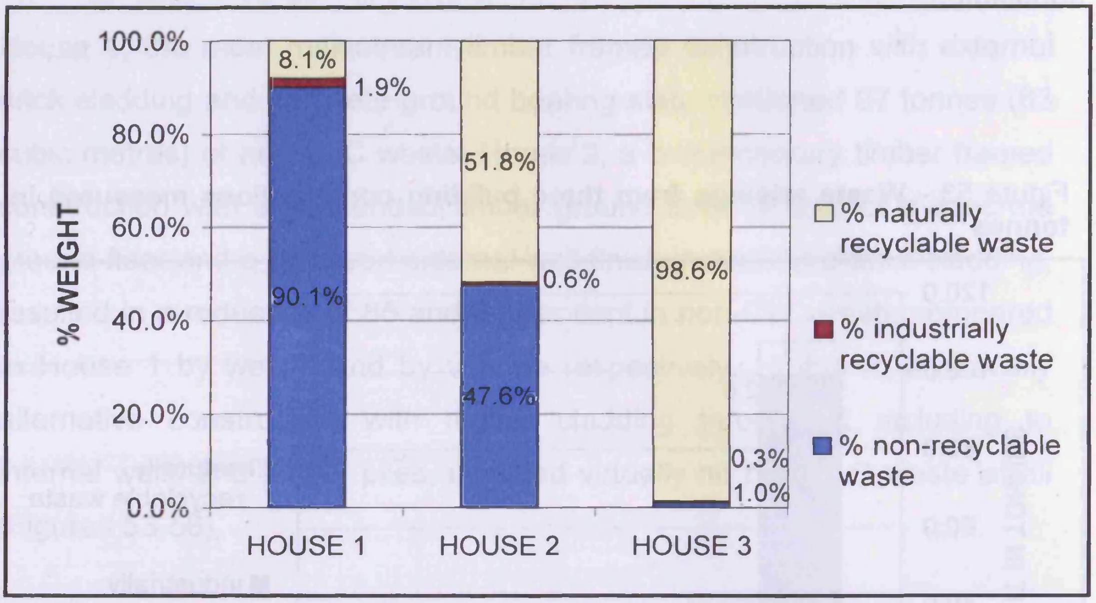
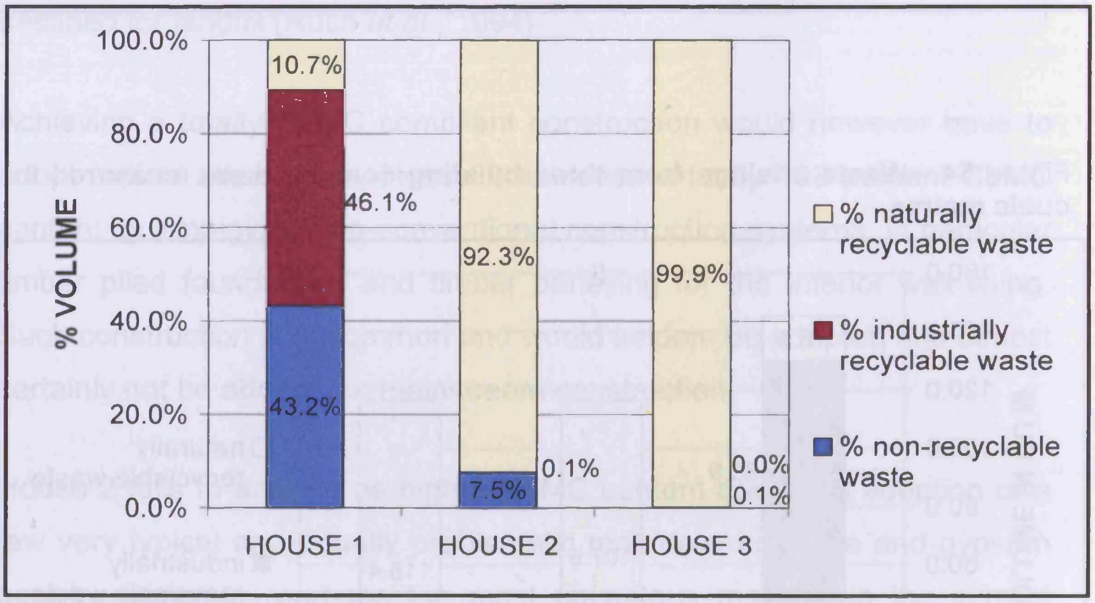


Figure 56 - **Waste arisings from three building constructions measured by volume as a percentage of total volume**



House 1 uses all the non-CLC materials used in House 2 plus bricks as external cladding, concrete roof tiles and thermosetting plastic insulation materials. These materials do have readily available and commonly used substitutes, as suggested by House 2, even if they are not so broadly used. Change here could be achieved through changes in specification alone rather than changes in attitude as required by anyone adopting House 3 as a model.

When considering the status of the current construction industry it is worth noting that House 1 does not represent the worse case scenario in terms of non-CLMC-compliant construction. The use of a timber frame improves the overall rating compared to the more mainstream blockwork construction. An interior block leaf would add at least another 30 per cent of non-recyclable waste to the design.

5.3.2 DISPOSAL COSTS

The analysis also highlights that the most significant items in terms of volume and weight are the masonry items. The cost of waste disposal is based on weight, it is therefore worth considering that the concrete elements in House 1 make up nearly half the total weight of waste and the brick cladding a quarter. As problematic as plasterboard is in terms of its disposal (the production of hydrogen sulphide is associated with its disposal in landfill), it makes up only 6 per cent of the total weight of waste.

The cost of disposal includes the transport, time and Landfill tax. In 2008 the Landfill Tax was set at £2.50 per tonne for inert waste and £32 per tonne for active waste. While the ratio of the disposal costs of House 1, House 2 and House 3 are 66:33:1, the actual cost is still relatively low for the option of House 1 which attracts the highest tax (Figure 57).

The tax on active waste is expected to rise by £8 per year, in five years it will reach £80 per tonne and it could be envisaged rising further to £120 per tonne. The resulting increases in Landfill tax are far more significant for the House 1 construction (Figure 58) and while still not of a level that will force necessarily a change in attitude on a one off development, for medium scale developments of 50-100 units and large scale developments such sums do become significant. If Landfill taxes could be charged to the developer during the construction phase, then designing for CLMC could show financial benefits.

Figure 57 - **Comparison of Landfill Tax charges for the waste arising from House 1, 2 and 3.**

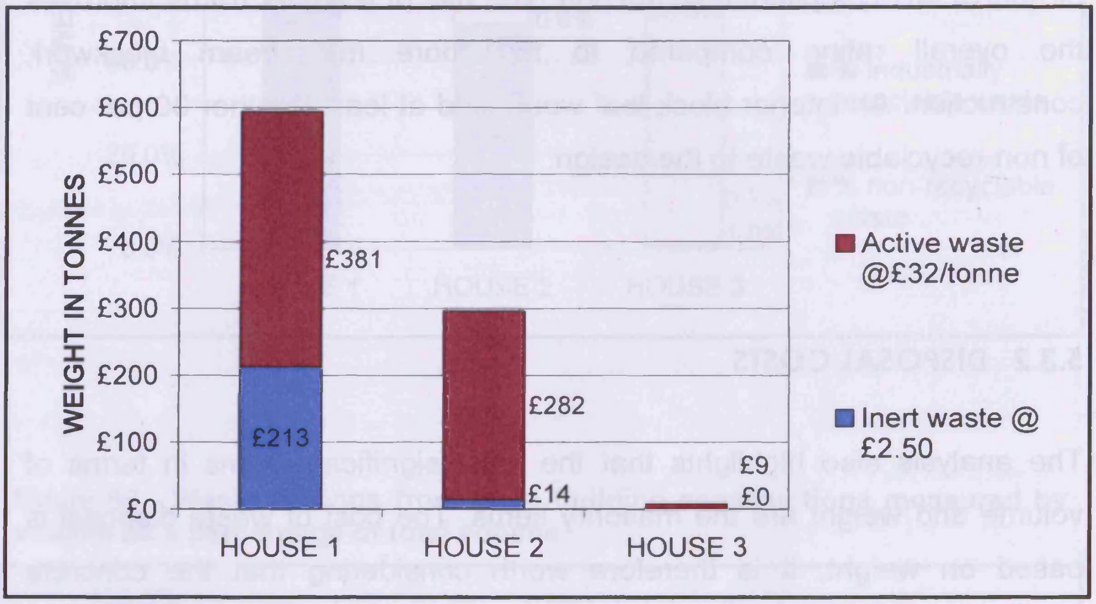
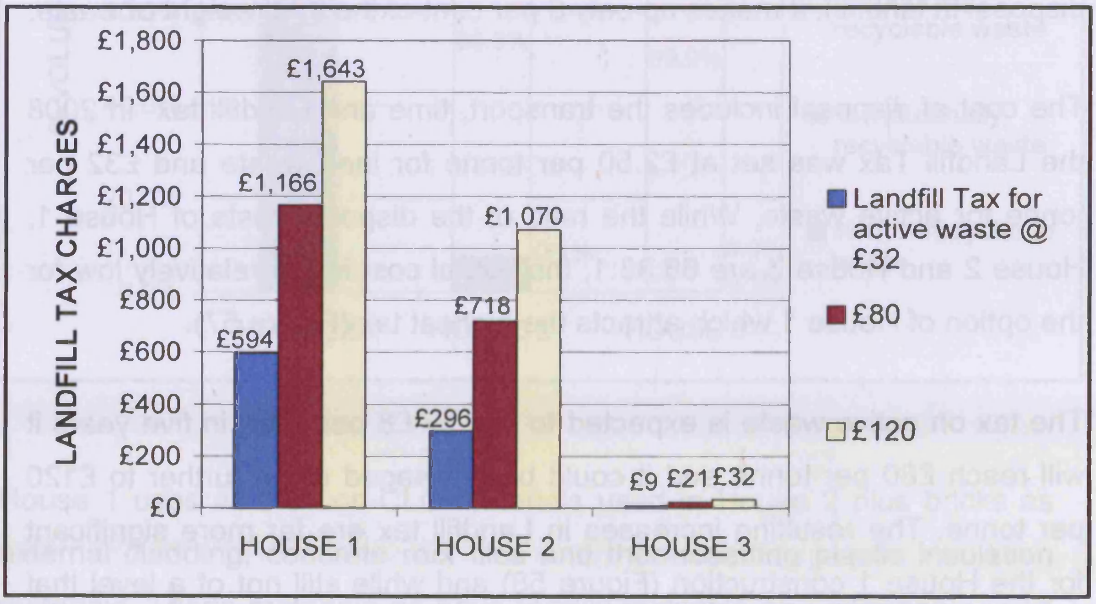


Figure 58 - **Comparison of Landfill Tax charges for the waste arising from House 1, 2 and 3.**



5.3.3 PROPOSED TARGETS FOR CLMC BUILDING

The whole building assessment of the three house specifications suggests that, in theory, buildings with a high CLMC content are possible. While many of the non-CLCM components are ubiquitous in the current building industry, the assessment also suggests that contemporary construction, as represented by House 2, already represents a better practice than the mainstream and could be further improved without excessively affecting its market conformity. The main improvements would include using a metal rather than slate roof and timber-based internal wall boards rather than plasterboard, which would reduce the non-CLMC-compliant construction by nine and 44 per cent respectively. The building performance is not affected by the use of CLCM construction and the aesthetics of CLCM construction is within, if perhaps at the edge, of mainstream acceptability. It is also worth noting that housing is a conservative of building type and that the CLCM aesthetics could be more acceptable for commercial or industrial buildings.

However, House 1 (with concrete foundations and ground floor, plasterboard walls and ceilings, and brick exterior) represents the most common housing in the UK and has as little as 10 per cent CLMC construction by weight and 56 per cent by volume.

In setting a good practice target for CLMC construction, House 2 represents a technically realistic model. Indeed House 2 with a metal roof would be an equally realistic option. From a commercial point of view considering what is a very conservative housing market in the UK, House 2 would represent somewhat of a departure from the accustomed aesthetics. In this respect one should consider that an increasing number of rendered and timber clad houses are being marketed as contemporary dwellings and this fashion could impact on the perception of both mainstream buyers and developers.

If House 2 with a metal roof is taken as a benchmark, a target could be formulated to require approximately 50 per cent of materials by weight to be CLC materials. However, the principle of setting percentages as targets has clear disadvantages. Considering the assessment systems studied as part of this research it is worth recalling some of the deficiencies of target systems that employ relative measures. For instance, the SAP rating requires a percentage improvement of energy use achieved through an improved fabric and building service design of the proposed building compared to the same building configuration with a basic Building Regulations-compliant construction. This comparative target fails to take into account the potential benefit of passive solar design measures to building performance. In the same way a percentage improvement on the amount of CLMC content would fail to establish an acceptable absolute amount of CLMC content and could even encourage a superfluous use of materials to justify the use of a high absolute amount of non-CLC materials.

To avoid such loopholes an absolute target is required which could relate to the floor area of the building. The house design in this research has a floor area of 90 square metres. The non-CLC content of each house is:

- House 1 - 97 tonnes total or 1074kg/m²;
- House 2 - 14.4 tonnes total or 160kg/m²; and
- House 3 - 0.3 tonnes total or 3kg/m².

A potential benchmark could be set between 160 kg/m² and 3kg/m² and indeed more than one benchmark could be set. It may be appropriate to adopt the terminology used by Feilden Clegg Bradley Architects in their project brief development. In their remarkably comprehensive sustainable design checklist, which is used to define a design brief with a client, Feilden Clegg Bradley Architects define design approaches by categories. The categories begin with Good Practice, followed by Best Practice, then Innovative and Pioneering (Gething, 2005). This would allow for an escalation of targets that recognise improved practice compared to mainstream practice as well as superior practice. Escalating targets can provide an entry level that can encourage beginning to adopt better practice. But the levels need to be set and described carefully not to suggest basic sound achievements are more than just a good beginning.

If House 1 can be taken to be representative of mainstream practice and not the worse case scenario of mainstream practice, it may be reasonable to suggest a percentage improvement on House 1 construction could be set as Good Practice. If House 2 represents a practice that is feasible subject to some technical specification changes and changes in aesthetical expectations, it may be appropriate to classify it as Best Practice. Innovative might be a further improvement and Pioneering would be approaching zero kg/m² of non-CLC material. In terms of what amounts this would represent Table 59 sets out the escalating requirements for Good to Pioneering practice. By setting the targets as a weight of material per metre squared good practice in terms of the total use of materials in line with the concept of dematerialisation would also be encouraged.

Table 59 - **Potential targets for maximum non-CLC material content in housing design**

Good Practice	**Best Practice**	**Innovative**	**Pioneering**
860kg/m² (20 per cent improvement on mainstream)	160kg/m² (Modelled on House 2)	80kg/m² (50 per cent improvement on House 2)	<5kg/m² (Modelled on House 3)

5.4 CHAPTER CONCLUSION: REVIEW OF ASSESSMENT SYSTEM

This chapter reported on three assessments using the criteria developed in Chapter Four. First, materials were assessed of for their compliance with CLC criteria, then building elements for their compliance with CLMC construction criteria. The third assessment used the building elements assessments to quantify the CLMC content of three building constructions. This required measuring the materials used to construct the three buildings and then assessing each element for its compliance with CLMC construction criteria. Based on the results of the latter test a proposal was made for targets for CLMC construction content, which would be used in conjunction with the whole building assessment.

Considering the assessment systems examined as part of this research it is possible to characterise such systems in relation to

- the ease of use for the assessors;
- the speed of use for the assessors;
- the potential for integration within the building design processes;
- the level of information required to undertake the assessment;
- the underlying complexity of the assessment system;
- the transparency of the assessment procedure;
- the reliability of the result in relation to the system's aims; and
- the potential for being used as a design improvement tool.

The CLMC whole building assessment could be characterised as straight forward, simple, transparent, reliable and with a reasonable scope for being used as a design improvement tool, but also slow, information demanding and not always directly related to the design processes of buildings.

In terms of ease of use it is similar to the CSH water assessment or the assessment of development density. Density assessments involve a simple calculation dividing the site area by the number of dwellings, habitable rooms, people and built floor area. The CLMC assessment requires assessing the installation of each building element in respect of five assessment criteria and then the constituent materials of each element in respect of five further criteria. In addition it requires measuring all materials used in the building construction. As such it is technically unproblematic. However, compared to the development density assessment the CLMC assessment is far more time consuming. Indeed compared to the systems investigated it is among the most time-consuming and can be compared to the energy assessments that require a full description of the building design and fabric specification to model the building energy performance. For building professionals the time required to measure all materials included in a building is likely to present a significant barrier to undertaking such an assessment, unless a full bill of quantities is prepared for tendering purposes.

There is reasonable potential for integrating the CLMC assessment within the design process. It is possible to envisage assessments being undertaken as part of the design of a building. This would not only facilitate completing the assessment but would also serve as design improvement process. In this respect it is again somewhat similar to the energy performance assessments that feed into the iterative processes typical of building design.

The level of information required for the assessment is at the moment a problem but could be addressed. While the information of the building design is available to the designers, finding sources of up-to-date information on recycling technologies is time-consuming and also difficult. If the CLMC assessment were to be widely adopted it would be necessary to make available such information.

A strength of the CLMC assessment is its transparency. The materials either comply or do not based on deconstruction technologies understandable to any building designer and recycling and composting technologies that can be verified by independent parties. This clarity is akin to the development densities assessment and the Passivhaus assessment, which is undertaken by means of an Excel workbook where all formulas are visible. It is in contrast to the 'Green Guide for Specification' or CSH energy assessments that are either mainly or totally obscure.

The transparency of the system is in line with its underlying simplicity. Again this is in contrast with the latter two systems mentioned above as well as the sustainable communities indicators. However, the underlying simplicity only applies to principles of the system and does not suggest that the process of assessment is simple. Collating the assessments for each building element and the material quantities, while conceptually simple, requires in practice the handling of a significant amount of data. Interestingly, the transparent Passivhaus Excel workbook also processes a large amount of data and it could be envisaged that a similar type of transparent workbook could be used for the CLMC assessment to make the underlying simplicity also simple to handle.

Finally the reliability in relation to the assessment aims is high. Like the Passivhaus assessment it measures the object of concern; for the CLMC assessment it is non-CLMC compliant material waste and for the Passivhaus assessment it is energy and carbon dioxide emissions. It does not measure a situation that is thought to bring about a certain outcome, as with the CSH energy assessment, but measures the actual outcome.

This last statement needs to be followed by a qualification. Most of the assessment systems to some degree do not assess performance but only the potential for good practice. Particularly vulnerable to user distortions is the use of water, but also energy performance of a building is subject to user behaviour. The same limitation applies to the CLMC assessment that can only rate the potential for minimising waste going to landfill. Whether it ultimately does or does not go to landfill will depend on the human decisions taken at the relevant times. The human factor that limits the validity of the most reliable assessment systems, such as the development density and Passivhaus assessment, apply also here.

Despite this critical limitation and the scope for improvement highlighted by these pilot assessments, the assessment outcomes were nonetheless suitable for formulating targets for good practice, concluding the original research aim.

6 CONCLUSION – SUMMARY OF RESEARCH AND CONCLUSION

This brief chapter formulates a conclusion in relation to the initial research question that aimed to establish whether it would be possible to identify and define a set of criteria by which building materials and elements could be assessed in terms of forming part of a CLMC and whether it would be possible to formulate targets for CLMC construction content in buildings that could represent good practice in terms of sustainable building design.

6.1 THE MAIN CONCLUSIONS

This dissertation has shown that it appears possible to identify and define a set of criteria by which building materials and elements can be assessed in terms of forming part of CLMC.

To do this, a concept for a comprehensive approach to sustainable material design was developed drawing from an analysis of the synthesis of existing sustainable material philosophies and relating this to the current practice in the building industry. As part of this new comprehensive approach to sustainable material design CLMC construction was characterised in order to develop a set of criteria for CLMC construction.

The driver for this research has been a concern with improving the sustainability of material use in the building industry. Therefore, of equal interest to the conceptual formulation of the principles for CLMC was the mechanism by which such principles can be employed to improve the sustainability of material use in the building industry. To this end this dissertation has developed a CLMC assessment system and has shown that it should be possible to develop quantifiable measures and quantifiable targets for CLMC content in buildings.

By using the assessment system developed to test three different types of housing construction, this dissertation also demonstrates that constructing a virtually 100 per cent CLMC house, while requiring a non-typical construction approach, is theoretically possible.

Finally, by analysing the research results of the housing construction this dissertation concludes that good practice targets can be formulated that are both realistic to achieve and can bring significant benefits in terms of improving the sustainability of construction developments. In line with the considerations regarding other systems that set targets for good practice, it is suggested that the targets are absolute and not set as a percentage improvement on mainstream practice; and also that they provide a progression from a basic level of good practice to a pioneering level.

The adoption of such targets in the building industry, potentially in conjunction with the proposed protocol for a comprehensive approach to sustainable material design and other complementary systems, could therefore contribute towards creating a more sustainable industry.

6.2 CRITICAL REVIEW OF KEY RESEARCH OUTCOMES

This research and the above conclusions, which overall support the original thesis, do not preclude a critical review of the main elements covered. In particular some decisions taken in respect of the criteria for CLMC and the CLMC assessment system and some of the results in relation to the availability of CLMC construction in the building industry warrant a brief review at this stage. Further considerations related to potential further research are included in Chapter Seven.

6.2.1 THE PROCESS OF FORMULATING CRITERIA FOR CLMC CONSTRUCTION

As stated above, this dissertation has defined a set of criteria by which building materials and elements can be assessed in terms of forming part of CLMC and has also employed these criteria with reasonable success. However, a review of the process of formulating the criteria has identified aspects of the characterisation of CLMC construction and the relevant criteria that might have been addressed differently and potentially with more practical relevance.

The characterisation and consequently the criteria for CLMC construction are based on an uncompromising model that may ultimately prove too ambitious and too rigid for its adoption in practice. This is evident in relation to two aspects: firstly the complete exclusion of reuse as a CLMC compliant approach and secondly in the definition of an element adopted for the purpose of the assessment.

Reuse was excluded as an end-of-life solution as it has the potential of only minimally lengthening the life of a material in use before it is landfilled. However, as will be discussed in Chapter Seven, were the CLMC concept to incorporate the concept of multiple reuse of durable materials, it would increase the building elements that would comply with the CLMC concept and include commonly used materials such as brick and stone. While simply compromising the CLMC concept has no benefit, a reconsideration of concept of long term multiple reuse would improve the CLMC concept by increasing its relevance to current industry practice.

This same rigidity presents a possible problem, or at least room for improvement, in respect of the assessment of building elements. As discussed in Chapter Five the definition of what constitutes an element for the purpose of a CLMC assessment lacks clarity. The criteria proposed in this thesis were formulated based on the assumption that a building element is the smallest independent building entity. For instance a window is made of a frame, ironmongery and a glazing unit. All of these, according to the proposed system, are independent building entities. An alternative point of view could, however, consider the three elements to be a single entity. The currently proposed system aims to assess the smallest independent building entities because the system does not allow for a partial compliance. A timber window with double glazed units and steel ironmongery would fail a CLMC assessment if the assessment related to the complete window as the building element. If the window were assessed as three elements (glazing unit, frame and ironmongery), as currently proposed, the timber frame and the steel ironmongery would pass the CLMC assessment while glazing unit would fail. This latter approach was adopted and appears to provide reliable results, however if the assessment system were to allow for partial compliance, composite building elements (e.g. window including glazing unit, frame and ironmongery) could be assessed as one element and the CLMC assessment would result in a percentage of CLMC compliant material.

Partial compliance would provide at least one advantage. The element of assessment could more easily be related to individual building products and their manufacturers. For instance the window manufacturer would be responsible for making sure that its products comply with the CLMC criteria. Materials that are essential to a building component but are also impossible to recycle or biodegrade would not disqualify the component but could nonetheless be identified. The percentage compliance might de defined by the weight of material that can be considered as CLC material as percentage of the total weight of the element. This would allow for a comparison to be made between different manufacturers of the same element more easily than with the proposed definition of building element.

6.2.2 THE CLMC ASSESSMENT SYSTEM

In addition to showing that it is possible to develop quantifiable measures and targets for CLMC content in buildings, it was also of interest to establish whether the system developed could be an effective tool in practice. The formulation of the assessment system drew lessons from other assessment systems studied (outlined in Chapter Two) and when complete was again compared to other systems to assess its ease of use. Taking into account the overriding interest related to this thesis to improve the sustainability of the building industry, it was essential that the assessment system was reasonably user-friendly.

The CLMC assessment system developed requires assessing the installation of each building element in respect of five assessment criteria and then the constituent materials of each element in respect of five further criteria. The criteria are clear and the system transparent, which gives the assessors, designers or builders the power to improve their designs while benefitting from the knowledge of where the problems lie.

However, the assessment process requires a large amount of information that may or may not be available to the building professional using the assessment, including full bills of quantities and information of the recyclability of materials and on the demountability of building elements. Consequently the assessment could be very time consuming. Furthermore, as discussed in Chapter Five, the assessment forms include insufficient information for a novice to undertake the assessment but too much information for an expert. The conclusion of the assessment systems review suggests that perhaps two assessment documents may be required: the first to record the assessment results and the building material quantities and the second to provide supporting guidance for those undertaking the assessment.

Despite its shortcomings, the assessment system was shown to be reliable and was used to assess sufficient materials and building elements to be able to draw some conclusions about the availability of CLMC construction elements in the building industry.

6.2.3 CLMC CONSTRUCTION ELEMENTS AND BUILDINGS IN THE BUILDING INDUSTRY

By using the assessment system developed it was possible to make an initial assessment of the status quo of the building industry in respect of CLMC compliance and the potential benefits of adopting CLMC construction.

Firstly it became clear that there are sufficient materials in the building industry that comply with the CLC criteria to build whole buildings. Furthermore, some general rules could be established. Elements made of minimally processed and homogeneous material that are mechanically fixed or fixed with compatible materials have a high potential for complying with the CLMC criteria. On the other hand composite and compound elements with adhesives or applied coatings are unlikely to comply. The ability to deconstruct elements is critical for complying with CLMC criteria and some elements were disqualified simply due to their installation method, suggesting there is scope for specification changes to improve the compliance with CLMC criteria.

However, the assessment was not able to take into account the continuous changes in the recycling industry. With pressure from the European Directive on Waste EU member states are introducing fiscal and legislative measures designed to reduce waste. This is pushing recycling technologies forward and what is not part of a CLC today may in future become so.

The whole house assessment highlighted some potential benefits of adopting CLMC construction. The assessment of the end of life disposal options of the materials included in House 2 identified a reduction of 85 and 86 per cent in non-CLC waste compared to House 1 by weight and by volume respectively. These results suggest that a radical reduction in waste destined for landfill is possible by adopting a contemporary construction. The very significant difference in weight of non-CLC waste was unexpected and considering that House 1 does not represent the worse case scenario in terms of non-CLMC-compliant construction and that the more typical block construction would add another 30 per cent of non-recyclable waste to the design, the benefits of adopting CLMC-compliant construction begins to become clear. Indeed quantifying accurately the non-CLMC waste produced by using a block construction would have been informative addition to this dissertation.

A further significant finding is that while the construction industry suffers from a number of major barriers to the adoption of more CLMC construction, there is scope for substantial improvement without unbalancing the industry's status quo. The ubiquitous use of concrete and plasterboard, two non-CLMC-compliant materials, present a major barrier to improvement and moving to substitutes for these materials would require an industry shift that is currently unlikely. On the other hand, House 2 already represents significantly better practice than the mainstream, having reduced the amount of concrete used, but is still within the market expectations in terms of aesthetics and construction technology. As such it represents a way forward for CLMC construction.

6.3 IMPACT OF RESEARCH

The research and the above results could impact on the academic and industrial context by introducing a new material design concept and tools that could contribute to improving the sustainability of the building industry.

From an academic perspective this thesis proposes the new concept of CLMC construction and a set of criteria that define the concept and enable an assessment of construction in practice. The CLMC construction concept was formulated through logical deductive thinking and by drawing from various sectors, including some from outside the building industry, and by analysing data gained about current and potential construction techniques. The CLMC construction concept embodies a critical rejection of some existing sustainable material ideologies, in particular those promoting reuse and deconstruction without considering the issue of waste in a comprehensive and long term manner. While, as discussed, the CLMC construction concept would benefit from a further conceptual reiteration, it presents a clear model for a sustainable material design approach to minimising waste.

In relation to the building industry in practice, this research could have a positive impact on the construction industry by helping to reduce the material waste associated with buildings over their life span.

This thesis and the papers published on its topic could help to inform professionals in the building industry and academics about the problems with material waste and the beneficial potential of adopting the proposed concept of a CLMC construction. As has been discussed in this thesis, information alone is unlikely to engender action and the adoption of the CLMC construction concept on a large scale. Therefore, it would also be necessary to develop legally binding targets in relation to CLMC construction for the building industry as well as a system to enable the taxing of non-CLMC waste. This thesis provides a starting point for the development of such binding targets and potential tax system.

This research could be defined as a pilot study and additional research is required to expand its scope and also review and refine its fundamental principles. Chapter Seven outlines some of the topics identified requiring further research and the expected outcomes of such research. Further work could result in guidance to inform building designers about the concept of CLMC and help encourage good practice, and an assessment system to set targets for minimum amounts of CLC materials to be included in buildings and assess the waste liability associated with specific building designs. The assessment system could also be instrumental in the development of new products and the improvement of existing product to reduce their waste impact.

In conclusion, the proposed conceptual model for CLMC construction, with its long-term perspective that differs from other models aiming to reduce construction waste, combined with the assessment and target-setting tools developed provide a clear starting point for a new framework for minimising construction waste.

7 FURTHER RESEARCH

This final chapter concludes the dissertation by reviewing some of the aspects of the study that suggest the need for further research including:

- the conceptual framework for CLMC construction;
- the practical application of the CLMC assessment system and good practice targets for CLMC content;
- the development of CLMC construction technologies; and
- the practical applicability of the CLMC assessment system.

7.1 THE CONCEPTUAL FRAMEWORK FOR CLMC CONSTRUCTION

The concept for CLMC buildings developed in this dissertation adopts what could be described as a purist viewpoint. The concept is based on an ideal involving buildings that can be dismantled and all constituent parts recycled or made to biodegrade. This ideal would indeed create a low, even zero, waste industry and as such it provides a true model of good practice. This approach may, however, be too idealistic and it may be beneficial to adopt a different point of view as well. Rather than considering what constitutes a ideal of achievement, which in practice is likely never to be completely achieved, it is also worth considering what good practice does take place in reality that effectively avoids waste in the building industry.

This different point of view highlights one building-related characteristic that has historically proved very effective at preventing waste from being formed, namely durability. Durability of buildings as a whole as well as building elements and materials is evident in the extensive existing building stock that is one hundred and more years old and the history of material element reuse. Certain materials, notably masonry materials, such as stone and brick, do not qualify as CLC materials according to the concept described, however they are very durable materials that can be in use and, if installed in a manner that allows their deconstruction, reused for hundreds of years, even thousands.

The limitation of the CLMC concept as currently defined is its lack of consideration of durability. Not factoring durability in the assessment has to be seen as a limitation as the ultimate aim of the development of the criteria is one of improving the sustainability of material design in real terms, not only in relation to an ideal model. This limitation needs to be addressed without losing the strength of the concept, which lies in its long term perspective. This is in contrast to the reality of design for disassembly, design for reuse and certain types of recycling that often only prolong the life of a material rather than avoiding waste indefinitely, and in certain instances even the extended life is short. The concepts of design for disassembly, design for reuse and recycling represent one fundamental aspect of waste minimisation and may well yield short term improvements, but fail conceptually and practically to address the long term. The more comprehensive concept of CLMC addresses the long term in an ideal situation and needs to be further developed to acknowledge the importance of the durability of materials and buildings in practice.

For the current assessment system to address durability may require a conceptual shift to introduce the element of time in the assessment. The introduction of time may impact on the assessment of other building elements and materials, which in turn may require a review of the whole concept.

Perhaps the concept of durability can be simply introduced by developing a further criterion that takes into account materials that have a life in use of over several hundred years and can be repeatedly reclaimed and reused. The potential for a criterion for 'endlessly reused' materials that conforms to the recycling and biodegradability efficiency standards advocated in the criteria developed could be envisaged. Initial thoughts in this respect are conditioned by literature on building obsolescence that identifies the reasons for obsolescence as including technological, but also functional, economic, social, legal, and aesthetic (Ashworth, 1997; EKOS and Ryden Property Consultants, 2001). Technical durability can therefore not guarantee economic or other resilience and the need to prematurely demolish a building cannot be excluded. Such realities point towards the need to limit the concept of 'endless reuse' to elements and materials and not apply it to whole building durability.

The concept of 'endless building element reuse' would have to take into account that the reuse of materials is subject to their acceptability as second hand materials with potential problems of aesthetics, performance and certification. Guidance that recommends a blanket approach to promoting reuse fails to recognise this reality. An analysis would be required to identify materials the reuse of which is not limited by non-technical barriers. The challenge in introducing a function for time to acknowledge the long life span materials and elements or an additional criterion for 'endless reuse' is to maintain an assessment system that is relatively simple. Complexity at a conceptual level may be acceptable, even appropriate, but if the concept is to be the basis for a practical assessment, then complexity can make a system unworkable.

Further iterations of the concept and assessment system would no doubt yield constructive developments of the system, and more research in this area could prove very fruitful. A research agenda in respect of the conceptual development of the CLMC principles would include:

- a review of the impact of considering time as a factor in the CLMC criteria;
- an investigation of the durability and life span of building materials and elements and their technical potential for repeated reuse;
- an analysis of the commercial potential of reuse of durable building elements (the technical ability of reusing elements is not a measure of the likelihood of these being reused in practice, e.g. ceramic sanitary ware); and
- development of criteria for 'endless building element reuse'.

7.2 TESTING THE CLMC ASSESSMENT SYSTEM AND GOOD PRACTICE TARGETS

While formulating a conceptual framework may occur in an abstract realm, developing the concept into an assessment system, which can be easily used, involves relating the concept to actual and current building practice.

In practice as opposed to the abstract realm, recycling as well as biodegradation cannot be achieved one hundred per cent. In the building industry both biodegradability and to a lesser degree recycling are unusual practices that do not currently benefit from standards that define efficiency. In this study the quantitative limits for loss of material mass and residue from natural disintegration have been taken from the EN 13432:2000 standard for natural recovery, and this appears to be appropriate standard to apply. The limits of the standard have also been used to define limits for recycling and natural disintegration losses. This transfer of values as well as the application of the packaging composting standards to building materials needs to be considered in a wider forum. Ideally materials manufacturing and recovery experts would be consulted to establish whether the adopted quantitative limits are appropriate and if not how they should be defined. Indeed the whole assessment system would benefit from an industry review.

The same question relating to benchmarks applies to the targets for CLMC construction content. Are the target levels of CLC construction content suggested in Chapter Five realistic enough for developments to achieve them but ambitious enough to push practice forward? This dissertation undertook a pilot study that can only suggest a way forward. To answer this question, this pilot study would have to be repeated on a much larger scale and expanded to assess buildings other than housing.

Further development of the CLMC assessment system would benefit from a programme of industry led review of the criteria and targets and further testing including:

- materials (focusing on material characteristics and recovery technologies);
- building systems (focusing on installation systems and their disassembly); and
- whole building constructions.

7.3 DEVELOPING CLMC CONSTRUCTION TECHNOLOGIES

To facilitate the implementation of a CLMC approach to design it would be beneficial if some of the technical limitations that exist could be eliminated. These could be addressed through a combined effort of research and industry development. The following barriers were identified.

- Installation specifications - The study of individual building elements identified materials and components with CLMC potential but that are currently non-CLCM. These are components that could be dismantleable subject to changes to their typical installation. An example highlighted was that of rubber flooring typically glued, but that could be loose laid. New specification recommendations are required from manufacturers that would enable a CLCM installation. Alternative installation methods may have to be developed and tested.

- Falling short of expectation – The study also identified components that are theoretically designed for dismantling and reuse, but seldom are. Further investigation would be necessary to establish where the failure in these systems lies, before redesigning the component in conjunction with the manufacturer.

- Improving technologies and economics of deconstruction – The cost of demolition activities is seldom studied (Pun *et al.*, 2006), yet this is considered one of the major reason for the preference of demolition over deconstruction. Research comparing the cost of deconstruction of different building systems would help to identify building systems that are cost-effective to deconstruct and this in turn would help direct the development of both deconstruction techniques and building element design to facilitate deconstruction.

- Bio-composites – While still in its infancy the use of bio-composites could form an alternative to some of the materials that are most problematic in terms of creating a CLC. If bio-composites like polylactide have been used for liquid food containers then future technical developments may extend the durability of such materials sufficiently to make them a feasibly alternative for the building industry.

From a technical perspective some fundamental changes may need to be made. The age old wisdom of not wasting time by reinventing the wheel might have to be overridden. Following the example of the Rocky Mountain Institute and their design for the Hypercar (Rocky Mountain Institute, 2009), which involved reconsidering the fundamental ingredients of a car design, a reconsideration of the critical performance requirements for building elements and how to address them may be required.

7.4 THE PRACTICAL APPLICABILITY OF THE CLMC ASSESSMENT SYSTEM

As has been discussed from the beginning of this dissertation, sustainable practice has to be enforced rather than simply encouraged. However, both encouragement and enforcement are essential and can work together. The criteria and assessment system could help promote good practice in three main ways:

- as a tool to inform, guide and raise awareness among designers, builders and clients;
- to identify economic benefits for building owners and occupiers; and
- to form the basis for legislation aimed at limiting the use of non-CLC materials.

7.4.1 EDUCATION

The criteria could be developed into guidance or be supplied with guidance to building designers and builders. More information on building materials, systems, their installation and their recovery methods and efficiencies would be made available with the guidance. The guidance would help inform building designers about the concept of CLMC and help encourage good practice. In their simplest form the criteria could be employed as a design or building checklist.

If fully applied, the assessment system could be used by building designers to assess their designs and maximise the amount of CLC materials included. It could also be used by builders and other professionals for the same purpose. To address a potential lack of information on recovery processes, such information could researched and made available and easily accessible, which at present it is not. The application of the criteria could be facilitated by assessing typical construction systems using the CLMC criteria and making the assessment results available to building professionals. This would enable them to make informed choices in respect of which materials and building systems to use to achieve a CLMC construction.

The assessment system could also be used by clients to assess building designs and suggest changes. Indeed clients could set targets for minimum amounts of CLC materials included in their buildings.

7.4.2 ECONOMIC INCENTIVES

The CLMC criteria could be used to quantify the amount of CLC materials included in a building versus non-CLC materials destined for landfill. This information could be used to assess the waste liability associated with specific building designs, including material waste and disposal costs over the building life and at its disposal phase. This in combination with the continuously rising Landfill Tax could encourage more waste conscious designs.

To maximise the economic advantage of building using CLMC construction, a cost function related to the assessment system could be developed. Even though the economic context of the building industry is not static, a cost function that identifies the CLC materials and elements that can be easily and cost-effectively integrated into buildings would encourage a wider adoption of such principles in practice. Guidance is required on how to achieve 'easy' and 'quick' gains, in other words, how to achieve the maximum CLC material content in a building at minimal effort and cost.

7.4.3 LEGISLATION

The CLMC criteria and in particular the targets for CLMC content could be used to formulate legally binding standards. The model and indeed the implementation vehicle for such legally binding targets could be the Code for Sustainable Homes once it has become part of the Building Regulation approval system.

In the Netherlands recycling rates of 90 per cent of construction and demolition waste were achieved through the introduction of 'The Demolition and Construction Wastes Landfill Ban' in 1997 which prohibits the landfilling of reusable or burnable construction and demolition waste (Kowalczyk *et al.,* 2000). Despite most of the C&D waste being used for road building, the impact of this legislation cannot be ignored (Te Dorsthorst, *et al.,* 2000). In the UK the Landfill Tax is the main legislative tool employed to support an increase in recycling and indirectly the principle of designing for CLMC. Current levels of tax are thought unlikely to substantially reduce the construction and demolition waste, however higher levels of taxation may have more impact.

The use of the assessment system would also enable the identification of building materials and systems that are non-CLC and form the basis for developing take-back schemes or tax disincentives to reduce their use and or environmental impacts associated with their use. As with the Directive 2002/96/EC on waste electrical and electronic equipment (WEEE) which entered into force on 2 January 2007, building materials and elements manufacturers could be required to take back their products and dispose of them in an environmentally friendly manner at the end of the product's life. The reprocessing of CLC materials would be non-problematic and inexpensive. The elevated disposal costs of non-CLC materials, having now become the responsibility of the manufacturer, would encourage the manufacturers to take the final disposal of their products into account in their product design.

7.5 CHANGING CULTURE

The implementation of the Directive 2002/96/EC on waste electrical and electronic equipment (WEEE) could instigate a change in culture. Transferring the responsibility for waste from one organisation to another will change values, interests and attitudes. It is no longer in a manufacturer's interest to make inseparable elements of different waste classifications, when they are responsible for taking the products back and paying for their disposal. It is now in their interest to consider how the products are dealt with at the end of their useful life. This is a critical change of culture.

There is some evidence of a move away from a traditional product sales relationship where a sales transaction involves the transfer of responsibility from the manufacturer to the purchasers. Xerox machines and Interface carpets, are examples of a move to a service economy as envisaged by Swiss analyst Walter Stahel and German chemist Michael Braungart where 'the product is a means, not an end.' (Hawken *et al.*, 1999, p.18) and the responsibility for the product rests with the manufacturer.

Whether the building industry can move in that direction remains to be seen. Yet the buildings built today may last 10, 50, 100 or more years and their end of the life will occur at a time where resources are becoming increasingly scarce and or expensive and land for landfill sites virtually non-existent (in the UK and elsewhere). A more resource- and waste-conscious approach to design and construction is therefore already overdue.

8. APPENDICES

The appendices are ordered in order to relate to the main thesis text. They include summaries of literature reviews, original developmental research work, interim research results and original research data to illustrate and explain the research and thought processes described in the main text.

APPENDIX 1 – EUROPEAN UNION DIRECTIVES RELATED TO THE BUILT ENVIRONMENT (LITERATURE REVIEW)

APPENDIX 1 IS RELATED TO SECTION 2.1.3 'CARROT AND STICK'

Appendix 1 summarises selected European Union Directives that were retained to be of relevance to the investigation into methods of implementing sustainability. The use and success of European Union Directives to implement more sustainable performance supports the thesis that sustainability improvements have to be enforced through regulations and cannot be introduced by means of education and appealing to ethical principles alone. A number of European Union Directives were examined for the purposes of understanding the impact such legislation can have and the list below is a record and brief outline of European Union Directives that are relevant to the building industry.

- The Environmental Impact Assessment Directive EEC/85/337 passed in 1985 was enacted within the Town and Country Planning (Assessment of Environmental Effects) Regulations 1988 and updated in 1999. It requires developments likely to be associated with significant pollution to be assessed environmentally as part of the planning proposal. A mandatory assessment applies to major infrastructure projects such as oil refineries or landfill sites. Discretionary assessment applies to developments such as holiday villages or food manufacturing depending on the likelihood of the development constituting a significant environmental impact.

- Protocol on Strategic Environmental Assessment to the Convention on Environmental Impact Assessment in a Transboundary Context (2008) requires member countries to prepare strategic environmental assessments for plans and programmes affecting activities governed by the Environmental Impact Assessment legislation. These plans, policies and legislation should ensure that environmental, including health, considerations are taken into account. (Official Journal of the European Communities, 2008).

- European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste amended in 2005 (Directive 2005/20/EC) lays down measures aimed priority at preventing the production of packaging waste and additionally at reusing packaging, at recycling and other forms of recovering packaging waste and, hence, at reducing the final disposal of such waste (Official Journal of the European Communities, 1994; ibid 2005).

- European Parliament and Council Directive 2003/108/EC of 8 December 2003 amending Directive 2002/96/EC on waste electrical and electronic equipment (WEEE) aims to reduce waste by placing the financial responsibility for recovering and recycling of electronic equipment on the producers of such equipment. The public should be able to dispose of electrical and electronic equipment for recycling free of charge. Producers have the option of making independent arrangements to stratify the directive or joining a group collection and processing service. The directive further requires producers to provide a guarantee when placing a product on the market that would ensure and its environmentally sound disposal should the producer cease trading. The aim of the directive is also indirectly to encourage producers to design their products in a way that will facilitate their disassembly and recycling at the end of their life (Official Journal of the European Communities, 2002; Official Journal of the European Communities 2003a).

- Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings came into force in 2006. The Directive promotes the improvement of the energy performance of buildings and has been implemented in the UK by measures including the introduction of the Energy Performance Certificates (EPCs), which were discussed in Section 1.1. Related to the EPCs is the requirement for the development of a common method of calculating the energy performance of buildings and the requirement for improving the energy performance of existing buildings over a specific size undergoing major building work. Other means to improve energy efficiency stipulated by the directive include the regular inspection of boilers and air conditioning plants (Official Journal of the European Communities, 2003c).

- Directive 2006/12/EC of the European parliament and of the council of 5 April 2006 on waste aims for the Community as a whole and individual countries to become self-sufficient in waste disposal and that processes associated with such activities should not negatively affect human health or the environment. The directive requires member states to encourage the reduction of waste production, the recovery of waste by recycling, and reuse as well as incineration with energy production

(Official Journal of the European Communities, 2006). This directive has to be considered in conjunction with other waste-related directives such as the Landfill directive and in the UK its aims are incorporated within the Waste Strategy for England 2007 (Department for Environment, Food and Rural Affairs (DEFRA), 2007). The UK has implemented aspects of the waste directive by means of a number of initiatives of which the Mandatory Site Waste Management Plans (SWMP) introduced in England in April 2008 for construction projects over £300,000 are relevant to the building industry. The SWMP require construction companies to consider and reduce the amount of waste going to landfill. It is one of the initiatives aimed at halving the waste disposed to landfill by 2012. Amendments to the waste directive agreed in 2008 and due to come into force in 2010 will set targets for reuse, recycling and recovery of 70% of construction and demolition waste by 2020. An interim target of 50% by 2012 was agreed by the Strategic Forum for Construction (Department for Business, Enterprise & Regulatory Reform. Construction Sector Unit, 2008).

APPENDIX 2 - SUSTAINABLE DEVELOPMENT CASE STUDIES (PRIMARY RESEARCH RESULTS)

APPENDIX 2 IS RELATED TO SECTION 2.2 'REVIEW OF SUSTAINABLE DESIGN GOOD PRACTICE PRINCIPLES AND ASSESSMENT SYSTEMS' AND IN PARTICULAR 2.2.2-2.2.7

Appendix 2 includes the case studies that resulted from the Objective One research aiming to identify current principles and practice of sustainable design and are referred to in Section 2.2. The research process is detailed in Section 1.5.1 and involved examining secondary data and triangulating this with primary data from a field study.

An overview of the theory and practice of sustainable design and of methods assessing sustainable design was gained by means of literature review. The review also resulted in an extensive list of potential case study buildings that could be further investigated for the purpose of triangulating the study. The information gained was also used to develop an assessment matrix that was adopted to evaluate completed case study projects. The long list of potential case study buildings was analysed with the matrix and reduced to a total of sixty buildings to be further studied. The final selection of case study buildings aimed to include a comprehensive catalogue of sustainable design principles put into practice. The sixty buildings were visited and the designers and or building occupants interviewed to establish the drivers for the designs, theoretical sustainable design principles adopted, the barriers and the extent of successful implementation of the sustainable design principles.

The sustainable material design aspects were studied as part of this study. Table A01 lists the sixty case study buildings studied against the sustainable design approaches adopted. Material selection constitutes the last set of criteria of the matrix.

This research resulted in the publication of the book Strategies for Sustainable Architecture (Sassi, 2006), which aimed to provide the reader with the theory of sustainable building design and examples of successful implementation of sustainable design principles.

The case studies included are:

- **Urban design good practice case study: solarCity, Linz, Austria.**
- **Building communities case study: Fairfield Housing Estate, Perth, Scotland, UK.**
- **Energy good practice case study: Solarsiedlung, Freiburg, Germany. A cutting edge version of the Passivhaus.**
- **Energy good practice case study: Solar-Fabrik in Freiburg, Germany. Zero carbon dioxide emissions commercial buildings.**
- **Water use good practice case study: The Vale house, Southwell, Nottinghamshire, UK.**
- **Water use good practice case study: Hockerton Housing, Hockerton, Nottinghamshire, UK.**

Table A01 – **Matrix of case study buildings identifying sustainable design approaches adopted – Part 1: Urban, community, health and energy design issues.**

DESIGN APPROACHES / PROJECTS	Compact city centre living	Reduced car dependency	Enhancing flora and fauna	Local food production	Community participation	Affordable living	Promoting training / employment	Enhancing community facilities	Actively promoting sustainability	Indoor air pollutants avoided	Zero potential toxins, e.g. PVC	Focus on accessibility	Restorative environment	EMF considered	Minimise heat loss and passive heating	Passive / natural ventilation & cooling
21st Century Homes						o						o			o	o
Akademie Mont-Cenis			o		o		o	o				o	o		o	o
Argonne Centre	o	o	o	o	o			o	o	o			o		o	o
Barling court	o	o				o									o	o
BCZEB		o	o					o	o	o			o		o	o
Bed Zed	o	o	o			o		o	o						o	o
BRE Building 16									o	o					o	o
Buoy Wharf	o					o	o									o
Carlisle lane	o	o				o									o	o
Chorlton Park			o			o							o		o	o
College Library SCU								o					o		o	
Design Centre Linz								o		o						o
Dyfi Eco Park			o				o			o					o	o
Eden Bus Shelter										o	o					o
Ellenbrook			o		o	o		o	o				o		o	o
Environmental Discovery C.			o						o	o			o		o	o
Fairfield Housing			o		o	o	o	o		o	o	o			o	o
Gallion EcoPark	o		o			o									o	o
Glashaus	o	o	o		o		o	o		o			o		o	o
Glencoe Visitor Centre								o					o		o	o
Göthean Science Centre			o	o	o		o	o	o	o	o	o	o		o	o
Greenwich Sainsbury			o					o	o				o		o	o
Gusto Housing			o		o		o	o	o	o					o	o
Hidden villa			o	o	o		o		o	o			o		o	o
Hockerton Housing			o	o	o	o	o	o	o	o	o		o		o	o
IGA		o	o					o					o			
Integer Home									o	o		o			o	o
Lewis Centre			o	o	o		o	o	o	o		o	o		o	o
London Field	o	o		o	o	o	o	o							o	o
Loudoun Ecovillage			o	o	o			o	o	o		o	o		o	o
Lyola			o									o	o			o
Macoskey Centre			o	o	o		o	o	o	o			o		o	o
Mile End park		o	o		o			o				o	o		o	o
Petuel Ring		o	o					o					o			
Phillip Merrill Centre		o	o		o		o	o	o	o			o		o	o
Phoenix Ecohouse			o						o	o					o	o
Phoenix Central Library								o								
Pinakarri	o	o	o	o	o	o	o	o	o			o	o		o	o
Piney Lakes			o		o			o	o	o					o	o
Powergen HQ			o										o		o	o
Queens Building	o	o					o		o	o					o	o
Refurb House Phoenix						o							o		o	
Resourceful Building	o					o				o					o	o
Robin Hood Chase					o		o	o		o					o	o
RWE			o					o					o		o	o
Sandy Information Centre			o					o				o	o			o
Schreiber House			o	o		o				o			o		o	o
Slateford Green	o	o	o	o		o		o				o	o		o	o
solarCity Linz	o	o	o		o	o	o	o		o	o	o	o	o	o	o
Solar Fabrik			o					o	o	o			o		o	o
Solar House Freiburg									o	o					o	o
Solarsiedlung	o	o	o			o		o	o	o	o				o	o
The Point	o	o			o			o							o	o
Thurgoona			o				o		o	o		o	o		o	o
Uluru			o		o		o	o		o						o
Vale House				o						o					o	o
Vaubon Freiburg	o	o	o		o	o		o								
Weald & Downlands					o		o	o	o	o					o	o
Winter Gardens			o					o				o	o		o	o
York Road Housing						o				o		o	o		o	o

Table A02 – **Matrix of case study buildings identifying sustainable design approaches adopted – Part 2: Energy, water and material design issues.**

DESIGN APPROACHES / PROJECTS	Maximum natural light provision	Energy efficient services & equipment	Performance assessment/ monitoring	Renewable energy systems	Water efficient appliances	Waterless toilets	Grey or rainwater recycling	Rainwater collection for all uses	Alternative sewage system	SUD	Design for longevity and flexibility	Use of waste materials	Use of renewable / certified mat.	Use of low manufacturing impact mat.	Waste minimisation in construction	Waste minimisation in use
21st Century Homes	o	o			o						o		o		o	
Akademie Mont-Cenis	o	o			o					o	o		o			
Argonne Centre	o	o		o	o							o	o	o		
Barling court		o			o						o				o	
BCZEB	o	o	o	o	o					o	o	o	o		o	o
Bed Zed	o	o	o	o	o		o		o	o		o	o		o	
BRE	o	o	o	o	o					o	o	o	o	o	o	o
Buoy Wharf											o	o			o	
Carlile lane					o								o	o	o	
Chorlton Park	o	o								o			o	o	o	
College Library SCU	o				o											
Design centre	o				o					o	o					
Dyfi Eco park	o	o	o		o					o		o	o	o		
Eden Bus shelter	o	o										o	o	o		
Ellenbrook										o			o		o	
Environmental Discovery	o	o		o							o		o			
Fairfield Housing	o	o										o	o			
Gallions EcoPark	o	o	o	o	o		o						o			o
Glashaus	o				o											
Glencoe Visitor centre	o	o			o				o	o	o		o	o		
Göthean Science Centre	o	o		o	o	o	o			o			o	o	o	
Greenwich Sainsbury	o	o	o	o	o		o				o	o				o
Gusto Housing	o	o		o	o		o			o	o					
Hidden Villa	o	o		o								o	o	o		
Hockerton Housing	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
IGA										o						
Integer Home	o	o	o	o	o		o			o	o	o	o		o	o
Lewis Centre	o	o	o	o	o				o	o	o	o	o			
London Field	o	o			o						o	o	o			
Loudoun Ecovillage	o	o		o	o				o	o	o	o	o	o	o	o
Lyola	o				o								o			
Macoskey Centre	o	o		o	o	o			o	o		o	o			
Mile End Park	o	o								o	o					
Petuel Ring																
Phillip Merrill Centre	o	o		o	o	o	o			o	o	o	o	o	o	o
Phoenix Ecohouse	o	o		o	o		o			o		o	o			
Phoenix Central Library	o										o					
Pinakarri	o	o	o							o		o				o
Piney Lakes	o	o	o	o	o			o	o			o	o	o		
Powergen HQ	o	o								o	o					
Queens Building	o	o	o		o					o	o					
Refurb house Phoenix	o										o	o	o			
Resourceful Building	o				o						o	o	o		o	
Robin Hood Chase	o	o			o		o					o	o	o		
RWE	o	o	o	o	o					o	o					
Sandy Information Centre	o				o					o						
Schreiber House	o	o			o					o	o	o	o		o	o
Slateford Green	o	o			o					o		o	o			
solarCity Linz	o	o		o	o				o	o			o	o	o	o
Solar Fabrik	o	o	o	o	o		o			o	o					
Solar House Freiburg	o	o	o	o	o					o	o					
Solarsiedlung	o	o		o	o					o	o		o		o	o
The Point	o	o	o		o											
Thurgoona	o	o	o	o	o	o	o		o	o		o	o	o		o
Uluru							o		o				o	o		
Vales House	o	o	o	o		o		o	o		o					o
Vaubon Freiburg										o						
Weald & Downlands	o	o								o	o	o	o	o	o	o
Winter Gardens	o										o		o			
York Road Housing	o	o			o					o						

URBAN DESIGN GOOD PRACTICE CASE STUDY:

SOLARCITY LINZ , LINZ, AUSTRIA

The solarCity was intended as a model of sustainable city development, the name referring to the all-encompassing use of the sun, which ranges from providing passive and active heating and electrical needs to contributing to human comfort and plant growth. All buildings are low energy and the development addresses issues of occupant's health, women's needs (which focus on security and safety), sustainable water use and drainage, community building and restoration of natural environments.

The idea for the solarCity came about in 1990 in response to a housing shortage in the Linz region. In 1992 the city of Linz commissioned Professor Roland Rainer to prepare a masterplan for the area of Pichling, located south of the city centre. The development was to have a potential to accommodate 5000 to 6000 dwellings and by 1995 the city of Linz had the commitment of 12 non-profit housing developers to develop a first phase of 1317 mixed tenure dwellings on 32.5 hectares of land. The development density is 40 dwellings per hectare equivalent to 100 persons per hectare or 0.65 ratio of built footprint to overall area. Over a third of the construction cost is associated with development infrastructure including community facilities, transport network and landscaping.

The houses are of mixed tenure with approximately half shared ownership, 40 per cent for rent and the rest for purchase. Half of the dwellings are generously sized three bedroom flats or terraces, a quarter are two bed and a quarter four bedroom dwellings. Fourteen fully accessible flats are available for disabled individuals plus a ten person shared and supervised accommodation. Car parking is underground, creating landscaped car-free spaces between terraces and children's play areas with sand boxes, climbing frames and other games.

The development has been designed as a self-sufficient neighbourhood. A commercial and community centre is located at 300m from all houses thus the need for a car. The commercial and community centre includes general facilities (grocery shop, bakery, medical centre, pharmacy, bank, citizens' advice office, hair dresser, bookshop, tanning studio) as well as facilities for leisure activities (library, children's club, seniors' club, adult college, café, restaurant). The centre building consists of timber- and glass-clad blocks joined by glazed roofs, forming attractive all-weather covered streets.

A school and a nursery are located on the south side of the development and can be accessed through safe pedestrian routes. On the north side is a landscaped park that connects with a nature reserve with a lake. A tram line links the solarCity to the centre of Linz and the tram stop at the commercial and community therefore accessible on foot from any of the houses.

BUILDING COMMUNITIES GOOD PRACTICE CASE STUDY:

FAIRFIELD HOUSING ESTATE, PERTH, SCOTLAND, UK

The Fairfield housing estate is an example of a successful application of the principles of sustainability at community level to transform a crime-ridden estate into a highly desirable development with a waiting list of 300 families. The Fairfield housing estate in Perth was built in 1935 and thrived up to the mid 1960s with a strong community feeling. But by 1985 only 500 of the original 1500 residents were still living on the estate and 75 per cent of these wanted to leave. However, fifteen years later the estate was again a popular place to live.

The key to the transformation was tenant participation and an intense period of community consultation. The community was invited to a number of meetings and workshops designed to identify the needs and wishes of the community and relate them to the interests and potential for implementation of the other organisations involved. The workshops enabled the community to identify problems, such as crime levels, poor street lighting, vandalism, litter, the lack of any facility for meeting with other residents, lack of confidence by the elderly residents to leave their homes and lack of work for young residents. Further workshops identified where aspirations and the means to achieve them coincided, and helped to formulate a feasible programme that addressed the wishes of the community.

One of the aims of the consultation process was to identify a way of ensuring the sustainability of the project after development work was completed. This was achieved by handing control of the management of the estate to its residents. In 1988 the Fairfield Housing Co-operative was set up with help from the Scottish Homes and Perth and Kinross Council. The co-operative, run by a management committee of volunteer tenants, manages and maintains more than 300 dwellings.

Fairfield's success is primarily the result of the community itself driving the development process forward and retaining control of the development. Other developments have focussed on other aspects of community development. The Robin Hood Chase community building development in Nottingham aimed and succeeded in integrating a training aspect to the building construction process and trained approximately 30 underprivileged individuals during the construction of the building. The Glashaus multipurpose community building in Herten, a small town in Germany suffering economically from the closure of the coal pits, successfully helped revitalised the town centre, providing the town with a meeting and cultural centre, and creating a psychological focus for the community.

ENERGY GOOD PRACTICE CASE STUDIES:

ZERO CO_2 RESIDENTIAL BUILDING

SOLARSIEDLUNG, VAUBAN, FREIBURG, GERMANY

The Passivhaus standard has been used extensively and exceeded at the Solarsiedlung (solar-community) housing development in Vauban, Freiburg. This development uses the Plusenergiehaus® concept to provide housing associated with zero carbon dioxide emissions and to generate energy from renewable sources to exports to the grid. The renewable energy is generated by a photovoltaic array sized, not based on the electricity needs, but on the maximum area available for the installation effectively creating a small electricity generating plant.

All the roofs are covered with photovoltaic panels. The roof is asymmetrical: the south facing roof is larger than the north facing roof. Each house has a photovoltaic installation with a 3-10kW peak output, which is expected to generate 2,800-9,600kWh of electricity per year. The modules are 13 per cent efficiency and have a 20-year guarantee. They are installed directly over a waterproof membrane on a timber deck covering the insulated timber frame avoiding the need for other roof covering materials.

The houses are also the classic example of creating an energy efficient envelope by reducing energy needs, and then providing the remaining energy requirements by renewable means. They are highly insulated and built to be airtight. Wall construction comprises a composite timber framed with 300mm of mineral wool insulation, providing a U-value of 0.12 W/m²K and the timber frame roofs incorporate 350mm of insulation. The houses make maximum use of solar gains: the south façade is virtually completely glazed with high performance windows with a U-value of 0.7 W/m²K. Protection from the summer sun is provided by large south facing balconies, which shade the floor below, and the top floor is shaded by the roof-mounted photovoltaic array. Heating requirements are expected to range between 10-20kWh/m²/yr depending on the size of the house, its location in the terrace and the occupants' habits. The hot water for heating and washing is provided by a district heating system that serves the whole Vauban neighbourhood and burns wood waste and is considered carbon dioxide neutral. Carbon dioxide neutrality generally refers to the use of biofuels. These are fuels that are either a biodegradable waste product or are renewable plants that absorb CO2 during their growing phase, so that when they are burnt the CO2 emitted is the same quantity as that absorbed.

ZERO CO_2 COMMERCIAL BUILDING

SOLAR-FABRIK, FREIBURG, GERMANY

The Solar-Fabrik in Freiburg, a manufacturing plant for photovoltaic modules with associated offices, has been built to achieve a carbon dioxide neutral building by combining passive building design approaches with active systems.

The building is designed to have low energy consumption by insulating the fabric well, providing thermal mass and maximising solar gains. The external walls have a U-value of 0.22W/m²K and the glazed curtain walling has a U-value of 1.1W/m²K. Thermal mass is provided by concrete floor slabs and a solid stone wall at ground floor. The south facing façade is glazed along its full length and solar gains through the glazing are estimated to contribute 43MWh/yr to the heating requirements of the building. The manufacturing block is heated by means of mechanical ventilation with heat recovery and has a heating requirement of 17.1 Kwh/m²yr, while the offices' heating requirement is 13.4 Kwh/m²yr.

The heating needs are covered with a boiler run on rape seed oil providing 50MWh/yr, and a combined heat and power system also burning rape seed oil providing 150MWh/yr heat. The combined heat and power system also generates 90MWh/yr of electricity and further electricity is provided by 450m² of PVs, which generate 40MWh/yr. With further heating needs covered by passive means, the building is CO_2 neutral. The 30,000 litres of oil required to run the building are derived from rape seed cultivated following ecological agricultural principles on a 30 hectare site.

The summer operation is largely free-running, with internal temperatures not exceeding external temperature by more than 2°C. The south facing elevation is shaded with 210m² of PVs, automatic windows at high level open to allow the hot air to escape, the thermal mass helps to absorb day-time heat gains and earth ducts supply cooled air to the entrance and exhibition space. The earth ducts can further cool the space by introducing cool air at night to cool the thermal mass. The offices can be cross ventilated and the manufacturing block is naturally ventilated.

Why not more buildings are designed to be CO_2 neutral clearly does not depend on the technology available today as the examples described above illustrate. The inability, due to lack of knowledge, and reluctance to change as well as prioritising other issues are more likely to be the reasons for which zero CO_2 buildings are still only a very small minority of the buildings built today.

WATER USE GOOD PRACTICE CASE STUDIES:

THE VALE HOUSE, SOUTHWELL, NOTTINGHAMSHIRE, UK

The Autonomous house was designed to be completely autonomous from mains connections for power, water and sewer. The building is designed with Passivhaus standards of insulation and relies on a small woodburning stove to achieve a comfortable environment all year round. All water needs, including drinking water, are covered by rainwater collected from the roof of the house. Waste water is dealt with by installing waterless composting toilets, which save over 30 per cent of water needs, and the greywater produced is filtered and drained in a soakaway in the garden.

The house collects rainwater from the roof and purifies it to drinking quality standard. All the rainwater is collected from the clay tile and glass roof into a copper gutter. The smoother the collection surfaces are the fewer contaminants are trapped and can be washed off with the rainwater. Copper was chosen for its slightly disinfectant effect. The rainwater is then drained through a downpipe that discharges over a standard gulley, which filters leaves and other large particles, and is covered with a copper sheathing to stop any contamination of its surface. The water is collected in nineteen 1500 litres recycled orange juice tanks connected in parallel and series and located in the basement. The tanks are filled simultaneously and have an overflow to a soakaway in the garden.

The stored water is then pumped through a sand filter and then into another tank which stores the clean water. The sand filter removes suspended particles. Layers of increasingly fine sand are used to filter different sized particles. On top of the sand an active layer of organic and inorganic particles naturally develops called the 'Schmutzdecke', 'dirt cover'. This layer helps break down the organic particles contained in the water. Below this layer, there is a layer of microorganisms that feed on organic contaminants. The Schmutzdecke has to be removed when it gets too thick; this is done by replacing the top layer of sand. The storage tank for the filtered water holds enough water for two weeks of use and enables the filter bed to be drained when maintenance becomes necessary.

The filtered water is then pumped from the 1500 litre tank to a 250 litre header tank on a platform above the kitchen. A battery-operated 12-volt pump, activated by the lowering of ballcocks in the clean water storage tank as the water level drops, is used to pump water to the header tank as well as directly to the kitchen tap. The water for the kitchen tap is forced through a carbon core ceramic filter candle under the sink. This filter finally purifies the water to drinking standards (Vale, 2000).

HOCKERTON HOUSING, HOCKERTON, NOTTINGHAMSHIRE, UK

While the Vale house achieves water autonomy at a small scale, the Hockerton Housing Project, a development of five earth-covered terraced housing, achieves it at a small community scale. Hockerton Housing Project is also designed to carbon dioxide neutrality by minimising energy requirements and generating enough green energy on site to cover them. It also collects enough rainwater to serve all the residents' water needs, and treating all waste water on site.

Water for non-potable uses, such as bathing, clothes washing and flushing WCs, is collected from throughout the site, including from the access road and from the fields, and directed through swales to a sump. From there the water is pumped to a reservoir. The stored water is then passed through a sand filter and gravity fed into the houses. Water use is reduced by the use of low flush WCs and aerated taps and shower heads. Water for potable uses is collected from the conservatory roof via copper pipes and stored in a 16 m^3 tank. It is filtered with a 5µm string filter and a carbon filter, then purified with a ultraviolet light treatment.

All the waste water, including black and grey water, is transferred to a communal septic tank for a five- to ten-day period where the solids are separated through settlement. The liquid is then passed through the reed bed treatment area, a process which takes an estimated three months. The reed beds are integrated in an artificial lake 120metres long and 30 metres wide, which holds approximately 3000 cubic metres of water. The lake is 2.2 metres deep in the middle and has shallow edges to support a variety of plants and animals. It was formed by machine puddling a layer of clay, creating a sealed enclosure for the water. The reedbed is planned in a spiral with the inlet form the septic tank at the centre to maximise the length of the treatment circuit before the water passes through a gabion wall made of 30-60 mm blocks of limestone and planted with irises, which separates the treatment area from the main part of the lake. Three different species of reeds are planted (Typha, Phragmytes, and Iris) in different areas and supply oxygen to the bacteria living around their roots, which digest the pathogens in the effluent as it slowly passes through. The reedbed system is expected to cope with up to 40 residents and cleans the water to a similar standard than that treated in a typical mechanical treatment plant and the lake water has met European Union bathing quality standards when tested and is used as a recreation facility for boating and swimming.

APPENDIX 3 - PUBLICATIONS ON SUSTAINABLE MATERIALS FOR BUILDING CONSTRUCTION (LITERATURE REVIEW)

APPENDIX 3 IS RELATED TO SECTION 2.2.7 'MATERIALS' AND SECTION 3.1 'SUSTAINABLE MATERIAL PHILOSOPHIES'

Appendix 3 includes brief outlines of the key material publications studied at the start of the research process. It includes a table used for an initial assessment regarding the qualitative (mainly related to natural building technologies) versus quantitative (mainly related to life cycle analysis approaches) assessment approaches adopted by different building materials related publications.

The Green Guide to Housing Specification by Anderson, J. and Howard, N., (2000), BRE, Watford and **The Green Guide To Specification** by Shiers, D., Anderson, J. and Sinclair, M., (2002), Blackwell Science, Oxford.

These publications are designed to be used by practising architects and contain primarily quick reference tables rating and comparing different types of constructions typically used in the UK building industry. The whole construction is assessed rather than individual materials. An introductory section discusses the environmental imperative and the rationale behind the assessment system and identifying the main environmental issues considered.

Handbook of Sustainable Building by Anink, D., Boostra, C. and Mak, J., (1996), James and James, London.

This publication is similar in approach to the above aiming mainly at practitioners who have limited time to research different environmental options and therefore need a quick reference guide. This one however compares mainly materials rather than whole construction systems. Each selection includes some background information.

The Green Building Handbook Vol. I & II by Woolley. T. *et al.*, (1997 / 2000), E&F Spon, London.

This publication amalgamated the **Green Building Digest** journal publications to form two volumes. Each issue of the original journal was dedicated to a building element (e.g. roofing) and discussed each environmental impact associated with different materials. Environmental preferred options were also suggested.

Ecology of Building Materials by Berge, B., (2000) Architectural Press, London.

This publication analyses in detail some of the main materials and products used in the building industry from an ecological point of view. Unlike the above publications, this one does not provide a comparison between materials but rather considers each material individually and explains the environmental impacts and advantages of each material discussed.

The Whole House Book by Borer, P. and Harris, C., (1998), Centre for Alternative Technology, Machynlleth.

This publication is a mixture between an in depth analysis of the environmental aspects of different material selection and a guide for building designers and specifiers who simply want to find out which solution is more environmentally friendly.

Table A03 – **Matrix identifying foci of sustainable material publications**

Sustainable materials Publication Key ✓ = Description applies to publication	Qualitative	Quantitative	LCA applied	Natural building	Other aspects
Adams C. and Elisabeth L. (2000). *Contemporary Natural Building Methods.* London: John Wiley & Sons.	✓			✓	
Anderson,J., Shiers, D., and Sinclair, M. (2002). *The Green Guide to Specification.* Oxford: Blackwell Science.		✓	✓		
Anderson, J. and Howard, N. (2000). *The Green Guide To Housing Specification.* Watford: Building Research Establishment .		✓	✓		
Anink, D., Boostra, C. and Mak, J. (1996). *Handbook Of Sustainable Building.,* London: James and James.	✓		✓		
Berge, Bjørn (2000). *Ecology Of Building Materials.* London: Architectural Press.		✓	✓	✓	
Borer, P. and Harris, C. (1998). *The Whole House Book.* Machynlleth: Centre for Alternative Technology.	✓		✓	✓	
Hall, K. and Warm P. (1995). *Greener Building.* Llandysul. Carmarthenshire: The Green Building Press.	✓			✓	
JT Design and Build Ltd (1993). *The Green Construction Book. A Manual for Clients and Construction Professionals.* Bristol: Cedar Press.	✓		✓		
Kennedy, J. F., Smith, M. G. and Wanek, C. (2002). *The Art of Natural Building. Design, construction, resources.* Gabriola Island, CA: New society Publishers.	✓			✓	
Fox, A. and Murrell R. (1989). *Green Design. A Guide to the Environmental Impact of Building Materials.* London: Architecture Design and Technology Press.	✓		✓		
Parker-Laporte, P., Elliot E. and Banta J. (2001). *Prescriptions for a Healthy House.* Gabriola Island:New society Publishers.	✓			✓	✓
Talbot, J. (1995). *Simply Build Green.* Findhorm: Findhorn Press.	✓			✓	✓
Woolley. T. *et al.* (1997 / 2000). *The Green Building Handbook Vol. I & II.* London: E&F Spon		✓	✓		
Woolley. T. (2006). *Natural Building. A guide to Materials and Techniques.* Marlborogh, UK: Crowood Press.		✓		✓	

APPENDIX 4 – BUILDING ELEMENT LIFE EXPECTATION ANALYSIS (ORIGINAL RESEARCH ANALYSIS)

APPENDIX 4 IS RELATED TO SECTION 4.3.5 'REUSE IN THE CONTEXT OF CLC'

Appendix 4 includes an analytical study undertaken to inform the question regarding the relevance of reuse to the concept of closed loop material cycles as discussed in Section 4.3.5.

As discussed in the main text an issue fundamental to this question is the potential life of buildings and building elements and the relation of the two. There are different ways to characterise the life of a building and building element that include its life for insurance purposes, its service life (also known as the predicted life) and its economic life (that is related to fashion and other economic drivers). To understand the potential for reuse as a sustainable end-of-life disposal option, an analysis was undertaken of

- **selected building elements' potential life span and the reason for their obsolescence (economic or service life);**
- **typical building work related to these building elements; and**
- **their relation to the typical lifespan of different building types.**

Table A04 is a working progress document used to analyse and compare these building and building element characteristics and understand the priorities in terms of sustainable end-of-life treatment options and consequently the design approach to achieve that end-of-life solution. The design approaches considered include reuse and recycling as well as design for durability.

The analysis concludes that most building elements should be designed for recycling and composting as well as reuse and only very long life building elements (such as the main structural elements of long life building types) should be designed for durability and recycling. The results of Table A04 are summarised in the main text in Tables 33 and 34.

Table A04 - **Building element life expectation analysis table.**

Key:
[1] (Sassi, 2000).
[2] (British Standards Institution, 1992).
[3] (Duffy and Henney, 1989).
[4] (Yates, 2003).

Notes: Maximum potential life of generic building element as per BS 7543:1992
Temporary = Up to 10 yrs
Short life = 10-30 yrs
Medium life = 30-60 yrs
Normal life = 60-120 yrs
Long life = More than 120 yrs

Material / product	Insurance life i.e. guaranteed service life	Service life or economic life which ever is shorter according to Green Specification (Anderson *et al.*, 2002)	Listed for each building element - Replacement reasons including potential for premature end of service life Listed for each product - Relation between economic and service life assuming a maximum economic life E>S E<S E=S	Recommended design approach Design for: D=Durability RU= reuse RC= recycle C=compost
STRUCTURE AND ENVELOP			Structural alterations, conversions and extensions every 25 yrs [1] Housing refurbishments every 30-60 yrs[2] The 'Shell' 50 yr lifespan[3] High quality refurbishments public buildings every 60-120 yrs[2]	
Ground floors		Life of element = building life i.e. 10-120+	Structural material should be selected based on expected building life	
Ground floor Concrete joists to BS8110	35+	60	E=S	D + RC
Mild Steel for intermediate floors and stairs with min 1420g/msq post-galvanising	35+	60	E=S	D + RC
Mild Steel for intermediate floors and stairs with min 920g/msq post-galvanising	35	60	E=S	D + RC
Mild Steel for intermediate floors and stairs with min 600g/msq post-	30	60	E=S	D + RC

galvanising				
Mild Steel for intermediate floors and stairs with min 275g/msq post-galvanising	20	60	E=S	D + RC
Mild Steel for intermediate floors & stairs with less than 275g/msq post-galvanising	10	60	E=S	D + RC
Treated softwood intermediate floors and stairs	35+	60	E=S	D + RC
Untreated softwood intermediate floors and stairs	25	60	E=S	D + C
Boarding in floor constructions		Life of element = building life i.e. 10-120+	Structural material should be selected based on expected building life	
Portland cement particle board damp areas	30		E=S	RC
Fully protected chipboard to BSEN 312 damp areas	25		E=S	C
Unprotected wood chipboard damp areas	5		E=S	C
Marine ply to BS 1088 bonded with WPB adhesive to BS 6566 part 8 damp areas	35		E=S	C
Plywood to BS EN 636-3 for use in unprotected external conditions damp areas	30		E=S	C
Fully protected OSB to BSEN 300damp areas	20		E=S	C
External walls		Life of element = building life i.e. 10-120+	Certain facing bricks with a predicted service life of 60+ years may fail after 5-20 years due to saturation from rainwater and freeze thaw cycles.[2]	
Clay facing bricks	35+	60	E=S	D + RC
Stone and slate facing blocks	35+	60	E=S	D + RC
Concrete loadbearing blocks	35+	60	E=S	D + RC
Pre-batched and/or ready mixed sand and cement render to BS 5262 and BS 8000	35+	60	E=S	D + RC
Lime based render to BS 890	35		E>S	D + RC
Sand cement render to BS 5262	30	60	E>S	D + RC
Insulated render system lightweight polymer modified cementitious render on rigid foam or mineral fibre insulation	30	20(service life)	E>S	D + RC
Coping stones		Normal life		
Coping stones natural stone	30	[5] 60	E>S	RC
Coping stones concrete	35	[5] 60	E>S	RC
Coping system s/s	25	[5] 60	E>S	RC
Coping system mild steel	20	[5] 60	E>S	RC
Cladding		Life of element = building life i.e. 10-120+	Replacement of external non-structural elements every ca29 yrs[1] Organic coatings with a predicted life span of 30 years have failed in high temperatures after 5-15 years.[2]	Normal life

Timber boarding hardwood		40	E>S	RC
Timber boarding softwood treated	30	30	E>S	RC
Heartwood only untreated	25	30	E>S	RC
Softwood untreated	10		E>S	RC
Plywood timber boarding	25		E>S	RC
PVC-U to BS 7619	20	25	E>S	RC
External wall terracotta, concrete, clay tiles on battens		40yrs	E>S	RC
Fibre cement reinforced	25		E>S	RC
Precast concrete external wall cladding		40yrs	E>S	RC
Stainless steel	35+	40	E>S	RC
Mild steel hot dipped galvanised	25	25	E>S	RC
Aluminium to BS EN 755	30		E>S	RC
Sealants		Life of element = building life i.e. 10-120+	Sealants with a predicted service life of 20 years can fail prematurely. [2]	Short life
Joint sealants oil based, butyl or bitumen rubber external wall sealants	5		E>S	RC
External wall sealants acrylic	15		E>S	RC
External wall sealants two part polysulphide to BS 4254 and polyurethane and silicone to BS 5889	20		E>S	RC
Pre-compressed foam strips made of open celled expanded polymer foam impregnated with bitumen or neoprene and resin mix BBA and 3rd party certified	20		E>S	RC
Pre-compressed foam strips made from open celled expanded polymer foam impregnated with not BBA	15		E>S	RC
Timber frames, concrete and steel frames		Life of element = building life i.e. 10-120+		
Steel frames	35+		E=S	D + RC
Concrete frames	35+		E=S	D + RC
Timber frames treated	35+		E=S	D + RC
Timber frames untreated	20		E>S	D + RC
Sheathing wood chipboard to BS En 312	35		E>S	D + RC
Sheathing Marine ply	35+		E>S	D + RC
Sheathing OSB to BSEN 300	35		E>S	D + RC
Sheathing wood fibre to BSEN 622 bitumen impregnated	20		E>S	D + RC
Timber battens treated	35+		E>S	D + RC
Timber battens untreated	10		E>S	D + RC
Tanking asphalt		Life of element = building life i.e. 10-120+		
Tanking asphalt	35+		E=S	D + RC
Tanking single ply membrane self-adhesive	35		E>S	D + RC
Tanking single ply membrane non-adhesive	35		E>S	D + RC
Insulation		Life of element = building life i.e. 10-120+		
Insulation to studwork cellulose fibre	35+	60	E=S	D + RC
Insulation to studwork rigid rock fibre	35	60	E=S	D + RC
Roofing		Life of element = building life	Replacement of external non-structural	Long life / Normal life

		i.e. 10-120+	elements every ca29 yrs[1]	
Roofing tiles concrete/ clay / slates	35+	60	E=S	D + RC
Roofing tiles metal	25		E>S	D + RC
Roofing tiles resin based slates	30		E>S	D + RC
Roofing tiles fibre cement slates	25	30yrs	E>S	D + RC
Sheeting			Organic coatings with a predicted life span of 30 years have failed in high temperatures after 5-15 years.[2]	
Lead sheet roofing and stainless steel sheet roofing and stainless steel self-supporting covering	35+	40	E=S	D + RC
Zinc sheet roofing	30		E>S	D + RC
Aluminium self-supporting roofing	30	40	E>S	D + RC
Double skin with outer coated steel sheeting		25yrs	E>S	D + RC
Copper sheet roofing	35		E>S	D + RC
Fibre cement self-supporting roofing	25		E>S	D + RC
Flat roofs			Build up fibre based felt roof membranes with a predicted service life of 30 years have been now to fail after7-15 yrs [2]	
Cold roof timber structure with asphalt covering	20	25yrs	E>S	D + RC
Inverted roof with steel deck, concrete with asphalt covering	25	30yrs	E>S	D + RC
Warm roof with steel, timber or concrete deck with polyester reinforced bitumen felt	15	15yrs	E>S	D + RC
Warm roof with steel, timber or concrete deck with asphalt		25yrs	E>S	D + RC
Flat roof single ply membrane on timber cold roof	20	15yrs	E>S	D + RC
Rain systems		Life of element = building life i.e. 10-120+		
Rain systems plastic	25		E>S	RC
Rain systems metal aluminium polyester powder coated and cast iron	35+		E=S	RC
Rain systems galvanised steel	30		E>S	RC
SECONDARY ELEMENTS		Temporary /Short life / Medium life 10-60 yrs	Major commercial office refurbishment (every 20 yrs) [2] Replacement of external non-structural elements every ca29 yrs[1]	
External doors				
External doors timber	10-35		E=S	RC
External doors aluminium	10-35		E=S	RC
External doors PVC-U	15-25		E=>S	RC
External doors GRP	5-30		E=>S	RC

Windows			Sealed double glazed units with a predicted service life of 30 years can deteriorate after 5 [2]	
Glazing sealants gaskets and compounds to beads	10-15		E>S	RC
Windows hardwood	10-35	30	E=>S	RC
Windows softwood stained	10-35	25	E=>S	RC
Windows steel	15-35	30	E=>S	RC
Windows PVC-u	10-25		E=>S	RC
Windows aluminium and wood and aluminium composites	30-35	35	E=S	RC
Coated steel curtain walling		25yrs	E>S	RC
Metal curtain walling		25yrs	E>S	RC
Structural glazing		25yrs	E>S	RC
INTERNAL ELEMENTS AND FINISHES			Major commercial office refurbishment (every 20 yrs) [2]	
Internal partitions and ceilings and wall and ceiling finishes		Temporary /Short life / Medium life 10-60 yrs	Work to retail and bar and restaurants every 5 yrs[1] Cosmetic refurbishments every 5 yrs [4] Internal remodelling every 10 yrs[1]	
Wall and ceiling finishes		5yrs	E=<S	D + RU
Brick, blocks plastered partitions	35+	60yrs	E=<S	D + RU/RC
Plasterboard partition with timber or steel studs standard		15yrs	E=<S	D + RU
Demountable office partition		15	E=<S	D + RU
Frameless glass partition		30yrs	E=<S	D + RU
Glass blocks partitions		30yrs	E=<S	D + RU
Suspended grid ceilings		25yrs	E=<S	D + RU
Suspended plasterboard ceiling fixed direct to substrate		40yrs	E=<S	D + RU
Internal doors			Internal remodelling every 10 yrs[1]	
Internal doors flush doors	10-35		E=<S	D + RU
Internal timber panel doors	30-35		E=<S	D + RU
Floor finishes			Work to retail and bar and restaurants every 5 yrs [1] Cosmetic refurbishments every 5 yrs [4] Internal remodelling every 10 yrs[1]	
PVC sheets floor finishes to BS EN 649	10	10	E=<S	D + RU
PVC sheets floor finishes not to BS EN	5	10	E=>S	D + RC
Linoleum	10	15	E=<S	D + RU
Cork / synthetic rubber	10	10	E=<S	D + RU
Carpet various types	10	5	E=<S	D + RU
Unglazed Ceramic tiles or quarry tiles	30	30	E=<S	D + RU
Glazed ceramic tiles	20	20	E=<S	D + RU
Wood blocks	35+	20	E=<S	D + RU
Hardwood parquet	30	20	E=<S	D + RU

Softwood parquet	25	20	E=<S	D + RU
Kitchen units				
Kitchen base and wall units	5-30		E=<S	D + RU
Kitchen tops	5-20		E=<S	D + RU
SERVICES		Temporary /Short life / Medium life 10-60 yrs	Replacement of services 10-15 yr [1], [3] Major plant is replaced every 15-20-yr[4]	
Hot and cold service pipes copper/ stainless steel/ blue polyethylene	35+		E>S	D + RC
Hot and cold service pipes cross-linked polyethylene/ polybutylene /PVC	30-35		E>S	D + RC
Servicing values	25			
Mixer taps	15		E>S	D + RC
Radiators pressed steel	15-20		E>S	D + RC
Domestic boilers	5-15		E>S	D + RC
Hot water cylinders	25		E>S	D + RC
Unvented hot water storage cylinders	2—25		E>S	D + RC
Central boiler plant	15-25		E>S	D + RC
Central oiler plant pumps	5-20		E>S	D + RC
Fire detection and alarm	5-15		E>S	D + RC
cable	25-35		E>S	D + RC
Consumer units	25		E>S	D + RC
Sockets and outlet	20		E>S	D + RC
Extract fans	5-10		E>S	D + RC
Shower heads	5		E>S	D + RC
Light switches	10		E>S	D + RC
Heating programmers	10		E>S	D + RC
Convector heater, panel heaters and fan heaters	10-20		E>S	D + RC
Immersion heaters	10-15		E>S	D + RC
Circulation pumps	5-15		E>S	D + RC
Sanitary ware				
Sinks plastic	10-35		E=>S	D + RC
Stainless steel sinks	20-35		E=<S	D + RU
Vitreous China sinks	35		E=<S	D + RU
Cast iron baths and showers	35+		E=<S	D + RU
Shower trays other mats	5-20		E=>S	D + RC
WC cisterns plastic	5-15		E=>S	D + RC
WC vitreous china	15-25		E=<S	D + RU

APPENDIX 5 - CHARACTERISING DECONSTRUCTION, REUSE AND RECYCLING: SEMI-STRUCTURED INTERVIEWS WITH BUILDING DESIGNERS (PRIMARY RESEARCH DATA)

APPENDIX 5 IS RELATED TO SECTION 4.2 'WASTE MINING IN THE BUILDING INDUSTRY' AND THE RESEARCH METHOD USED IS OUTLINED IN SECTION 1.5.3

Appendix 5 includes summaries of ten semi-structured interviews undertaken with architects and designers interested or involved in designing buildings for recycling and with recycled and or reclaimed materials.

These interviews were part of an initial investigation aimed to gain an understanding of the views of building industry designers in relation to design for deconstruction and reuse and recycling and the use of recycled and reused building elements. The interviewees were selected as a result of a questionnaire detailed in the methodology Section 1.5.3.

The interviewees discussed issues relating to technical aspects of reuse, recycling and design for deconstruction as well as economic and procedural aspects, including barriers and examples of good practice. The information gained from the interviews informed the considerations made in sections 4.2.1-4.2.3 regarding the current practice and the advantages and barriers to designing buildings for CLMC.

The semi-structured interviews

The focus of the interviews varied according to the experience and interests of the interviewees, but generally followed the structure in Table A05. The main relevant points are summarised in the following pages.

Table A05 – **Outline structure for semi-structured interview**

1. Background of practice **2.** Type of work / client Typical contract sum Size of practice View of sustainability **3. Designing for disassembly and recycling** **4.** Views on principles Need for recycling? (e.g. sustainability) Benefits of recycling other than sustainable ones?	**5. EG of designing for dismantling and recycling** Selection process? What other specification options? Reasons for final selection? Aesthetics (rate 1-5) Performance (rate 1-5) Cost (rate 1-5) User requirement (rate 1-5) Construction requirement (rate 1-5) Did dfr satisfy the requirements set? Aesthetics (rate 1-5) Cost (rate 1-5) Performance (rate 1-5), User requirement (rate 1-5) Construction system (rate 1-5) Problems? Aesthetics (rate 1-5) Performance (rate 1-5) Cost (rate 1-5) User requirement (rate 1-5) Construction requirement (rate 1-5) Technical experience (rate 1-5)	**6. What to consider technically when designing for dismantling and recycling** Guidance for dfr (wanted – not wanted)? **7. Examples of where designing for dismantling and recycling could be beneficial** Where would you suggest the use of dismantling designs? **8. Barriers to designing for recycling** Client / cost / technical? **9. Case study building where elements were designed for dismantling and recycling** Details: location / Client / Date of completion / Design team / Contract sum Contribution of designs for recycling to project (rate 1-5) Problems with designs for recycling? Client and user views?

INTERVIEW 1

Name of interviewee – Gil Shalom

Company and location – Mark Stewart Architects, Nottingham

Description of occupation – Architect in small practice (4 architects), primarily small scale residential, historic and community developments

Main relevant experience

GS is interested in sustainable design and has been involved in promoting sustainable good practice. He regards recycling as an important part of a sustainable strategy. Recyclability can bring flexibility of use and a longer life to the building (extensions possible). However he considers designing a whole building for recycling a challenge as it is not in line with current mainstream building practice. Certain building systems do now already lend themselves to being disassembled and reused e.g. timber or steel frames or bricks with lime mortar.

GS has been involved in a number of residential refurbishments where he was able to introduce recycled materials. GS also advocates the use of good quality materials, because from his experience these could be reused indefinitely in the future. Good quality bricks, stone elements, timber sections of aesthetic as well as performance quality have a resale value.

Cost is the biggest barrier to reusing materials and designing for reuse and recycling. E.g. screwing instead of nailing costs more. The cost barrier applies to designing for recycling, but also for most sustainable design as well. From GS's experience clients have little interest in environmental issues and even less in recycling issues.

INTERVIEW 2

Name of interviewee – Chris Morgan

Company and location – Gaia Architects, Edinburgh

Description of occupation – Architect in small practice, primarily small scale residential or community developments

Main relevant experience

Gaia Architects have many years of experience in ecological design and have always been interested in saving resources. As a result they have been interested in designing to minimise waste, both on site through recycling and through designing to ensure efficient use of materials.

The Glencoe Visitor centre is the first building where they were able to fully apply their ideas of designing to enable later reuse and recycling. The visitor centre is the best example in the UK of this design approach.

The experience Gaia Architects have had on this project highlighted the following issues.

- The whole building is essentially designed for disassembly. There are always grey areas, but all the timber structure is bolted or screwed. Architraves are screwed and they're visible, they're just countersunk screws, they are not plugged there is not wood glue, not nailed no secret nailed. The only thing that is not recyclable is the external render which was installed for aesthetics.
- Gaia Architects developed a new flooring detail, but otherwise all technology used is existing.
- The builders did not find the building process problematic. They were consulted throughout the building process and considered part of the design team.
- Designing for recycling should be applied to building elements that are likely to be worn down quickly as a priority.
- There are advantages in designing for recycling in relation to facilitating the building process and its commissioning.

- One barrier they encountered was the request for warranties, many environmental materials do not have adequate warranties.
- It was also felt there was a cultural barrier to repairing things in the current consumer society. Also many products such as sandwich panels are virtually impossible to repair.
- High value products are more likely to be reused.

In respect of maintenance CM considers that almost always maintenance-free things aren't really (maintenance-free). And also as they tend to go against nature's natural processes they tend to be ungreen and tend to be rather expensive. So Gaia Arch. pushed for the idea that you do a little bit of maintenance and you do it every year and you keep it regular and that way you can use natural materials and products and just keep an eye on the building and while that sounds like it would be more maintenance, it will probably be less in the long run and it means that everything can be natural.

Gaia Architects were also involved in designing some life time homes where they additional lintels, plumbing and facilities for lifts have been installed. However these still rely on traditional building methods (i.e. plaster) as finishing materials.

INTERVIEW 3

Name of interviewee – Rosi Fielden

Company / location – The Simon Group, Lincoln

Description of occupation – Architect in large practice specialised in commercial retail work

Main relevant experience:

RF has specialist experience in retail design, ranging from high quality retail shops to large budget chains.

The retail industry is dictated by cost, in particular due to the relatively high turnover of installations. Storage of fittings is not usual due to storage costs. The second imperative in the design of retail installations is time, again linked to cost. The longer a premise is left unoccupied the higher the loss of revenue.

Design methods are therefore largely selected for their speed of installation and cost. However, the industry has a number of reusable fitout systems (see case study), which are universally used and sometimes reused.

In terms of incentives to push recycling and, particularly relevant to the retail sector, reuse, RF suggested the Landfill Tax is too low to have an impact, especially when compared to storage costs. In a financially driven environment the cost of disposal has to rise before alternatives are taken up.

INTERVIEW 4

Name of interviewee – Eric Reynolds
Company / location – Urban Space Management, London
Description of occupation – Developer

Main relevant experience

As a client with experience of working with architects, Eric Reynolds was able to highlight some of the problems he experience in relation to building designers. He feels his agenda of creating affordable, reusable and preferably recycled units is sometimes overlooked by architects in preference of aesthetic considerations, whereby these appear influenced by conservative and timid (with reference to planners) thinking. He further felt that there is a lack of understanding of building and construction processes among some architects that prevents a system like his to become fully and optimally developed. He believes some architects find it difficult to derive a design from the construction and to provide construction information. These low cost construction systems are aimed at the creative society on low incomes (a third container fitted out as an office is £5000 and was relocated already three times) and cost and construction efficiency is paramount.

He confirmed in his capacity as one who rents out space for conferences and events that the overriding thinking among designers, project managers and users of such facilities is one of a throw away society. The idea of salvaging material used for as little as a couple of days does not enter their thinking. Also there are no effective financial measures that encourage salvaging materials. The systems he sells and rents out have been relocated on numerous occasions for reuse by relocating the whole unit in one element. Dismantling of the different elements of one unit is too expensive, but recycling (possible due to construction in one material only) has happened and is cost effective. The systems he has used in the past include precast concrete garage structures, lorries, tents and timber buildings in addition to the container structures.

Considering the issues of designing for flexibility ER believes creating flexible structures by increasing the number of, for examples, socket outlets, hidden lintels in walls and the like increases cost. Other ways to create flexible structures should be sought.

INTERVIEW 5

Name of interviewee – Peter Joel
Company / location – RGP Architects, Leicester
Description of occupation – Architects, medium sized practice (22 architects) undertaking medium to large mainly residential architectural work for Housing Associations, also some community work.

Main relevant experience
The practice work is good example of an average commercial practice very much driven by client requirements. While individuals in the practice have an interest in environmental issues, cost remains a major driver for all projects. Designing for recycling is seen as increasing cost and is therefore not possible on most projects.

The practice has shown initiative in suggesting flexible designs that would enable the recycling or reuse of products at the end of the building life on the Damtry School project (12 classrooms). This project included environmental strategies as part of the brief, which were translated into a timber framed construction. PJ highlighted a number of barriers experienced in respect of designing environmentally and for recycling. These include

- the absence of warranties on new materials,
- client scepticism in respect of untested and unusual materials,
- lack of choice from manufacturers.

Even when in principle the building design is detailed to enable future dismantling and recycling, the construction process can result in a change of detail as PJ experienced on a Design and Build Contract where the contractor substituted the recyclable detail with a non-recyclable one. PJ also reported on personal experience of the inability to reuse suspended ceiling tiles, a theoretically reusable material.

INTERVIEW 6

Name of interviewee – Peter Sanders
Company / location – Levitt Bernstein, London
Description of occupation – Architects, medium to large architectural work

Main relevant experience

The main relevant experience of the practice is in refurbishing exiting buildings, in particular housing. The practice also has been involved in such projects as the Manchester Royal Exchange, where they inserted the new freestanding theatre in the old structure, and dismantleable and recyclable design methods were used.

PS's main experience in reuse and recycling is with Victorian buildings, which were thought to lend themselves to be refurbished and effectively recycled. The bricks in lime mortar allow for the reconfiguration of walls. The internal lath walls are lightweight and easily removed (if not recycled). The structural setup often allows for internal reconfiguration, which enable the buildings to have a long multi-use life.

A point of interest which was discussed was one of scale of building components. Bricks are used and reused because they can be reclaimed, but also because they do not restrict the design of the new building they are to be used in. As opposed to wall panels or windows that if reused, will dictate the design. If modular elements are to be used they have to be sized to allow for flexibility in the design. It is rarely possible and desirable that large building element can be reused in a new building, while small ones can. The disadvantage of small units is that they are more time consuming to install and in particular to remove without damaging them.

The ideal in principle is a system such as that of toilet cubicles, which is relatively standardised, but made of large units and are installed and removed quickly. The disadvantage and challenge for such products is to make them aesthetically appealing.

INTERVIEW 7

Name of interviewee – Morag Tait

Company / location – Alford Hall Monaghan Morris, London

Description of occupation – Architect in medium sized practice with varied size and types of projects

Main relevant experience

Designing the relocatable housing units for Peobody trust a number of issues have emerged as significant.

Design challenges:

Designing the services for the prefabricated and reusable units was found to be the main design problem. Linking the services from one floor to another has meant that each container layout has to have a service duct in the centre of the container. The connection of the services would have to happen on site, connecting the services from one unit to another requires enough tolerance. Access to the services should be made as easy as possible and the design makes that possible by having a utility cupboard with access to the main service connections through the cupboard back wall.

Long term maintenance was also considered. Reusable designs aim to have a long life and therefore have to be able to be maintained in the future. Specially fabricated building components need to be avoided on the basis that future maintenance should be feasible using the components of a variety of manufacturers. This would ensure replacement components would be easily available and not overpriced. Using existing technology was therefore seen as an important aim.

The same thinking applies to the possibility of upgrading the unit. The premise for the unit is that it can be relocated elsewhere at a later time. Current thinking is that when the units were relocated they would be regarded as a new building having to comply with current building regulation of the time. This is likely to involve higher levels of insulation and possibly other issues affecting the fabric of the units. In this case it is important to be able to upgrade the building fabric, which is in fact possible. Whether or not relocated units, it may in future be necessary for any refurbishments work to include the upgrading of the building fabric to comply with new regulations as in now happening with boiler replacements.

Barriers identified

The main barrier to producing more buildings that can be relocated was felt to be the lack of interest on the clients' side. The initial feasibility study done for Peabody Trust and Hackney Council is now complete, but Peabody is not pushing forward the idea. AHMM is continuing with the project with the shipping container manufacturer and constructing a prototype, which they hope will illustrate the advantages to housing associations and local authorities. This second phase of work is speculative.

Benefits and advantages identified

It was felt that the relocatable concept addresses the many issues of the Egan agenda. Construction time on site is brought down to an absolute minimum. This is thought to improve the overall speed of construction in future. It also improves the construction process for the neighbourhood by reducing time, disruption, noise, dust and other construction related nuisances.

Work happens inside the factory with improved working conditions and health and safety for workers. The simplicity and reduced work on site also reduces risk to the site operatives.

INTERVIEW 8

Name of interviewee – Chris Hay

Company / location – Lincoln University, Lincoln

Description of occupation – Client representative for new building work

Main relevant experience:

As a client representative with an understanding of architecture CH was open and encouraging of innovative and ecological design, however had to keep in mind the limited budget for the project.

The main point of interest was that the issue that dictated the approach to designing for reuse and recycling was the need to have a temporary building as an investment that the university could own and use on a number of sites.

Environmental good practice was of interest as was good design practice, but the push for designing for recycling came primarily from the economic and practical rather than the environmental strategies.

INTERVIEW 9

Name of interviewee – Robert Webb

Company / location – Robert Webb Architects, London

Description of occupation – Architect

Main relevant experience:

RW was indirectly involved in a project for relocatable housing in London, which resulted from the temporary availability of land. He thought this concept of temporary availability was a good example of the sort of drivers that are effective in pushing specific technologies forward.

INTERVIEW 10

Name of interviewee – Ian McKay

Company / location – BMM Sustainable design, London

Description of occupation – Architect, small to medium work

Main relevant experience:

IM pointed out that there are many historic examples of reuse. Kent barns constructed as timber frames were designed on a module (4/6/8 ft) , which meant that elements could be reused from one building to another. The elements were mechanically fixed and oversized, which allowed for multiple types of uses. Consequently IM promotes the concept of materials and building components that are in set modules. This enable elements to be interchanged and reused if integrated in a building using the same module. To some degree this happens today e.g. bricks, but should be extended. IM expressed concern about today's volumetric which might be out of date and not have replaceable parts in 20 years time.

IM reported the idea that recycling materials such as plastics can justify and promote an industry that is in essence not sustainable. He suggests recyclability is often greenwash. The main driver for recycling he thought was environmental (resource saving) and not other social or economic issues. IM considers that there are too few financial incentive and too little political will to promote sustainable construction and in particular recyclable technologies. Clients lack interest and architects need legislation on their side. However he considers that it is still necessary to change the mindsets of architects as well as clients. In fact, he thought, many architects were ignorant of the issues associated with recycling. IM also thought there is definitively a need to address the supply chain to ensure manufacturers are supplying dismantleable and recyclable materials. IM thought designing for recycling was probably going to be restrictive.

APPENDIX 6 - CHARACTERISING DECONSTRUCTION, REUSE AND RECYCLING: BUILDING CASE STUDIES (PRIMARY AND SECONDARY RESEARCH DATA)

APPENDIX 6 IS RELATED TO SECTION 4.2 'WASTE MINING IN THE BUILDING INDUSTRY' AND THE RESEARCH METHOD USED IS OUTLINED IN SECTION 1.5.3

Appendix 6 includes descriptions of eighteen buildings studied in relation to their potential for being dismantled and the components reused or recycled. Eight of the case studies are were undertaken as a desktop study and ten case studies involved building visits.

All buildings selected for the study illustrate different aspects associated with designing for recycling, ranging from technical issues to economic issues. The building outlines that follow include brief descriptions of the buildings studied and highlight the main aspects relevant to the dissertation.

Table A06 - **List of buildings studied in relation to design for deconstruction, reuse and recycling**

1. Relocatable housing project
2. Container city
3. Walter Segal housing
4. Elm Street Lane house
5. Glencoe visitors' centre
6. The Geoffrey Museum of English domestic interiors
7. Romeny Marsh visitor centre
8. Great Binfields primary school
9. Centre for excellence in the built environment
10. Offices
11. and 12. Two demountable exhibition building
13. Temporary sports buildings
14. Foundation administration building - Eden
15. Heath care buildings
16. and 17. Retail buildings
18. Heathrow Terminal Three

1- RELOCATABLE HOUSING PROJECT

London

Client: Peabody trust

Architect: Alford Hall Monaghan Morris

Project background – a new trend

There are a number of temporarily available housing sites in London (in particular possibly elsewhere as well). These may be sites

- owned by the council that have been earmarked for other uses, which are however are not going to be implemented in the immediate future;
- or sites that the council may have a leasehold on with an outstanding, which however is too short for a non-temporary building construction

There may be space on existing council housing estates that can be used for temporary housing while the estate undergoes a refurbishment programme, which could span a ten year period.

Temporary housing may be a less expensive and more appropriate solution for housing council family tenants in bed and breakfast accommodation and asylum seekers.

Two architectural practices have been addressing this new scenario by designing housing that can be relocated when necessary.

PCKO is the second architectural practice involved in designing relocatable housing.

Their design is made using prefabrication technology and manufactured in Poland. The housing is designed to be positioned on a temporarily available site and is currently being manufactured.

Design principles:

The proposed design encompasses three interchangeable modules of identical dimensions dictated by typical prefabricated volumetric constraints of transport. Each module can be linked to another module to produce a variety of housing types.

- One module contains a living room and central kitchen area dining room,
- a second unit contains two bedrooms with a central bathroom and the possibility of a corridor
- and the third unit contains two bedrooms with two central bathrooms which can be designed to be accessed from different sides of the unit from different units.

Each unit has four positions for openings on the long side of the unit to accommodate doors where required. The pod includes a private balcony on one side and a deck access on the other side. The feel of the units is meant to seem homely in a modern, holiday home like way making the future users feel comfortable without replicating their original home.

Construction:

The project was sent to tender to a shipping container fabricator, a traditional volumetric manufacturer and an innovative volumetric manufacturer. The shipping container manufacturer won the tender and further developed the design of the container.

The current design makes use of the typical container construction that consists of a welded steel frame with profiled metal panels fixed to the sides giving it stability. The short ends are open and make up the balconies and open walkways of the design. The crucial element of the system is the jointing element. This occurs at the four corners of the container and consists of a cast steel block. Two containers are fixed by connecting two blocks together. This is done by inserting a jointing element in the blocks and locking it in place.

Timber framed panels pre-fabricated with installed windows and doors will make up the short ends of the containers. Internally the containers will be lined with insulation and finishing elements. The finishing materials are presently envisaged to be timber. Finishes in wet areas are also envisaged as timber with a waterproof sheet bent around the corner of the bath to provide a water-proof, but flexible finish. The flexibility is necessary in order to make sure that the finishes are not damaged in transit where the frame is expected to flex enough to crack junctions between finishes or in a rigid finish such as tiling. The internal and non-steel elements are still to be designed

Each individual container is weather tight, which means that they can be finished with all elements including internal and external finishes. The only on-site activity remaining is the connection of the services.

The containers will be supported on pre-cast, preferably removable foundations, the type depending on the ground condition. A container located centrally in a block of flats will be used as a services distribution centre, thus minimising the services run in the ground.

2 - CONTAINER CITY

Buoy Wharf, East London
London, UK
Client and developer: Urban Space Management
Completed: 2003

Urban Space Management, headed by Eric Reynolds, has been providing reusable and recyclable units as housing, shops and workshops at very low cost, made from 'recycled' containers used to ship products from China to the UK and disposed of in the UK.

The principle is simplicity. All connections are in steel thus creating a basic structure in one material, which can easily be recycled. Finishes are bolted onto a subframe in timber. Windows are cut into the profiled steel 'skin' in circular shapes to maintain the structural strength of the profiled steel. The containers are generally stacked with the corners coinciding as these are the main structural elements of the system, but also have been arranged in more adventurous ways creating bridges and the like and in these cases additional framing is needed.

The aesthetics of the system is unusual and not what is normally accepted. The target population for this system is that of creative people with low income who need workshop space as well as living space and cost effective solutions are a priority above the aesthetics. These systems may prove difficult to introduce in urban and conservative environments.

3 - WALTER SEGAL HOUSING

Architect: Walter Segal/ Architype

Walter Segal developed a building system which addressed a number of issues. The system was a post and beam timber frame calculated and based on modular dimensions to avoid waste and to facilitate alterations and enlargements. The system aimed to minimise 'wet trades' of concreting, bricklaying and plastering, by reducing the sheer weight of the building and by using cladding, insulating and lining materials in their standard sizes. The system allowed the buildings to be erected entirely by hand. By building in this way Segal believed the system would enable untrained people to build their own high quality homes to meet their housing needs.

Hedgehog housing, Brighton

Internal finishing panels divided and fixed through timebr tirms creating the distinctive Segal aesthetics

The principles relevant to this study are the way this system of building enabled easy maintenance and provided scope for extension or alteration.

The Segal building system has been adopted and developed by architects such as Architype (see examples on the right hand side) and is promoted by The Walter Segal Self Build Trust.

Self build house

Design features that enable reuse and recycling

- A post and beam timber structure with bolted fixings can be disassembled and equally allows internal flexibly of use.

- The infill panels are standard panel widths (1200mm) using a 600mm structural grid. The panels are fixed with screws over timber trims. This allows the panels to be removed and replaced with other structure e.g. window or building extension.

- All finishes can be designed to be mechanically fixed (carpet, timber floor, wall panels)

Testing the system for dismantleability and recyclability

Mary Kelly is an architect, self-builder and supports The Walter Segal Self Build Trust. She has been involved in the dismantling of a number of Segal original buildings, which she reports has been without problems. The reclaimed timber and building boards were mainly reused on new buildings without difficulty.

Disadvantages of system

- Aesthetically the panelling system is unusual and not accepted by many.

- Current building requirements for airtightness require additional work not fully compatible with the Segal simplicity.

4 - ELM STREET LANE HOUSE

Cardiff, Wales, UK

Architect: Sassi Chamberlain Architects

The Elm Street Lane housing is the development of two one bedroom flats in the city centre of Cardiff. This development aims to address issues of housing affordability and resource efficiency, including material resources, energy and water.

The development is designed to be as affordable as possible by reducing building costs and running costs. Building costs are reduced by designing a compact building that makes efficient use of space and using easily buildable technologies. Running costs are reduced by providing a zero heating building, making use of solar thermal panels to provide hot water and recycling rainwater to reduce the need for mains water.

Street elevation

Garden elevation

Internal panelling

The building also aims to reduce the need for building resources, in particular primary virgin resources, and reduce the production of waste throughout the building process and the potential for waste at the end of the building's life. To achieve this aim the building is being designed to include the maximum amount of recycled and reclaimed materials. It is also designed to be dismantleable and will only include materials that can be reused and recycled or composted.

<u>Designing for maximum recycled and reclaimed content and for closed loop material cycle</u>

The building will make use of some well established building technologies and some more innovative systems. The specification which is currently being developed includes the following elements listed below and identified as being reclaimed, recycled, downcycled, dismantleable, reusable, recyclable, compostable and downcyclable.

- Sub-base – hardcore (downcycled / recyclable)
- Concrete foundations and ground floor slab (recycled aggregate / downcyclable)
- DPM and DPC (recycled / dismantleable, recyclable)
- Masonite timber frame (recycled / dismantleable, reusable, compostable)
- Cellulose insulation (recycled / dismantleable, reusable, compostable)
- Timber cladding (reclaimed or locally resourced / dismantleable, reusable, compostable)
- Roof slates (recycled / dismantleable, reusable, downcyclable)
- Render panels (recycled / dismantleable, reusable)
- External timber doors and windows (locally resourced / dismantleable, reusable, compostable)
- Internal doors (recycled / dismantleable, reusable, compostable)
- Ironmongery stainless steel (recycled / dismantleable, recyclable)
- Timber stairs and partition studs (reclaimed or locally resourced / dismantleable, reusable, compostable)
- Floor finishes rubber (recycled / dismantleable, recyclable)
- Sanitary ware stainless steel (recycled / dismantleable, recyclable)
- Sanitary ware ceramic (reusable)
- Wall finishes timber (reclaimed or locally resourced / dismantleable, reusable, compostable)
- Wall finishes plastic (recycled / dismantleable, downcyclable)
- Wall finishes plaster panels (reusable)
- Service pipes (dismantleable, reusable, recyclable)

5 - GLENCOE VISITORS' CENTRE

National Trust of Scottish Visitors' Centre
Glencoe, Scotland, UK

Client: National Trust of Scottish
Architect: Gaia Architects
Landscape architect: Gaia Architects
Quantity Surveyor: Ralph Ogg & Partners
Main Contractor: R.J. McLeod
Completed: 2002


The timber sections of the covered entrance area are bolted or screwed to facilitate their dismantling

In 1994 Gaia Architects were commissioned by the National Trust of Scotland to design a new visitor centre for their site in Glencoe, the site of the massacre of the MacDonald clan. Following a consultation period with the local community and the Trust itself and a lengthy search for funding, the construction of the new centre started in 2000 and was completed in 2002.


View of the external wall and roof timber boarding

The Trust wanted the building to be 'green' and the brief was therefore developed by the architects to cover sustainability issues regarding the site, resources, energy and health.


View of the village-like grain of the visitor centre

Under the heading of 'resources' Gaia Architects considered the use of materials and focused on the principle that the most effective way to reduce the use of materials is to maximise the life of the building. This aim was pursued by following the principle of building in layers, a concept put forward by Steward Brand in his book 'How buildings learn'. Brand promotes a layered

construction where each layer is designed to be as independent as possible providing both flexibility and the ability to upgrade or modify the exposed layers.

The theory of building in layers was put into practice at Glencoe by designing the structural frame, the services and the finishes as distinct elements with minimal interconnections. A timber portal frame was chosen and designed to be structurally independent from internal partitions. This produced a flexible internal layout, where internal partitions could be repositioned without affecting the structural frame, thus facilitating future changes to the internal layout and use. The frame is built as a breather wall construction with a waterproof layer externally fixed to a processed timber board, insulation between framing elements and a board internally and constitutes both the essential structural and weather-protecting layer of the building. The external cladding and the internal finishes are two layers independent from the main structural frame, which can be maintained, upgraded and altered without affecting the frame. To enable the various layers to be accessed all fixings are generally bolted or screwed and adhesives are avoided all together. This enables elements to be removed without damage. The dismantled elements can then be reused elsewhere or if reuse is impossible, allows them to be recycled.

SUSTAINABLE DESIGN FEATURES

Site and Ecology
The existing building was demolished and recycled and the new building located on the site of an old caravan park was designed to nestle in the landscape. The original site was returned to natural use, an existing culverted stream was reopened and native planting reintroduced.

Community and Culture
The design involved a community consultation. The materials used are mainly local both in character and production, thus supporting the regional economy.

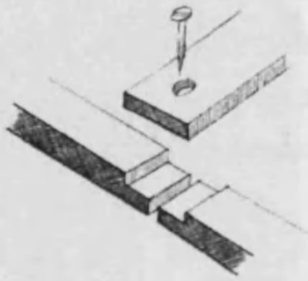
Health
The timber was not treated, avoiding preservative and relying on appropriate detailing and the correct choice of durable timber for each purpose. Polyvinylchloride (PVC) was not used and glues associated with volatile organic compounds off gassing kept to a minimum.

Materials
The timber specified was a local grown Scottish timber.

Energy
The building structure has a U-value of approximately 0.14 W/m²K and was detailed to be air tight. The heating is supplied by a woodchip boiler making the development including the caravan site carbon neutral.

Water
Water is supplied to the building from a spring fed reservoir. The water is not chlorinated but treated with silver copper ionisation. The sewage system, which is linked to the camp site, was upgrade to return clean water to the River Coe. Low flush toilets, aerating taps and other water saving approaches were included.

Fixings are generally left exposed to facilitate their access. Speed of disassembly not only facilitates the dismantling of a building, it makes dismantling more economically viable and facilitates maintenance reducing maintenance time and therefore costs. Due to cost constraints the external timber cladding is nailed rather screwed, this concession was made taking into account the requirement for removing the cladding will mainly arise when the timber has deteriorated and can at best be recycled, but not reused. The cladding is fixed with only two nails per board, this allows the timber to move, but also reduces the number of fixings and potential contaminants should the timber be recycled.



Timber floor showing the cover strip screwed to the subfloor with exposed fixings

Timber screwed skirtings

View from the covered entrance area towards the museum and viewing platform

The layering approach has also been used for the services. Between the frame and the internal finishes are service voids located in the floors, walls and ceiling housing the electrical wiring and heating pipes. The voids are easily accessed through skirtings and a specially detailed flooring system (below), which again relies on exposed fixings. The flooring system, which involved rebating each floor board and locating a fixing trim between two rebated edges, already proved its worth during the fit-out contract which involved repositioning services.

In order to maximise the potential for recycling, materials were specified without coatings and finishes where appropriate and composite materials were avoided. Timber was used rather then chipboard and mill finished aluminium rather than coated steel.

A few areas of the building remain traditionally inflexible and not dismantleable. The rendered exterior finish and the tiling to the wet areas are traditional single use finishes. But also the plasterboard internal finish, while it is screwed with taped joints would prove difficult to disassemble and the boards are notoriously impossible to reuse. Solutions to these culturally sensitive finishes are still in their infancy. Perhaps, in this primarily timber building, a timber boarding with exposed fixings as an internal finish could have made this building virtually 100% recyclable.

6 - THE GEOFFREY MUSEUM OF ENGLISH DOMESTIC INTERIORS

East London, UK

Completed: 2003

The Geoffrey Museum of English Domestic Interiors in East London has made use of reclaimed strength grade pitch pine timber beams that were originally installed in a maltings in Suffolk in 1720. All timber connections are bolted enabling the timber to be reused in future. The timber is already nearly three hundred years old and its life is further extended.

The reuse of timber is particularly common where the timber quality is good and the timber can be exposed an influence the aesthetics of the building.

Examples of traditional pegged timber joints

Site and Ecology

The museum is set in an existing building, the former almshouses of the Ironmonger Company, and therefore makes use of the existing structure and site.

Community and Culture

The almshouses of the Ironmonger Company built in 1714 are Grade 1 listed (London Borough of Hackney). The reuse of the building ensures the retention of cultural heritage, which contributes to a sustainable community.

Materials

The use of reclaimed materials such as the pitch pine beams supplied by Victorian Wood Works reduce the impact of virgin material resourcing.

7 - ROMNEY MARSH VISITOR CENTRE

Dungeness, Kent, UK

Architect: BBM Sustainable Design

Contractor: Eco-librium Solutions

Completed: 2003

The visitor centre is constructed with barley straw bales infill walls within a bolted timber frame. Straw bales structures are generally disassembleable, but this depends on the external finish used. In this case minimal use of cement or glues was made in the construction so as to avoid composite constructions that would prove difficult to disassemble. Lime render was used on the exterior of the bales and applied on a Hessian fixed to the bales, which can be removed should it be required and the straw bales can be composted. The timber frame elements were mechanically joint allowing for future dismantling. The straw also proved repairable where small areas were rotting they were simply cut out and replaced.

The same methods of construction was used by the architects for a temporary pavilion at the Glastonbury festival in 2004. Straw and hazel was used to build a round structure. At the end of the festival the timber and straw structure was disassembled very quickly.

<u>Site and Ecology</u>

The materials used (timber and straw) link the building to its surroundings. The roof has a sedum cover.

<u>Materials</u>

Use of locally sourced materials, such as chestnut for the timber frame and straw for the wall in fill material, aggregate from only 5km away from resurfacing work to the M20.

Standard size materials such as 250x50mm timber rafters reduced waste

<u>Energy</u>

Straw bales are relatively good insulants.

8 - GREAT BINFIELDS PRIMARY SCHOOL

Basingstoke, UK

Architect: Hampshire County Council Architects

Completed: 2003

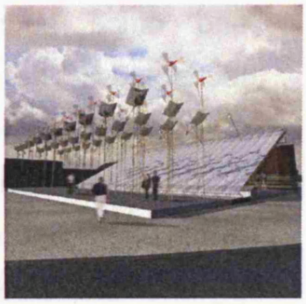
Great Binfields Primary School is one of Hampshire's most environmentally friendly schools and has been designed to enable the reuse of building materials in particular bricks. The building envelope has been constructed using a Parallel Strand Lumber structural frame with brick cladding externally laid in hydraulic lime mortar with no cement content. The use of lime rather than cement will enable the reuse of the bricks at a later date.

9 - CENTRE FOR EXCELLENCE IN THE BUILT ENVIRONMENT

Hull, UK

Architect: Niall McLaughlin

Client: Lincoln University



Site and Ecology

Temporary use of a site

Community and culture

The scheme involved a community consultation.

Materials

The prefabricated pods and building elements are design ed for reuse.

Energy

One of the pods houses a woodchip boiler that should burn local woodchip.

Outside the building is a 'thicket' of small photovoltaic panels and wind turbines.

The Centre in Hull is one of the buildings of the National Architectural Centres Network. With a budget of approximately £550,000 it is mainly funded by Yorkshire Forward out of their Social Regeneration Budget. The centre has an educational focus and school children are expected to be the main users, learning about the environment and architecture. Adults are also expected to use the centre.

The building is to be located on a site that is only available for three years, virtually for free. The building will remain the property of the university and it will be dismantled and re-elected on a new site after three years.

The construction system used is that of a caravan design, which is locally available. The local caravan manufacturers are supplying the windows to the development.

Images: Niall McLaughlin

The demountable/ reusable features include

- Pads rather than foundations (no ground penetration)
- Prefabricated floor cassettes which incorporate underfloor heating

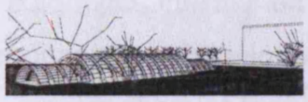
- Prefabricated toilet, kitchen and plantroom and office pods made using caravan technology. The pods are transported by trailing them on wheels on their side. They are then turned on their back and joined at the top with a truss. The pods are made of ply and fibreboard faced with other material, while faced boards can not be recycled, in this case they are designed for reuse.

10 - OFFICE BUILDINGS

Traditional office design uses numerous dismantleable and reusable systems such a suspended ceilings, raised floors and relocatable partitions.

The challenge is to create an office design that not only is includes a flexible and recyclable internal layout, but also includes a reusable or recyclable structure.

11 and 12 - DEMOUNTABLE EXHIBITION BUILDING



Exhibition design often involves demountable technology. Metal structural elements are common for concert structures and lightweight fair stands. Two examples of temporary structures in timber are illustrated below.

PROJECT FOR DEMOUNTABLE ECOLOGICAL EXHIBITION STRUCTURE

Architect: Robert Webb Architects

WRA has been involved in sustainable design for some years and as part of their involvement in the field developed a design for a low energy demountable exhibition hall to exhibit energy efficiency and ecological products.

THE HOUSES OF PARLIAMENTS TEMPORARY TICKET OFFICE

Architect: Pringle Richards Sharratt Architects

The Houses of Parliaments temporary ticket office is to be used between July and October and is then put in storage for eight months while the parliament is not open to visitors.

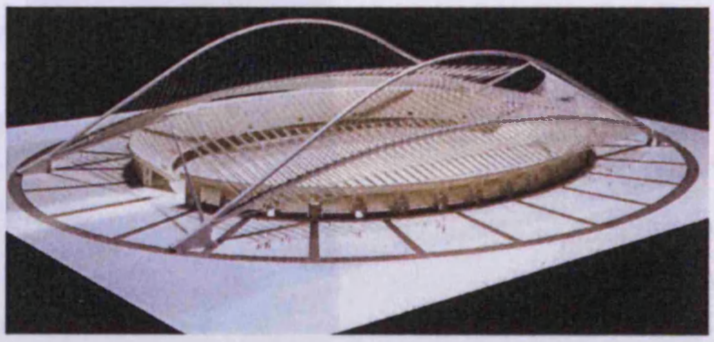
The ticket office is a laminated timber structure with steel bolted connections and a textile roofing material.

13 - TEMPORARY SPORTS BUILDING PROPOSALS

The current Olympics games have triggered a couple of suggestions for dismantleable and reusable stadiums.

Lifschutz Davidson proposed a demountable stadium for the 2004 Olympics and designer James Burland (the designer for the City of Manchester Stadium) proposed a temporary stadium for the 2012 Olympics, should the games be taking place in London.

Lifschutz Davidson's concept was promoted on the basis of the speed of construction typical for temporary structures. The James Burland's proposal was promoted on the basis that a temporary structure could be re-elected where the facility is most needed after the Olympic event.



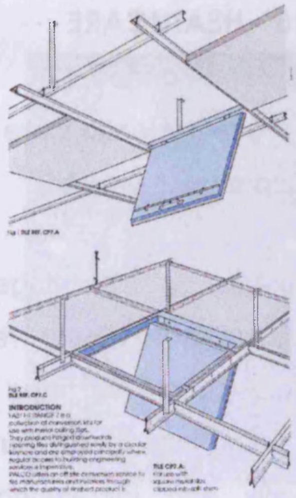
14 - FOUNDATION ADMINISTRATION BUILDING - EDEN

St. Austell , Cornwall, UK

Architect: Grimshaw Architects

Client: Eden Project

Completed: 2003



Michael Pawlyn and David Kirkland of Grimshaw Architects were involved in designing the new Foundation Building at the Eden Project housing the administration department. In an interview with BD David Kirkland suggested the whole building (structure and fit-out) could be easily dismantled and virtually everything reused, however unfortunately the architects were not available for an interview.

The structure is a laminated timber structure that enables a flexible fit-out of the space inside and should accommodate changes in the future. The timber can be reused or recycled.

The cellulose insulation used in the wall construction can be reused or biodegraded at the end of the building's life. Aluminium roofing was selected for its recyclability.

15 - HEATHCARE

Greater London, UK

Architect: Health Care Buildings

Completed: varies

Health care buildings including hospital wards and nursing homes require flexibility of services and space. Designing for flexibility of space is still incompatible with building traditional plastered walls and increasingly dismantleable partition systems are used.

Flexibility of services is provided by surface mounted trunking which allows for the distribution of electrical, gas and IT technology throughout. It also allows for the repositioning of outlet positions and can be changed without creating disruption to the running of the facilities.

Other products used in places where operations need to be continuous are quick release floor finish films that enable the floor finishes, generally carpet or flexible rubberised finish, to be removed and relaid quickly so that such changes can take place out of hours.

16 AND 17 - RETAIL

London, UK

Architect: varies

Completed: varies

The retail sector is one of the construction sectors that has the highest turnover of internal fitouts. Retail displays are changed as frequently as every few years and retail refurbishments can potentially result in high levels of waste production, of which most is likely to be sent to landfill.

The high frequency of refurbishments is only one of the retail sectors typical requirements. Retail outlets also reconfigure their shop layouts several times in the time period between refurbishments to accommodate changes in stock. This reconfiguration work has to take place quickly and with the least disruption to the retail activities that will generally continue while this minor work takes place. To address this need a number of retail display systems have be developed, which make the installation of a fitout and its reconfiguration or disassembly easy and quick to undertake.

These display systems often allow the shell of the building untouched. They often consist of a frame and panel system, whereby the panel can support the display elements as well as simply act as an aesthetic lining sheet. The panels cover the walls of the shell, thus reducing the need to

decorate the actually structure of the building. These systems can be used in a range of different retail outlets ranging from the low cost to the sophisticated outlet, by varying the layout and the choice of finishes.

These systems could be reused until they become damaged and in many cases the retail merchandise covers most of the display panel making minor blemishes irrelevant. Once disassembled the system can be stored 'flat packed' and requires relatively little storage space. The inherent dismantleability of the systems, couples with the speed of erection and the ability to store in a compact manner contributes to giving a long life to the system.

Health

The use of dismantleable retail display and fitout systems has a positive impact on the health and safety of building operatives using these systems. The use of dry construction reduces the risk of air pollutants from applied surface treatments. For the installers this helps create a better working environment. Similarly only a limited amount of cutting material on site is required as most building elements are standard sizes and mainly minor adjustments are generally needed.

Certain retail outlets have developed their own display system, which they adapt for different uses. The same basic system can be transformed in terms of finish and display elements to accommodate different merchandise. The system is designed to be used for a decade or more and it can be envisaged that it would be maintained, repairing and replacing elements as required.

The one area of improvement that could be developed further is the constitution of the panel elements. Currently many panels are made of composite materials, for example melamine on chipboard. This makes the recycling of the panels impossible. A change of material to, for example solid timber, MDF painted, metal or other solid non-composite material would reduce the waste produced which can only go to landfill.

18 - HEATHROW TERMINAL THREE

Heathrow London, UK

Architect: D.Y.Davies Architects

Completed: 1989

Large transport buildings, like airport terminals, need to accommodate a substantial amount of services and also need to have flexible spaces that can accommodate changes of use. Terminal three is designed with large areas of exposed services which can be easily accessed, upgraded, maintained or reconfigured. Other areas make use of suspended ceilings to provide the same access, with some visual screening.

In just over ten years the terminal is hard to recognise, having undergone numerous changes in all areas of the terminal, while still in operation. The flexibility and accessibility is essential for this.

APPENDIX 7 - CHARACTERISING DECONSTRUCTION, REUSE AND RECYCLING: INTERIM RESULTS (INTERIM RESULTS OF ORIGINAL RESEARCH)

APPENDIX 7 IS RELATED TO SECTION 4.2 'WASTE MINING IN THE BUILDING INDUSTRY' AND APPENDICES 5 AND 6 THE RESEARCH METHOD USED IS OUTLINED IN SECTION 1.5.3

Appendix 7 reports on the main results relating to the technical and practical aspects of designing deconstruction, reuse and recycling. This early research had not yet considered introducing the concept of recycling through natural processes and only considers recycling through industrial processes. The research was undertaken as part of a wider investigation into the economic and social benefits of designing buildings for deconstruction, reuse and recycling. The complete results of the complete study are contained in the 'Final report to the RIBA Research Trust on the Environmental, social and economic benefits of recyclable technologies' (Sassi, 2004a).

The content of this Appendix 7 informed the deliberations in sections 4.2.1-4.2.3 regarding the current practice and the advantages and barriers to designing buildings for CLMC.

The extracts from 'Final report to the RIBA Research Trust on the Environmental, social and economic benefits of recyclable technologies' (Sassi, 2004a) included here attempt to answer the following questions:

- **Are recyclable building technologies currently available?**
- **What are the barriers to the use of recyclable materials and components?**

The results contributed to the deliberations in section 4.2 'Waste mining in the building industry'.

ARE RECYCLABLE BUILDING TECHNOLOGIES CURRENTLY AVAILABLE?

The study identified three different categories of building elements and materials.

- Recyclable and reusable materials and components.
- Materials and components with recycling and reuse potential.
- Materials and components with minimal or no reuse and recycling potential.

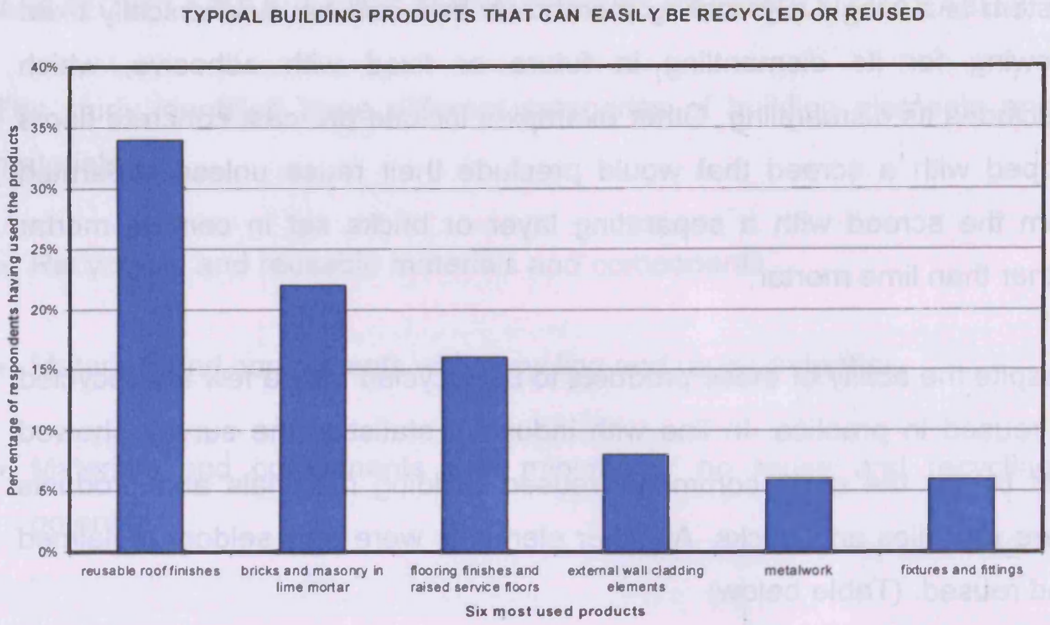
RECYCLABLE AND REUSABLE MATERIALS AND COMPONENTS

The first category includes a substantial number of building elements and materials that can be reused or recycled and are currently available to the construction industry. Recyclable materials include metals, concrete recycled into aggregate and certain types of plastics. Reusable components range from bricks and cladding panels to pre-cast foundations and timber structural elements. Materials have to be reasonably free of contamination to be recycled and building components have to remain intact to be reused and the appropriate building specification is crucial to achieve this. A framed building structure, be it concrete, steel or timber, can be detailed to enable its recycling or reuse: a timber structure can be reused; a steel structure can be reused or recycled; a concrete structure can be recycled or downcycled to hardcore. These are commonly used building systems which can be designed for reuse or recycling without changing the typical specification. Other such building elements include: masonry walls set in lime mortar, beam and block floors, suspended pre-cast foundations, rainscreen cladding systems, roofing tiles and sheeting systems. In certain cases it may be necessary to adopt a particular installation specification option rather than another to ensure the system is easily dismantleable and recyclable in future. An example of such as system is a single ply roofing membrane that can be mechanically fixed allowing for its dismantling in future or fixed with adhesive, which precludes its dismantling. Other examples include pre-cast concrete floors topped with a screed that would preclude their reuse unless separated from the screed with a separating layer or bricks set in cement mortar rather than lime mortar.

Despite the ability of these products to be recycled only a few are recycled or reused in practice. In line with industrial statistics the survey showed that by far the most commonly reused building materials and products were roof tiles and bricks. All other elements were only seldom reclaimed and reused. (Table below)

MATERIALS AND COMPONENTS WITH RECYCLING AND REUSE POTENTIAL

A second category of building elements and materials was highlighted as having potential for being made easily dismantleable and recyclable through changes to the standard specification. An example of such a building element is acoustic flooring, the tongue and grooved edges of which are normally joined with adhesives, but which could be made dismantleable by replacing the adhesive with a limited number of mechanically joined straps. This option is more time consuming to install, but the end product performs as the original specification, as was tested on one of the writer's built projects. Another example is rubber flooring which is generally fixed with adhesive, but could be loose laid in domestic situations allowing for its dismantling and recycling at a later date.

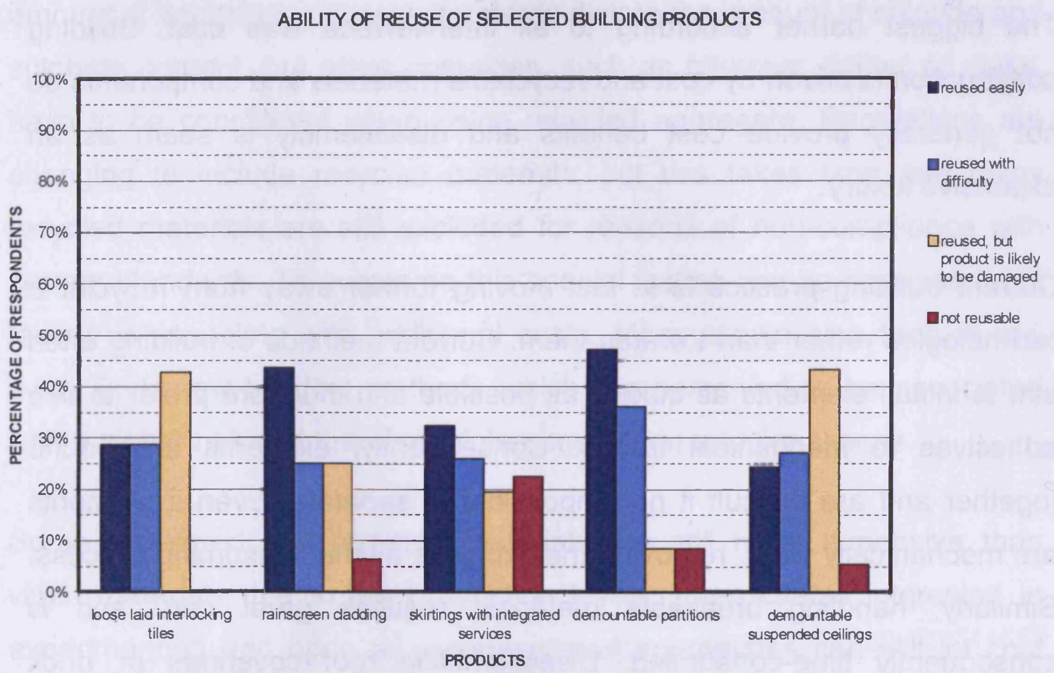


MATERIALS AND COMPONENTS WITH MINIMAL OR NO REUSE AND RECYCLING POTENTIAL

The third category includes building elements and materials which are impossible to reuse or recycle. To this category belong such building elements as applied finishes, both internal and external, including: renders, plasters, tiling and applied roofing finishes. Certain composite constructions, such as concrete walls cast in situ using insulation as sacrificial shuttering, are also impossible to reuse and recycle due to the contamination of the materials. A complete change of product design is required to make these building elements recyclable.

REUSABLE COMPONENTS FALLING SHORT OF EXPECTATION

What was not evident from the product survey, but became apparent as a result of the questionnaire responses was that some of the products designed for reuse were falling short of expectations. Building designers were asked about the feasibility of reusing specific building systems that were designed for reuse. Some of these products appeared not to perform well. Suspended ceilings, for example, were considered to be difficult, even impossible, to reuse due to their likelihood of being damaged in the process of dismantling and reinstalling (Table below).



WHAT ARE THE BARRIERS TO THE USE OF RECYCLABLE MATERIALS AND COMPONENTS?

The research identified three main barriers to expanding the use of recyclable materials and components: cost, awareness and technology.

COST

The biggest barrier according to all interviewees was cost. Building construction is driven by cost and recyclable materials and components do not generally provide cost benefits and disassembly is seem as an expensive luxury.

Current building practice is in fact moving further away from recyclable technologies rather than towards them. Current methods of building often aim to install elements as quickly as possible and therefore prefer to use adhesives to mechanical fixings. Consequently, elements are bound together and are difficult if not impossible to separate. Even if elements are mechanically fixed, removing the fixings is a time consuming process. Similarly, handling breakable materials requires great care and is consequently time-consuming. Disassembling roof coverings or brick walls, for example, requires careful manhandling each element to separate it from the rest and then bringing it to a safe store. Similar cost problems can be experienced with hazardous materials. Treated timber, when reprocessed can produce dust particles containing toxins, especially if treated with materials such as pentachlorophenol or c-benzene hexachloride. It may appear less hazardous and less problematic and therefore less costly to landfill the material than to reuse it. There are also costs associated with storage of reclaimed materials for reuse. Storage can be distant from the site and transport is associated with additional cost.

Designing for recycling and the use of recycled and reused materials go hand in hand. If recycled and reclaimed materials are not purchased, in other words if there is no market for them, no one will want dismantle buildings to supply them. Designing for dismantling would not have any outlet. The use of recycled and reclaimed materials has to be part of a strategy to supports designing for recycling and reduce waste. However the use of recycled and reused materials can have some drawbacks.

Recycled materials might not comply with current legislation. Concrete aggregate, for example, has to comply with standards regulating the amount of impurities. Current standards dictate the amount of chloride and sulphate content, but other impurities, such as bitumen, timber or glass, have to be considered when using recycled aggregate. Regulations are changing to include recycled materials, but this takes time and many recycled materials are still excluded for reasons of non-compliance with current standards. To overcome this special testing can be organised, but testing is associate with additional costs. Many clients also tend to shy away from new building methods which are perceived to be associated with a higher risk and therefore higher costs than traditional ones.

Some reclaimed and recycled materials are still more expensive than virgin materials due to low production levels. Even clients interested in experimenting and open to unconventional approaches can still let cost drive the decision-making and might exclude recycled and reused materials for this reason.

AWARENESS

The cost issues are aggravated by a lack of awareness among designers and clients of the nature and availability of recyclable materials and components including those associated with no additional cost. The benefits of recyclable materials are also not generally recognised.

TECHNOLOGY

While many commonly used materials and products can be reused or recycled, others remain impossible to reuse or recycle. Some components designed for reuse in practice perform less than satisfactorily. Building materials and components that present particular technological challenges include building finishes as well as the increasing number of composite materials.

APPENDIX 8 – DESIGN FOR DECONSTRUCTION, REUSE, RECYCLING AND DOWNCYCLING ANALYSIS OF BUILDING ELEMENTS (ORIGINAL RESEARCH ANALYSIS RESULTS)

APPENDIX 8 IS RELATED TO SECTION 4.2 'WASTE MINING IN THE BUILDING INDUSTRY'

Appendix 8 represents the results from a desk-top review of building products which aimed to establish whether the current building market offers the industry materials and building products that would enable buildings to be built so that they could be deconstructed and reused, recycled or downcycled at a later date.

The review was undertaken through a systematic analysis of manufacturers' product literature and was structured on the National Building Specification categories. The products' specifications and in particular their installation recommendations and material characteristics were considered.

The construction methods were rated using a set of criteria developed as part of a research project investigating the end of life options for materials and products (Sassi, 2002). The following spread sheets are designed to highlight the construction options available to designers and specifiers that are interested in designing buildings to enable the reuse or recycling of materials and building elements. Some examples of building products that can be found in the UK building market have been included to illustrate the generic principles discussed, and are not the only examples of building materials and products possessing the characteristics discussed.

This review contributed to the deliberations in section 4.2 'Waste mining in the building industry' in identifying technical barriers and solutions to designing for closed loop material cycles.

Table A07 - **Analysis of building elements for suitability to deconstruct, reuse, recycle and downcycle**

SECTION D GROUND-WORKS	Product and manufacturer's details	Ability to be disassembled, reused, recycled, downcycled YY=yes, easily YH= yes, with high work input N=no U=unknown V-varies according to product	Relevant system features	Non-disassemblea ble / reusable / recyclable alternatives	Issues to consider	Advantages of reusable/ recyclable option	Frequency of use / examples of reuse / recycling
Foundations	Product: pre-cast piles Main use: all types of buildings Manufacturer: Roger Bullivant www.roger-bullivant.co.uk	Reuse as new – YY Reuse 2nd hand – YY Recycling – YY Downcycle – YY	Precast concrete piles are hammered into the ground and often left insitu even after the building has been demolished.	Trench / strip foundations are virtually impossible to dig out and recycle.	Reusing or recycling pipes is unusual due to the difficulties of removing them and the lack of disadvantages of leaving them in the ground. However, if removed they would be able to be reused, subject to their integrity, or recycled to create aggregate for new piles or downcycled into hardcore. Note BRE is currently compiling information on the use of recycled aggregate, including case studies. Numerous case studies are already available on www.aggregain.org.uk	Installation is very fast and is less weather dependent and therefore economic There are no or less spoils to be removed from site. Ground works are often carried out in poor working conditions, therefore minimising this activity is desirable in terms of improving the work environment.	Common use Reuse uncommon Recycling uncommon
	Product: pre-cast ground beams Main use: all types of buildings Manufacturer: Roger Bullivant www.roger-bullivant.co.uk	Reuse as new – YY Reuse 2nd hand – YY Recycling – YY Downcycle – YY	Precast concrete piles and ground beam to take any type of floor	Trench / strip foundations are virtually impossible to dig out and recycle.	In order to reuse ground beams the sizes available have to be taken into account. The ability to recycle into new precast elements rather than downcycle into hardcore depends on the screening of the crushed concrete and the removal of metal and other contaminants.	As above	Common use Reuse uncommon Recycling common
Retaining walls	Product: Plastic Sheet piling Main use: bank retention schemes Manufacturer: HL Plastic Extrusions	Reuse as new – YY Reuse 2nd hand – YY Recycling – U Downcycle – YY	Installation system similar in principle to other materials	Metal sheets will rust over time making their reuse impossible. Timber will rot. Concrete retaining structures are more difficult to disassemble.	The product is made of recycled plastic. It is inert and has a long life and good potential for reuse. It is a synthetic material therefore in permanent landscaping developments natural materials are an appropriate alternative.	The product is light to transport and handle reducing health and safety risk on site. It is cheaper than steel and concrete.	Relatively new product

SECTION E CONCRETE	Product and manufacturer's details	Ability to be disassembled, reused, recycled, downcycled YY=yes, easily YH= yes, with high work input N=no U=unknown V-varies according to product	Relevant system features	Non-disassembleable / reusable / recyclable alternatives	Issues to consider	Advantages of reusable/ recyclable option	Frequency of use / examples of reuse / recycling
FORMWORK FOR IN SITU CONCRETE	Product: Reusable steel formwork	Reuse as new – YY Reuse 2nd hand – YY Recycling – YY Downcycle – NA	System designed to be reused.	Timber formwork can generally only be recycled for lower grade applications	All metal is easily recycled. Contaminants should be kept to a minimum, but do not preclude recycling.	There is a financial advantage of reusing formwork for structures with a high number of replicated elements.	Common use Common reuse Common recycling
PRECAST/ COMPOSITE CONCRETE FLOORS/ ROOF DECKS	Product: beam and block floors and precast concrete planks with dry finish Main use: suspended ground floors and upper floors Manufacturer: Marshalls (concrete and EPS Jetfloors) Termodeck (precast concrete hollow core slabs) termodeck@tarmac.co.uk	Reuse as new – YY Reuse 2nd hand – YY Recycling – YY Downcycle – YY	Precast concrete floors with a dry finish can be installed to avoid a screed bonded directly to the precast elements by installing a floating screed or by using an alternative (timber) finish.	Beam and block floors with a directly applied screed finish may be recycled, but are not reusable. Systems with insulating and concrete elements with a bonded screed cannot be reused and are difficult to recycle. In situ concrete floors can be recycled, but not reused.	The joints between planks are generally sealed with a cement mix, which makes the reuse of the planks difficult. Consider replacing the cement mix with compressible fillers.	Precast floors are quicker to install than insitu concrete floors and the installation is less weather dependant. Beam and block floors can enable late decisions in terms of services penetrations through floors.	Common use. Reuse and recycling increasing.

SECTION F MASONRY	Product and manufacturer's details	Ability to be disassembled, reused, recycled, downcycled YY=yes, easily YH= yes, with high work input N=no U=unknown V-varies according to product	Relevant system features	Non-disassembleable / reusable / recyclable alternatives	Issues to consider	Advantages of reusable/ recyclable option	Frequency of use / examples of reuse / recycling
BRICK/ BLOCK WALLING	Product: bricks laid in lime mortar Main use: walls	Reuse as new – YY Reuse 2nd hand – YY Recycling – N Downcycle – YY	Brick walls with lime mortar. Lime mortar is softer than the bricks themselves and will break in preference to the brick. Lime mortar is also reasonably easy to clean off.	Brick and block walls with cement mortar. Cement mortar is often stronger than the bricks and when an attempt to separate these is made there is a high risk of the brick breaking. Also the cement is difficult to remove from the brick making the cleaning of the bricks difficult.	Lime mortar takes longer to set and will require frost protection. Bricklayers experienced in using lime mortar are now the exception. Careful selection of a contractor will be required. (Gil Shalom) The same principle is valid for other types of masonry laid in mortar.	Bricks and mortar are inert, but bulky materials, therefore their disposal mixed with other materials will be expensive. If disposed as clean inert material the disposal costs are very much reduced. There is a thriving market for reclaimed bricks in particular those with character. Alterations to the building would be marginally easier to undertake as new openings in brickwork joined with lime mortar are easier to make. The use of reclaimed bricks can help make a building more acceptable to planners in certain cases. Disassembly, as opposed to demolition, of the brick walls would involve additional labour, thus providing work opportunities.	Common use, reuse and downcycling as hardcore. 1 - Groundworks headquarters in Jarrow, near Newcastle 2 - Gil Shalom building in Nottinghamshire
PRECAST CONCRETE SILLS/LINTELS /COPINGS/ FEATURES	Main use: masonry walls	Reuse as new – YH Reuse 2nd hand – YY Recycling – V Downcycle – YY	Concrete and stone sills set in lime mortar (as above)	Sills set in cement mortar (as above)	Sills relate to opening sizes and their reuse is therefore limited in design terms.	Quality products are more likely to the reused (Gil Shalom). By specifying a quality stone sill set in lime mortar there is an immediate advantage of benefiting from a quality product and an economic advantage at the demolition stage when the sill will have a resale value.	Use common, Reuse and recycling uncommon. E.g. of reuse at Gil Shalom's building in Nottinghamshire
PRECAST CONCRETE	Product: wall panels Main use: warehouses / storage applications Manufacturer: ACP Concrete	Reuse as new – YY Reuse 2nd hand – YY Recycling – YY Downcycle – YY	Wall panels are set within a frame to create a low quality wall. The panels are restrained and not fixed in any way.	In-situ concrete walls	The system does not provide thermal insulation or an airtight construction. Low grade uses only.	Very flexible system within a framed structure, layouts can be changed with minimal effort (subject to the availability of mechanical lifting equipment)	Use common Reuse common
GLASS BLOCK WALLING	Main use: internal and external walls Product: polystar Manufacturer: Rockwell Sheet Sales www.rockwellsheet.com	Reuse as new – YY Reuse 2nd hand – YY Recycling – YY Downcycle – YY	Interlocking polycarbonate blocks with clip fixings	Glass blocks set in mortar are liable to break when dismantled.	Aesthetics, durability and u-values have to be assessed for each particular use.	The system is very light therefore easy to handle and improving working conditions. Also mortar is not required and its abrasive characteristics avoided.	

SECTION G STRUCTURAL	Product and manufacturer's details	Ability to be disassembled, reused, recycled, downcycled YY=yes, easily YH= yes, with high work input N=no U=unknown V-varies according to product	Relevant system features	Non-disassembleable / reusable / recyclable alternatives	Issues to consider	Advantages of reusable/ recyclable option	Frequency of use / examples of reuse / recycling
STRUCTURAL STEEL FRAMING	Main use: building frames Product: steel	Reuse as new – YY Reuse 2nd hand – YY Recycling – YY Downcycle – YY	Steel beams and columns Steel framing bolted can be unbolted and reused	Welded steel sections are more difficult to reuse, but not impossible. These would have to be cut and appropriate plates welded on.	Sizes will limit the possible reuses. Fire protection has to be designed to be easily removed. Details of steel should be marked on steel section	Installation errors can be adjusted with limited disruption.	Use- common Reuse – uncommon Recycling - common Bed Zed reused steel beams and columns from nearby project.
TIMBER FRAMING	Product: Laminated timber Main use: wall and roof structures Manufacturer: Glulam	Reuse as new – YH Reuse 2nd hand – YY Recycling – N Downcycle – YY	Joints are bolted and easily dismantled	Welded steel or concrete frames are more difficult to recycle and difficult if not impossible to reuse	Glulam structures are extremely versatile in terms of use and are generally bolted in place making them easy to disassemble Reuse is limited by design constraints and only downcycling is possible		Use – common Reuse – seldom
	Product: reclaimed timber beams/ columns Main use: wall and roof structures	Reuse as new – YH Reuse 2nd hand – YY Recycling – N Downcycle – YY	All connections are bolted and easily dismantled	As above	Old timber beams often were fixed with pegs and can be disassembled or if necessary cut beyond the junction points. TRADA can assess the structural quality of old timber beams to allow their reuse	Old timbers are often thought to have character and enhance the aesthetics of a space	Use – common Reuse – common The Geffrye Museum of English Domestic Interiors in East London has made use of reused pitch pine structural beams
Timber floor structures	Main use: floors Product: solid timber. Composite beams or similar	Reuse as new – YY Reuse 2nd hand – YY Recycling – N Downcycle – YY	Any type of timber joists can easily be reused if fixed on joist hangers rather than set within the wall construction	By setting the joist within the wall construction, the disassembly of the floor is hampered, but not made impossible	Treated timber should be worked with care as treatment toxins can become volatile as a result of the working. Treated timber sections can be reused	Floor structures are generally not visible therefore reused material with potential aesthetic flaws is acceptable. There is therefore a potential long term cost benefit of having a material in the building that can be resold at the end of the building's life. Also any changes to the floor structure are more easily undertaken (a timber set in the wall structure being more difficult to remove than a joist hanger)	Use – common

SECTION H CLADDING / COVERING	Product and manufacturer's details	Ability to be disassembled, reused, recycled, downcycled YY=yes, easily YH= yes, with high work input N=no U=unknown V-varies according to product	Relevant system features	Non-disassembleable / reusable / recyclable alternatives	Issues to consider	Advantages of reusable/ recyclable option	Frequency of use / examples of reuse / recycling
CURTAIN WALLING	Main use: external walls Product: metal box section systems Manufacturer: varies	Reuse as new – YH Reuse 2nd hand – YY Recycling – YH Downcycle – YH	Infill panels are fixed within the metal box sections with rubber gaskets	Mastic bonded glass can not be reused and the separation of the building elements to enable recycling is time consuming and difficult	The gaskets should be easily removable in order to facilitate the recycling of the metal sections. When reusing elements the dimensions of the elements to be reused will have to be considered when designing.	Maintenance is greatly facilitated as well as the potential for upgrading the glass elements with improvements in technologies.	Common use
STRUCTURAL GLASS ASSEMBLIES	Main use: wall / roofs Product: varies	Reuse as new – YH Reuse 2nd hand – YH Recycling – YH Downcycle – YH	Glass elements are connected with spider connectors. The joints between the glass elements are sealed with mastic	Systems with extensive use of mastic are more difficult and time consuming to disassemble.	When reusing elements the dimensions of the elements to be reused will have to be considered when designing.	Maintenance is facilitated	Common use
TIMBER WEATHERBOARDING	Main use: external walls Product: screw fixed boarding	Reuse as new – YH Reuse 2nd hand – YY Recycling – N Downcycle – YY	The timber boarding is fixed with screws to the substructure	Nailed and secrete nailed boards are difficult to remove intact and reused	The choice of fixing material will affect the durability of the installation. Timber can not be recycled (implying into an equivalent product), but can be downcycled and made into a board material e.g. chipboard Timber also has a calorific value and can be burnt and it also decomposes over time. However in both these case care should be taken if the timber has been treated, as some treatment material can leach out into nature and are toxic.	Maintenance is facilitated	Common use
RIGID SHEET CLADDING (PLY, PLASTICS ETC)	Main use :external walls Product: cladding fixed with exposed fasteners Manufacturer: SFS Stadler www.sfs-online.com/construction	Reuse as new – YH Reuse 2nd hand – YY Recycling – V Downcycle – V	Cladding with exposed fixings	Cladding bonded or fixed with hidden self-tapers or nails can not be dismantled easily without damage. Reuse is therefore difficult. Recycling may be possible depending on the material used	Visible fixings may be liable to corrosion and tampering. Fasteners with integrated covers will protect fixing and may be aesthetically more acceptable.	Maintenance and refurbishment work is facilitated. Installation is quick compared to wet finishes e.g. render	Common use
CLAY CLADDING	Main use :external walls Product: clay tiling Manufacturer: various	Reuse as new – YH Reuse 2nd hand – YY Recycling – N Downcycle – YY	Clay tiling elements fixed on steel or timber support system	Cladding bonded to substrate can not be reused or recycled		Maintenance and refurbishment work is facilitated.	Common use
METAL PROFILES/ FLAT SHEET CLADDING/ COVERING	Product: metal cladding panel system Main use: commercial external walls Manufacturer:	Reuse as new – YH Reuse 2nd hand – YY Recycling – YH Downcycle – NA	Metal composite panel with rockwool core. Fixings rely on panels overlapping over each	Composite panels with PIR/PUR are more difficult to recycle, the separation of plastic core from the metal	Rockwool and steel and aluminium can be recycled. Steel's magnetic qualities make the separation of steel from other materials efficient and cost-	The relatively large panels and the quick fixing method makes the installation and dismantling a quick process.	Common use

	Euroclad www.euroclad.com		other with minimal fixings.	external layer may result in contaminants in the metal	effective. Coated steel can be recycled by using the basic oxygen steel-making process. Steel coatings are now available in low VOC water based formulations. The rockwool core can be recycled for lower grade applications. The panels can also be reused, however the sizes of the panels will have to be taken into account when designing the new building.		
NATURAL STONE SLAB CLADDING/ FEATURES	Main use: external walls Product: cladding fixed with metal cramps	Reuse as new – YH Reuse 2nd hand – YH Recycling – N Downcycle – YY	Cladding fixed with metal cramp and open joints	Cladding fixed with adhesive			
PLAIN ROOF TILING ETC.	Main use: roofing Product: tiling on battens	Reuse as new – V Reuse 2nd hand – YY Recycling – YY Downcycle – YY	Tiles of various materials fixed with metal clips and or nails using dry ridge and eves details	Roof eves bedded in mortar can prove more difficult to dismantle than mechanically fixed tiles	Reusing and recycling roof tiles is very common	The use of dry details eliminates risk of mortar failure, mechanical fixings ensure reliable fixing against uplift. It may prove simpler to build and eliminates wet trades reducing costs, ridge line can incorporate ventilation This installation methods also facilitates replacement and repair, reduces maintenance UK produced tiles (clay and slate etc) make use of local labour through manufacturing process and mining.	Use common Reuse common Recycling common
	Main use: roofing Product: metal tile look-alike panels Manufacturer: Decra www.decra.co.uk	Reuse as new – YH Reuse 2nd hand – YY Recycling – YY Downcycle – NA	DEKRA metal clay tile look-alike panels fixed mechanically	Traditional tiling as above and with eves bedded in mortar.	Removing metal panels at roof level is often associated with damage to the panels and therefore recycling is a more realistic end of use solution. Panels can be laid at 10/15°	Larger elements with fewer fixings increase the speed of construction and amount of work at heights reducing risk to health and safety as well as cost. Panels are one seventh of the weight of concrete and therefore require reduced less costly roof structure and are well suited to refurbishments where additional floors are added to an existing building.	Use increasing
METAL SHEET COVERINGS/ FLASHINGS	Main use: roof covering Product: mechanically fixed roofing sheets	Reuse as new – YH Reuse 2nd hand – YY Recycling – YY Downcycle – NA	Metal sheet covering are fixed mechanically independently from insulation	Composite roofing panels are more work-intensive to recycle Tiled roofs are more time consuming to dismantle	Metal has a high waste value and is generally already recycled	Waste roofing material has a resale value.	Common use Common recycling Reuse not viable

SECTION J WATER-PROOFING	Product and manufacturer's details	Ability to be disassembled, reused, recycled, downcycled YY=yes, easily YH= yes, with high work input N=no U=unknown V-varies according to product	Relevant system features	Non-disassembleable / reusable / recyclable alternatives	Issues to consider	Advantages of reusable/ recyclable option	Frequency of use / examples of reuse / recycling
SINGLE LAYER POLYMERIC ROOF COVERING	Main use: flat roofing Product: single ply mechanically fixed membrane	Reuse as new – YY Reuse 2nd hand – YY Recycling – YY Downcycle – YY	Single ply membrane fixed mechanically	Single ply membrane fixed with adhesive, liquid applied finish,	Reused membranes would not have a guarantee. Mechanically fixed roofing membranes can be easily dismantled and potentially reused, however the reuse is limited to a similar design as the one dismantled or alternatively the membrane will have to be reworked to fit a new design. Recycling of membranes depends on the material of the membrane	Mechanical fixing avoids use of adhesives and the contact with volatile organic compounds.	Limited use Reuse unusual Recycling unusual
	Main use: roofs, canopies Product: proprietary Manufacturer: Fabric architecture www.fabricarchitecture.com Manufacturer: Tensarc www.tensarc.co.uk	Reuse as new – N Reuse 2nd hand – YY Recycling – YY Downcycle – YY	Tensile membrane fixed at perimeter and as necessary with mechanical fixings		Issues as for single ply membrane Aesthetics will affect the possibility of reuse of the membrane ETFE membranes installed in smaller unit sections may prove more flexible in terms of potential for reuse on a different project.	Maintenance, such as replacement of damaged sections is facilitated The replacement of the complete membrane can be undertaken quickly.	Use increasing ETFE installation at Kingsdale School designed to be reused

SECTION K LINING, SHEATHING, DRY PARTITIONING	Product and manufacturers details	Ability to be disassembled, reused, recycled, downcycled YY=yes, easily YH= yes, with high work input N=no U=unknown V-varies according to product	Relevant system features	Non-disassemblea ble / reusable / recyclable alternatives	Issues to consider	Advantages of reusable/ recyclable option	Frequency of use / examples of reuse / recycling
RIGID SHEET FLOORING /SHEATHING/ SARKING /LININGS/ CASINGS	Main use: floors Product: screw fixed sheathing	Reuse as new – YY Reuse 2nd hand – YY Recycling – YY Downcycle – YY	Standard sized panels fixed with mechanical fixings without adhesive to receive finish	Adhesive fixed		Maintenance is facilitated through providing easy access to under floor services etc.	Common use Common reuse Recycling limited
RIGID SHEET TIMBER/ WOOD & PLASTICS VENEERED PANELLING & LINING	Product: Neatmatch Main use: wall lining Manufacturer: Neat concepts www.neatconcepts.co.uk	Reuse as new – YH Reuse 2nd hand – YY Recycling – YY Downcycle – YY	MDF profiled boarding to line walls, edges are profiled.	Timber boarding fixed with adhesives. Plastered walls. Plasterboard walls screwed and covered	Aesthetics are distinct and not acceptable to all.	Installation is dry and a quick process. Access to services behind wall can be facilitated.	Limited
	Product: Parklex Main use: wall lining Manufacturer: Composites Gurea	Reuse as new – YH Reuse 2nd hand – YY Recycling – U Downcycle – YY	Rigid board finish fixed with secret mechanical fixings	Timber panelling bonded to substrate would preclude the reuse and often the recycling of timber boards as their removal would involve their damage.	Some damage to the panels can occur when removed, therefore careful manhandling is essential. Using the largest size of boards possible will maintain the maximum flexibility when the boards come to be reused. Also the larger the units to dismantle the quicker the process and the most cost-effective the reuse.	The ability to easily reposition wall panels facilitates the re-planning of spaces and the access to services for maintenance.	Commonly used
	Product: retail display wall panels Main use: retail Manufacturer: various	Reuse as new – YY Reuse 2nd hand – YY Recycling – V Downcycle – V	Display wall system consisting of a frame, panels and fixing systems	Display systems making use of the structural wall as part of their display	The ceiling is unaffected by the display wall and has to be considered.	In retail areas the displays are changed far in advance of the display systems becoming unusable, reuse of these systems is therefore financially beneficial. The ability to easily reposition wall panels facilitates the re-configuration of retail displays, spaces and service.	Commonly used
	Product: Marbex wall panels Main use: lining of bathroom, kitchen and other walls and ceilings Manufacturer: Swish Building Products	Reuse as new – YH Reuse 2nd hand – YY Recycling – U Downcycle – U	Rigid plastic veneered boards fixed with mechanical fixings and visible jointing strips	Ceramic tiling is not reusable or recyclable and is difficult to downcycle due to the grout contamination of the tiles, which can otherwise be considered inert masonry waste and can be used	Wall boards are room height and ceiling boards are 4m long, but the width is only 250mm therefore numerous joints will be visible Aesthetics of the boards are not what is often expected in rooms other than bathrooms Marbex achieve Class 1Y fire rating and conforms to the requirements of the Food Safety Act 1990 and General Hygiene Regulations 1995	Speed of installation – requires half the time of tiling Allows access to wall for maintenance	Commonly used
RELOCATABLE PARTITIONS	Product: office partitions Main use: commercial Manufacturer: varies	Reuse as new – YH Reuse 2nd hand – YY Recycling – YH Downcycle – V	System generally is made of a framing element and infill panels, including solid and glazed panels, generally fixed to the framing	Traditional partitions can be designed to be reusable, but in the main are not.	Most relocatable partitions are reusable and depending on the materials used recyclable Framing should be of one material (eg steel or aluminium not mixed) to enable the recycling of the system	Provides flexibility in commercial office and retail and other commercial spaces. Provides opportunities for customising spaces with different infill panels and upgrading spaces without having to change all fixtures.	Common use Common reuse Recycling unusual

			systems mechanically		The elements to be reused have to be sturdy enough to not suffer in terms of aesthetics and performance when dismantled. The fixings have to be designed to be easily unfixed and refixed and not wear out (note screw threads)		
MOVABLE PARTITIONS	Product: Movable partitions Main use: all types of buildings, but mainly to split large meeting rooms into move than one small room	Reuse as new – YH Reuse 2nd hand – YY Recycling – V Downcycle – V	The wall panels are fixed with door ironmongery and are designed to slide or fold out of the way. The screw fixings can easily be dismantled, however this is time-consuming	Movable partitions are by their nature likely to be easily dismantled, making it easy to reuse the wall panels, however whether these can be recycled will depend on whether they are composite boards or mainly made of one material	Acoustical movable partitions are available to provide good acoustic separation if required.	Movable partitions provide a flexible use of space, which can prove economically beneficial as a number of room requirements can be accommodated in one flexible space.	Common use
PLASTERBOARD FIXED PARTITIONS/ INNER WALLS / LININGS	Product: Multipanel Main use: internal walls Manufacturer: Grant Westfield www.grantwestfield.co.uk	Reuse as new – YH Reuse 2nd hand – YY Recycling – N Downcycle – N	Wall linings systems made with tongue and groove or square edge panels screwed on timber backing framework.	Plasterboard partitions (timber and metal) are very difficult to reclaim and recycle. Plasterboard is virtually impossible to reuse, even if screw fixed, once the edges are taped and jointed the screws become inaccessible and the time required to release a panel makes the reuse financially unfeasible.	Multipanels are composite panels therefore not recyclable, however the design of the system could be used to develop recyclable panels Aesthetically this product is unusual and could prove unacceptable to some.	Provides flexibility for internal layouts. Facilitates maintenance and access to services in walls.	limited use
GLASS BLOCK WALLING	Main use: internal walls Product: polystar Manufacturer: Rockwell Sheet Sales www.rockwellsheet.com	Reuse as new – YY Reuse 2nd hand – YY Recycling – YY Downcycle – YY	Interlocking polycarbonate blocks with clip fixings	Glass blocks set in mortar are liable to break when dismantled.	Aesthetics, durability and u-values have to be assessed for each particular use.	The system is very light therefore easy to handle and improving working conditions. Also mortar is not required and its abrasive characteristics avoided. Provides flexible interior layouts.	Limited use
FRAMED PANEL CUBICLE PARTITIONS	Main use: toilets and changing rooms Product: single material (e.g. steel, ply) partitions Manufacturer: various	Reuse as new – N Reuse 2nd hand – YY Recycling – V Downcycle – V	Cubicle partitions consisting of boards and mechanical connectors and / or frames	Many cubicle partitions are dismantleable and potentially reusable, but most are made with laminated composite boards which can not be recycled	Fixing types can affect the reusability of the system Metal blade slots into timber panel – this detail is likely to damage panel when removed Fixing elements (EG ironmongery) should not need to be unscrewed from the board when dismantled, but rather unclipped from a second counterpart fixing element. This avoids screw holes in the boards from becoming enlarged and unusable.	Flexibility of layout Replacement of damaged boards is made easy Metal partitions have waste value when no longer used	Limited use
SUSPENDED CEILINGS	Main use: commercial Product: metal suspended	Reuse as new – YH Reuse 2nd hand – YY Recycling – YY	Metal ceiling tiles set within a metal suspension	Composite (e.g. metal and acoustic material) tiles	Reuse is very simple, but colour variations might occur over time. Metal tiles may be	Suspended ceiling systems allow for internal layout flexibility as well as	Common use Reuse limited

	ceilings Manufacturer: various	Downcycle – NA	system	within suspension system	damaged (mainly dented and bent) while being dismantled	reconfiguration of services Facilitates the commissioning of services and their replacement and maintenance	
	Main use: commercial Product: acoustic suspended ceilings Manufacturer: various	Reuse as new – YH Reuse 2nd hand – YY Recycling – N Downcycle – N	Acoustic ceiling tiles loosely set within a metal suspension system	Composite (e.g. metal and acoustic material) tiles within suspension system	Acoustic tiles need to be resurfaced if they are to be reused in a commercial environment, and there are companies that undertake tile refurbishments. Acoustic tiles are fragile and easily damaged	As above	Common use Reuse limited
RAISED ACCESS FLOORS	Main use: commercial Product: solid HDF boards Manufacturer: various	Reuse as new – YY Reuse 2nd hand – YY Recycling – YY Downcycle – YY	HDF boards screw fixed or loose laid on metal pedestals	Composite boards made with plastic or metal facing on HDF or MDF can be reused, but not recycled	Compared to faced boards solid HDF may become worn more quickly	Enables provide a flexible layout Facilitates the commissioning of services and their replacement and maintenance	Common use Reuse limited

SECTION L WINDOW, DOORS, STAIRS	Product and manufacturer's details	Ability to be disassembled, reused, recycled, downcycled YY=yes, easily YH= yes, with high work input N=no U=unknown V-varies according to product	Relevant system features	Non-disassembleable / reusable / recyclable alternatives	Issues to consider	Advantages of reusable/ recyclable option	Frequency of use / examples of reuse / recycling
WINDOWS/ ROOFLIGHTS / SCREENS/ LOUVRES	Main use: general Product: solid material windows Manufacturer: various	Reuse as new – YH Reuse 2nd hand – YY Recycling – V Downcycle – V	Solid material e.g. timber, aluminium or steel windows screw fixed and sealed with compressible fillers	Timber windows with applied finishes such as PVC coatings or composite materials such as timber and steel make the recycling and repair of the windows difficult.	Windows in general have the potential to be reused as a building element and this is made easier by avoiding mastic sealants and installing compressible fillers. This may however have an effect on the air tightness of the building. Recycling of the windows depends on having a solid material compound (e.g. timber and aluminium or polyester coating) are difficult to recycle.	Solid timber windows can be easily repaired if damaged.	Common use
DOORS/ SHUTTERS/ HATCHES	Main use: general Product: solid material doors Manufacturer: various	Reuse as new – YH Reuse 2nd hand – YY Recycling – V Downcycle – V	Door leaf is a solid material (e.g. timber, steel) and fixed mechanically to frame	Composite steel/ insulation/ timber/ honeycomb cardboard doors can not be recycled and are more difficult to refurbish for reuse	All doors tend to be easily dismantled and reuse is possible. Materials used for doors are generally metal, which is very recyclable and timber, which can be easily downcycled	Solid doors can be refurbished thus have a potential for a long life.	Common use Common reuse

SECTION M SURFACE FINISHES	Product and manufacturer's details	Ability to be disassembled, reused, recycled, downcycled YY=yes, easily YH= yes, with high work input N=no U=unknown V-varies according to product	Relevant system features	Non-disassembleable / reusable / recyclable alternatives	Issues to consider	Advantages of reusable/ recyclable option	Frequency of use / examples of reuse / recycling
RUBBER/ PLASTICS/ CORK/ LINO/ CARPET TILING/ SHEETING	Product: Quick release system Main use: bonding flexible floor finishes – hospitals, retail, airports Manufacturer: Laybond &Uzin	Reuse as new – NA Reuse 2nd hand – NA Recycling – NA Downcycle – NA	A sheet made of two easily separated layers installed in between the structural floor and the floor finish. To remove the floor finish the separating layer is split and the floor finish can be removed very quickly without damage to the finish and the substrate.	Bonding floor finishes directly to substrate	The release system enables the potential reuse of flexible floor finishes such as carpets and linoleum. Currently the release systems is used because of the time benefit and the lack of disruption to building use and the floor finish itself is not usually reused, however this could be done. Where alternative systems of laying carpets and plastic sheet materials are possible (e.g. edge fitted carpeting or interlocking loose laid rubber tiles) these should be used in preference to a bonded system.	Time requirements for the removal of floor finishes is minimal, therefore refurbishments and changes of layouts are facilitated. The disruption of the building use by the process of floor finish removal is also minimised minimising potential loss of income.	Increasing
RUBBER/ PLASTICS	Product: Interlocking floor tiles Main use: industrial, leisure, commercial Manufacturer: Scan-lock (recycled PVC tiles) Ecotile (recycled PVC tiles) www.ecotile.com Dalsouple (recycled rubber tiles) www.dalsouple.com	Reuse as new – YY Reuse 2nd hand – YY Recycling – YY Downcycle – YY	Floor tiles with interlocking edges which do not need adhesive for installation.	Floor tiles bonded to substrate		The replacement of a whole floor or individual tiles (when damaged) is very simple to do. This reduces maintenance costs and provides flexibility in terms of changing layouts. The work environment for the installers is healthier than when installing floor systems with adhesives. The floor system enable the inclusion of signs in the floor surface more easily than with large rolls of sheet material.	Common use Common reuse
CORK	Product: Corkloc Main use: flooring finish Manufacturer: Wincanders www.wincanders.com	Reuse as new – YH Reuse 2nd hand – YY Recycling – N Downcycle – U	HDF core is shaped to create a junction between floor boards that doesn't require glue. The junction can be opened with a special tool. The boards include an underlay.	Cork flooring fixed with adhesive to the substrate can not be reused and is very difficult and time-consuming to separate and clean	The laminated floor boards can be reused, but their composite nature means that the recycling of individual materials is impossible.	Of particular use in retail areas where the layout of displays is changed often or in temporary buildings. The ease of dismantling is also beneficial in domestic situations where layouts have to be changed or where an internal refurbishment is desired.	Increasing use
TIMBER	Product: glueless self-locking timber floor Main use: flooring finish Manufacturers: OSMO - www.osmouk.com (Unique toploc) Kährs (Woodloc) Karelia – www.kareliawoodflooring-	Reuse as new – YH Reuse 2nd hand – YY Recycling – N Downcycle – YY	Spruce core is shaped to create a junction between floor boards that doesn't require glue. The junction can be opened with a special tool.	Timber flooring fixed with adhesive to the substrate can not easily be reused and is very difficult and time-consuming to separate and clean. Nailed timber flooring is more time-consuming to	The boards can be reused and downcycled to lower grade timber products.	Of particular use in retail areas where the layout of displays is changed often or in temporary buildings. The ease of dismantling is also beneficial in domestic situations where layouts have to be changed or where an internal refurbishment is desired.	Increasing use

	uk.com (Profiloc)			remove There are some laminate glueless self-locking floors that can be reused, but can not be recycled or downcycled due to their composite nature			
CARPETING	Product: edge fitted carpeting Main use: domestic	Reuse as new – N Reuse 2nd hand – YY Recycling – V Downcycle – V	Carpet fixed with carpet grippers at the perimeter of a room	Carpet fixed with adhesive	End of line carpets are being used to manufacture interior products. It is therefore possible that in future post-consumer carpet waste could be used to produce similar products, but at the moment post consumer carpets are landfilled.	Fixing with without adhesives will avoid VOC emissions during the installation process providing a healthier work environment and during the first period of occupation of the building.	Common use Reuse uncommon
	Product: Solenium Main use: commercial Manufacturer: Interface www.interface europe.com	Rating: Reuse as new – N Reuse 2nd hand – YY Recycling – YY Downcycle – YY	Carpet tiles, which can be recycled 100%	Most other carpet can at best be downcycled to produce a different product, thus lengthening the life of the material, but not creating a closed loop.	Solenium is a virtually unique carpet product in that its life cycle is one of a loop rather than linear, as the waste materials are reused infinitely.	Interface offers a service whereby individual worn carpet tiles are replaced on a regular basis rather than replacing all flooring tiles on one occasion. This avoids the disruption associated with large scale maintenance work and ensures that the flooring looks good at all times.	limited market share

SECTION N FURNITURE EQUIPMENT	Product and manufacturer's details	Ability to be disassembled, reused, recycled, downcycled YY=yes, easily YH= yes, with high work input N=no U=unknown V-varies according to product	Relevant system features	Non-disassembleable / reusable / recyclable alternatives	Issues to consider	Advantages of reusable/ recyclable option	Frequency of use / examples of reuse / recycling
GENERAL FIXTURES/ FURNISHINGS / EQUIPMENT	Product: kitchen cabinets Main use: kitchen	Reuse as new – YH Reuse 2nd hand – YY Recycling – V Downcycle – V	Free-standing kitchen cabinets	Fully fitted kitchen cabinets. Some fitted units can be disassembled and reused or recycled, however the disassembly process can damage the units and the units may not fit in a new location.	Free-standing units will facilitate the reuse of units, however the recycling of the units will depend on the details of the materials used. E.g. composite boards are impossible to recycle efficiently.	Enables a more flexible layout.	Use increasing
	Product: Microslat - Retail display systems Main use: retail Manufacturer: Proloc www.proloc-online.com	Reuse as new – YH Reuse 2nd hand – YY Recycling – YY Downcycle – YY	Interlocking wall panels 125mm high and up to 6000mm long.	Systems fixed to the wall with individual supports.	The aesthetics of the system have to be considered and are appropriate for retail, perhaps less for offices. The grooved slats will collect dirt.	The speed of installation is high. The system can be used to cover the whole wall surface making the substrate quality not crucial.	Common

SECTION P BUILDING FABRIC SUNDRIES	Product and manufacturer's details	Ability to be disassembled, reused, recycled, downcycled YY=yes, easily YH= yes, with high work input N=no U=unknown V-varies according to product	Relevant system features	Non-disassembleable / reusable / recyclable alternatives	Issues to consider	Advantages of reusable/ recyclable option	Frequency of use / examples of reuse / recycling
SUNDRY INSULATION/ PROOFING WORK/ FIRE STOPS	Main use: thermal and acoustic insulation Product: wall, roof and floor insulation / rigid and non-rigid	Reuse as new – V Reuse 2nd hand – V Recycling – V Downcycle – V	Loose laid insulation	Insulation that has been bonded to another material can be difficult to separate from the other material and therefore not recyclable. However increasingly processes are being developed to separate composite materials.	Loose insulation made of expanded and extruded polystyrene, rockwool, cellulose fibre, blown and spun glass can be recycled. Loose insulation made with polyurethanes, polyisocyanurates and phenolic foams are difficult to recycle.	Where the insulation is loose laid, for example on a roof it is possible to replace the insulation when damaged or when an upgrade is necessary.	Common
UNFRAMED ISOLATED TRIMS/ SKIRTINGS/ SUNDRY ITEMS	Product: skirtings	Reuse as new – V Reuse 2nd hand – YY Recycling – V Downcycle – V	Timber, metal and plastic skirtings fixed with screws to substrate	Skirtings fixed with adhesive to substrate	Removing skirtings fixed with adhesive will damage both substrate and skirting. Removing skirtings fixed with screws is likely to cause less damage and if screws are left exposed can cause no damage at all.	Facilitates changes to layouts and decorations. Avoids emissions from adhesives during installation process.	Common Exposed screws are seldom used
HOLES/ CHASES/ COVERS/ SUPPORTS FOR SERVICES	Product: Heat Profile Main use: domestic Manufacturer: Heat Profile www.heatprofile.co.uk	Reuse as new – YH Reuse 2nd hand – YY Recycling – U Downcycle – U	Profiled skirting element fixed on brackets and integrating heating elements and other services	Services installed in walls or floors Skirtings fixed with adhesive to wall	In order to integrate service elements the skirting profile is slightly larger than a normal skirting	Allows flexibility of services including IT, electrical and heating within a space. Removes the need for radiators thus allowing furniture to be freely positioned Refurbishment work is facilitated through easy access to services and easy dismantleability to move walls.	Limited
	Product: cable management system Main use: commercial Manufacturer: various	Reuse as new – YH Reuse 2nd hand – YY Recycling – U Downcycle – U	Metal or plastic profiled trunking, installed at dado or skirting level, fully accessible and integrating sockets etc	Services installed in walls or floors	Aesthetics has to be considered as the trunking may appear utilitarian Laminated profiles can be difficult to recycle and even downcycle	Allows flexibility of services including IT, electrical and heating within a space.	Common use Common reuse
	Product: plug in lighting system Main use: commercial Manufacturer: various www.flexconnectors.co.uk www.hager.co.uk	Reuse as new – YY Reuse 2nd hand – YY Recycling – YH Downcycle – N	System consists of pre-wired elements that can be plugged in a distribution element	Hard wired services		Installation time is reduced Allows flexibility of services Installations can be easily upgraded	Increasing use

SECTION Q PAVING FENCING SITE FURNITURE	Product and manufacturer's details	Ability to be disassembled, reused, recycled, downcycled YY=yes, easily YH= yes, with high work input N=no U=unknown V-varies according to product	Relevant system features	Non-disassemblea ble / reusable / recyclable alternatives	Issues to consider	Advantages of reusable/ recyclable option	Frequency of use / examples of reuse / recycling
GRANULAR SUB-BASES TO ROADS/ PAVINGS	Main use: sub-base Product: granular material	Reuse as new – Y Reuse 2nd hand – Y Recycling – Y Downcycle – N/A		Most sub-bases can be recycled, but will only be recycled if recycled materials is generally accepted as a good alternative	The *Specification for Highway Works* enables the use of a wide range of secondary and recycled aggregates.	The M6 Toll motorway made extensive use of recycled aggregate and is expected to make an overall saving of £4 per tonne of material used, approximately £1M in total. Operational benefits are also expected. (*Local government news Nov 2003*)	Increasing use
COATED MACADAM/ ASPHALT ROADS/ PAVINGS	Main use: Road surfacing Product: tarmac	Reuse as new – N Reuse 2nd hand – N Recycling – Y Downcycle – Y		Most tarmac finishes can be recycled. The practice of mixing tarmac with concrete to form a sub-base for roads downcycles tarmac. Recycling tarmac should be undertaken in preference to downcycling to road base	Tarmac road coverings can be planed off and re-applied easily. Older tarmac may need to be mixed with new tarmac to comply with modern standards, but newer tarmac can be wholesale recycled, either directly on site or taken away and used elsewhere.	Recycling tarmac on site reduces the transport of materials (waste and new) to site, reducing energy costs, pollution, noise and traffic congestion. Kent council replacement of the A21 road base used recycled asphalt and saved over £500,000, around 10% of the contract sum. (*Local government news Nov 2003*)	Increasing use
INTERLOCKIN G BRICK/ BLOCK ROADS/ PAVINGS/ SLAB/ BRICK/ SETT/ COBBLE PAVINGS	Product: reinforced grass paving system Main use: parking areas / green spaces for services access Manufacturer: Polypipe www.polypipe civils.co.uk	Reuse as new – YY Reuse 2nd hand – YY Recycling – YH Downcycle – YH	Open grid paving systems made of plastic (often recycled) with interlocking connections	Tarmac and concrete areas to provide access for vehicles. See above	Dismantling of the system from a well established grassed area can be difficult, however the paving systems is tough and aesthetics are not crucial and therefore the system can be slightly damaged and still be reusable without repair work. There can be a risk in areas of high use and low watering that the grass does not grow as well as it could, resulting in the paved area failing from an aesthetic point of view.	Environmental advantages include the increase of green space, which can contribute to reducing ambient temperatures in cities through evaporation and to adsorbing air pollutants through plant growth. Increased green spaces can contribute to social well-being of	Common
	Product: paving Main use: external areas	Reuse as new – YY Reuse 2nd hand – YY Recycling – YH Downcycle – YY	Pavers set on a sand base	Concrete tops are downcyclable, but the recovery process is time-consuming and disruptive. Asphalt can be recycled – see above	Initial installation costs are higher than tarmac and concrete, but life cycle costs can be lower. Lifespan is longer, maintenance is simpler and less frequent	Paving is the preferred finish for the general public mainly on aesthetic grounds and has the potential to raise the quality of outdoor spaces and make them more desirable and consequently more sustainable.	Common

SECTION S PIPED SUPPLY SYSTEMS	Product and manufacturer's details	Ability to be disassembled, reused, recycled, downcycled YY=yes, easily YH= yes, with high work input N=no U=unknown V-varies according to product	Relevant system features	Non-disassembleable / reusable / recyclable alternatives	Issues to consider	Advantages of reusable/ recyclable option	Frequency of use / examples of reuse / recycling
HOT AND COLD WATER	Product: polybutylene plastic pipework Main use: hot and cold water supply Manufacturer: George Fisher www.georgefisher.co.uk	Reuse as new – YY Reuse 2nd hand – YY Recycling – YY Downcycle – YY	Flexible pipes joined by electro-fusion	Copper pipework can be recycled and reused, but the dismantling is more labour intensive		The installation time is typically 2% of that of copper. The work process poses less risk to health. The jointing system does involve soldering with a naked flame and therefore the risk of fire on site is reduced. The material is light and therefore easier to carry.	Commonly available
	Product: crosslinked polyethylene barrier pipe Main use: hot and cold water supply Manufacturer: JG Speedfit www.speedfit.co.uk	Reuse as new – YY Reuse 2nd hand – YY Recycling – YY Downcycle – YY	Pushfit system	As previous item. Pushfit are even more easily dismantled than electro-fusion connections	System can be linked to copper system.	As previous item	Commonly available

APPENDIX 9 - ANALYSIS OF CRITERIA FOR DECONSTRUCTION, REUSE AND RECYCLING (ORIGINAL RESEARCH ANALYSIS)

APPENDIX 9 IS RELATED TO SECTION 4.6 'ASSESSMENT CRITERIA FOR CLMC'.

Appendix 9 represents the results of an analytical process that rationalised principles for design for deconstruction, design for recycling and design for reuse advocated by researchers in the field. Seven sources of information on systems assessing deconstruction, recycling or reuse and or guidance on the same subjects were considered. The aim was to create a comprehensive set of criteria for deconstruction, recycling and reuse, based on existing literature, that could be analysed in relation to the definition for CLMC construction formulated in section 4.5, and then rationalised and expanded as necessary to form the basis for a new set of criteria for CLMC construction.

The criteria advocated by the researchers were compared and grouped according to broadly shared principles relating to 1) the deconstruction process, 2) the required processing to enable the reuse of elements and materials, and 3) the required processing to enable the recycling of elements and materials. Within these three main foci the criteria were then compared, grouped and set out in a table (Table A08) for further analysis. The table aided the analysis of the different issues and principles and enabled the existing guidance and criteria to be rationalised into a communal set. From the communal set of principles one was identified (and the text highlighted in yellow) as most comprehensively describing the shared principle.

These most comprehensive principles that were adopted as representing the shared concept were summarised in Table 38. This table was expanded to include criteria for recycling through natural

processes, adopted from those relating to recycling through industrial processes and adjusted to relate to the definitions formulated in sections 4.5.

The resulting comprehensive set of criteria for deconstruction, reuse, industrial and natural recycling in Table 38 then had to be analysed in terms of selecting the criteria that were compatible with the definition for CLMC formulated in section 4.5, which considers the concept of CLMC as a purely technical concept, therefore excluding economic parameters from the final set of criteria for CLMC construction. This final analysis that resulted with the conclusive set of criteria for CLMC (Table 41) is detailed in section 4.6, which provides the rational for the adoption or exclusion of each criterion.

Table A08 – **Analysis of criteria and guidance for deconstruction, reuse, recycling and downcycling.**

General principles divided into stages of recovery and reuse or recycling	Sassi and Thompson 1998	Crowther 2000	Fletcher et.al.2000	Thormark 2001	Sassi 2002	Addis and Schouten 2004	Morgan & Stevenson 2005	Comments
DECONSTRUCTION PROCESS								
Ability to access			Allow accessibility for maintenance and demolition.				Ensure all components can be readily accessed and removed for repair or replacement	*technical* Ability to access correct elements to allow for dismantling
Ease of accessibility	Accessibility of elements to be dismantled / removed How easily are elements accessed. E.g. is a ladder, scaffold or crane required?	Design for easy access.			Provide easy and safe access to building element and fixings with minimal machinery requirements.	Ensure the people, methods and plant used for deconstruction have been considered, in particular, safe and adequate access and appropriate speed of deconstruction.		*economics* Ease of access impacts on the speed and involvement of deconstruction
Order of accessibility		Hierarchy of disassembly relevant to component life span				minimise the number of levels of deconstruction to remove products or elements ensure that materials and sub-assemblies decay at similar rates or can be replaced individually.	Ensure that buildings are conceived as layered according to their anticipated lifespans.	*economics* The ability to directly access sections to be removed without the removal of others reduces time and cost.
Accessibility of fixings					Provide easy access to fixings	Ensure interface/connection points are identifiable and accessible		*technical* Fixings need to be accessible
Parallel disassembly		Design for parallel disassembly			Allow for parallel disassembly		Pay particular attention to the differential weathering and wearing of surfaces and allow for those areas to be maintained or replaced separately from other areas Carefully plan services and service routes so that	*economics* the ability to dismantle different area in parallel increases speed of deconstruction and reduces costs

							they can be easily identified, accessed and upgraded or maintained as necessary without disruption to surfaces and other parts of the building	
Number of components						minimise number and variety of components		*economics* Few large components can be handled quicker than many small ones
Tools for dismantling	Tools required to dismantle or remove element - What tools are required to remove the elements for its installation? E.g. is a screw driver sufficient or a crane necessary?	Use non-specialist assembly technology.			Simplify fixing systems and enable removal by means of small hand tools and handheld electrical tools avoiding specialist plant.			*economics* Non-specialist assembly and the use of common tools results in lower costs.
Types of fixings		Use mechanical connections rather than chemical – or chemical connections that are weaker than the bonded element		Fasteners have to be easily unfastened. Selection of correct joining / connection method is crucial.	Use mechanical rather than chemical fixing.	Use of sprung clips, wing nuts, etc that allow hand assembly and disassembly. Ensure fixings can be easily undone, when required. Use bolts in preference to rivets. Minimise variety of connection types. Specify mechanical alternatives to adhesives and welding Where adhesives have to be used, use water soluble adhesives.	Adopt a fixing regime which allows all components to be easily and safely removed, and replaced through the use of simple fixings. Design connectors to enable components to be both independent and exchangeable.	*technical* The type of fixing is critical in respect of the ability to dismantle i.e. fixings have to be • Weaker than the bonded element • Reversible fixings ie mechanical reversible fixings or soluble adhesives.
Durability of fixings					Design joints to withstand dismantling process.			*technical* fixings need to be durable enough to be used after a long time and reused
Sturdiness of components	Sturdiness of elements affecting recycling –			Material damage	Design components to withstand dismantling			*technical* components need to be sturdy

	Does damaging an element affect its recycling potential and are elements easily damaged? E.g. glass.				process.			enough to not disintegrate when dismantled and any damage to the material should not compromise the ability to contain it and transported it
Number of fixings and parts					Minimise number of parts, fixings and types of fixings	Minimise number and variety of components		*economic* minimising parts and fixings makes the process simpler, quicker and cheaper
Ease of handling		Provide means of handling elements. Use elements sized for ease of handling.	Fixings, lifting eyes and other aids for future deconstruction		Make components sized and of a weight to suit the means of handling and provide means of handling and locating	Specify components with sizes that are suitable for handling and transportation.		*technical* The ability to handle elements is essential to recover them from a building
Tolerances		Provide tolerances that facilitate disassembly.			Provide realistic tolerances for assembly and disassembly.			*technical* Insufficient tolerances could compromise the state of the elements being removed and compromise subsequent processes.
Hazard					Avoid toxic materials	Eliminate use of toxic or contaminated materials ensure materials cause no harm during deconstruction (eg toxic emissions, leechate)		*economic* removal of toxic material is very costly e.g. asbestos
Time requirements	Time requirements for dismantling operation. - How long does the removal of the elements normally take?		Prefabricated units would speed up deconstruction.	The time required to dismantle the building elements should be a short as possible. Modularity can help in terms of speed of dismantling.		ensure deconstruction can be done quickly		*economic* The quicker the deconstruction the cheaper the process
Information			Quality information not quantity is required. Material log for use during building life.		Provide As Built drawings and Maintenance Log including identification of points of disassembly, component and material and identify materials and points of disassembly on elements	Produce a plan describing the safe deconstruction of the building.		*technical* While some building elements can be dismantled without guidance the dismantling of others can be subject to the provision of information and instructions.
Other	Integration of recycling	Use flexible open	Design for flat-packing					

	facilities in the design.	building systems.	and transport efficiencies to minimise transport costs Design for materials reuse and recycling Require demolition plan to gain demolition permit.					
PROCESSING FOR REUSE								
Reprocessing	Preparation of materials and elements for reuse/recycling Requirements to ensure aesthetic standards- Aesthetics non-critical / easily achieved- 'As new' aesthetic unachievable		Use simple material design		Use materials that require minimal reworking	Design the product in a way that can be easily reconditioned /reused	Avoid the use of adhesives, resins and coatings which compromise the potential for reuse and recycling.	*economic* The less reprocessing required the more economic the reuse. The amount of processing may be dictated by the aesthetic expectations of the market.
Durability of material	Sturdiness of elements affecting reuse/recycling	Use minimal wearing parts that need replacing			Use sturdy and avoid fragile material	design for long life (ie a long second life) ensure products can be well-maintained during their life	Use only durable components which can be reused.	*technical* Sufficiently damaged elements will not be reused.
Durability of fixing		Use joints and connectors that withstand repeated use			Design joints and components to withstand repeated use			*technical* Damaged joints will not be reused.
Flexibility of reuse		Use modular design to facilitate interchange of elements.			Flexible installation options included.	Use standardise building elements and systems wherever possible. Use of identical, interchangeable elements to ensure quick and successful re-erection standardise dimensions, fixings, sub-assemblies, connections, etc		*economic* Standardised/ modular elements facilitate interchange of elements Unit size encourages reuse by reducing its effect on the building design.
Hazards	Content of toxic materials – Does the material contain	Avoid toxic and hazardous materials	Avoid hazardous materials	Information on hazardous materials is required	Minimise toxic content, if toxic content is unavoidable ensure the			*economic* It is assumed that toxic materials found in building

	toxic components that preclude or complicate recycling?				ability to release it in a controlled manner			elements can be handled without excessively elevating risk to health but precautions could be costly.
Information				Information on recycling/reuse potential is required, preferably included in a log book.	Provide product details and installation instructions.			*Technical* If the methods for reuse are not self-evident information is a prerequisite for reuse.
PROCESSING FOR RECYCLING								
Multiple reprocessing								*Technical* Unless the material can be indefinitely recycled it cannot be considered part of a closed loop
Reprocessing	Preparation of materials and elements for reuse/recycling - Is excessive preparation necessary to allow recycling or can the elements be reused immediately or reintroduced in the standard manufacturing process?		Fewer composite structures		Avoid non-recyclable materials such as composite materials and treatments and secondary finishes to materials that complicate reprocessing.	Use alternatives to fluid sealants and fillings.	Avoid the use of adhesives, resins and coatings which compromise the potential for reuse and recycling.	*Economic* Technologies now exist to separate composite structures therefore bonded elements can be separated at a cost.
Material purity		Make inseparable subassemblies in same material Minimise number of different materials. Avoid applied finishes		Materials should be a 'clean' as possible. 'Clean' means free from materials that complicate reprocessing or lower the quality of the end product.	Minimise the number of different types of components and ensure inseparable subassemblies are from the same material and components of different materials are easy to separate	Eliminate the use of secondary coatings. Use alternatives to synthetic composite materials. Minimise number and variety of materials. Design buildings using as few different materials as possible to reduce the number of separation processes ensure materials are clean (eg unpainted, free from glue) or	Try to use monomeric components.	*Technical* Material impurities that compromise recycling constitute a technical barrier.

						cleanable when they have been separated		
Hazards	Content of toxic materials		Avoid hazardous materials	Information on hazardous materials is required		do not specify materials that cannot be recycled because they are hazardous		*economic* It is assumed that toxic materials found in building elements can be handled without excessively elevating risk to health but precautions could be costly.
Material damage								
Informatio n		Provide material identification .		Information on recycling/reus e potential is required, preferably included in a log book.	Provide identification of material and component types.	Identify materials and components with a unique identification mark.		*economic* Identifying materials would make segregation of materials quick and avoid the need of specialist assessments.
INTRODUCTION INTO BUILDING INDUSTRY								
	Market demand for recycled elements - Is there an existing or potential market for the recycled material?	Use recycled materials to stimulate market.	Commitment to the use of recycled materials	Value of product in future.		specify materials for which a recycling market exists by taking advice from those engaged in the recycling industries		*economic* The likelihood of dismantling taking place is subject economic value or recovered material.

APPENDIX 10 – DATA SHEETS FOR ASSESSMENT OF MATERIALS' FINAL DISPOSAL (RESULTS FROM APPLICATION OF ORIGINAL ASSESSMENT TOOL)

APPENDIX 10 IS RELATED TO SECTION 4.6 'ASSESSMENT CRITERIA FOR CLMC' AND SECTION 5.1 'MATERIAL ASSESSMENTS'

Appendix 10 represents the results from the process of applying the criteria developed in section 4.6 to a selection of materials. The aim was twofold: firstly to establish whether the system of criteria was appropriate for its designated purpose, and secondly to assess a selection of material that would used in the subsequent assessments, including the building components assessment and the whole building assessment.

The assessments were based on information on material characteristics gained through a literature review of construction material texts and journal papers related in particular to end-of-life options for materials. The materials assessed are listed below and the following sheets include the information gained to support the assessment. Also for each material is a completed assessment form devised for the purpose of recording the results of the assessment. Compliance with the criteria for recycling through natural and industrial processes will be recorded with a tick (✓) and non-compliance with a cross (x).

Table A09 - **List of materials assessed for closed loop material cycle compliance**

Cementing and masonry materials	**Plastics / oil-based products**	**Metals**	**Materials of wood and other natural sources**
fired clay gypsum cement concrete ballast mineral wool insulation	PE/EPS (thermoplastics) PVC/UPVC (thermoplastic) PU (thermosetting plastic) glass	steel	timber cork recycled cellulose fibre

FIRED CLAY (BRICKS) (Cementing and masonry materials)

Building industry uses	**Facing bricks**, engineering bricks, brick slips (also non-brick materials include: clay tiles, wall tiles)
Recycling statistics	3.5 billion new bricks are manufactured, 2.5 billion reclaimable bricks are landfilled and only 40 million bricks are reclaimed (Salvo, 1995). Recycling of clay powder or clay and mortar powder is not common.
Environmental lifecycle impacts	**RESOURCING** brick-making clay contains silica and alumna and impurities including iron compounds lime magnesia, potash, soda, sulphur combined chemically into compounds such as feldspar and mica. Clay is won by excavating pits. **Natural resource depletion** Clay is generally abundant throughout the world (Keefe, 2005). **Environmental impact of mining** - Clay pits temporarily affect the local ecology by occupying large areas of land. However, clay pits are normally restored. Main emissions are particulates to air and water, surface or ground water courses can be interrupted (Clough and Martyn, 1995). **MANUFACTURE** - the clay including stones are crushed, ground and blended. / the clay is shaped by hand or machine by pressing in mould or extruding / then dried if necessary and fired. Bricks can be soft-mud moulded / wire cut with or without perforations all which require drying before firing. 'Green' bricks are dried before fired either in a separate drier or in a drying zone of a kiln. Perforated bricks require less material, processing time and energy, less weight. Bricks can also be moulded with a semi-dry clay or stiff-plastic clay and can go directly into the firing kiln. Flettons (made from lower Oxford clay) are made by semi-dry process: clay is ground to a powder, presses, dried and fired in a Hoffman kiln. Flettons contain natural fuel which contributes to economy of firing, yet the actual CO2 emissions are nearly as much as for clay bricks. (Ethical Consumer Research Association, 1995a) **Environmental impact of manufacture**- Emissions to air include particulates, fluorine and chlorine compounds, SO2 and NOx / Flettons produce slightly more toxic emissions than plain bricks due to the impurities of the clay. Emissions to water are negligible. solid waste is produced from the flue gas cleaning system (Ethical Consumer Research Association, 1995a). **EMBODIED ENERGY** 2.68GJ/tonne (Clough and Martyn, 1995). Fletton bricks –175 KWh/ tonne or 300 KWh/m³ (Talbot, 1995) or 2 MJ/kg (Berge, 2000) Non-fletton bricks - 860 KWh/ tonne (Talbot, 1995) 1,462 KWh/m³ (Talbot, 1995) 3 MJ/kg (Berge, 2000) Engineering bricks - 1,120 KWh/ tonne (Talbot, 1995) 2,016 KWh/m³ (Talbot, 1995) 3.5 MJ/kg (Berge, 2000) 'Adobe' sun dried bricks are used in other countries successfully Rammed earth buildings have very low embodied energy especially if the ramming is hand done. **TRANSPORT** - Bricks are dense and therefore transport impacts is relatively large, however in the UK bricks are manufactured locally and transport distances can be reduced. **DISPOSAL** – generally to landfill and is associated with land use.
Environmental benefits of recycling	The **reuse of bricks** reduces all resourcing and manufacturing impacts including embodied energy (taking into account additional transport of reclaimed materials) If **recycling of clay powder** were possible resourcing impacts would be avoided. Manufacturing of new bricks from clay brick dust would require a similar amount of energy as the manufacture of brick from virgin material (Hansen, 1994). Studies of pollution implications of re-burning brick powder were not found.
Recycling process	According to Coventry, Woolveridge, Hillier (1999) recycling is not possible, but downcycling into hardcore is common for bricks. Recycling may be possible in future. Hansen (1994) and Kristensen (1994) reported on experiments with crushing clay brick and cement mortar and then grading the crushed material and mixing the graded material with water to form bricks that were autoclaved. The end result was a calcium

	silicate brick with suitable characteristics for limited construction use. However the limitation was to find a suitable firing method. Considering the fact that Hansen's and Kristensen's 1994 research has not progressed it has to be taken that the process remains either technically unresolved or economically unfeasible. **REUSE** - Clay bricks generally require weak mortar group 2 or 3 as opposed to calcium silicate bricks which require a strong mortar group 3 or 4. None of the modern cement mixes(groups 1-4) allow for real movement. To reclaim bricks a weak mortar is best. The preferred mortar is lime mortar and weak Portland cement mortar. These are susceptible to acid rain dissolving the calcium carbonate, stronger calcium silicate bound mortars are less susceptible but less flexible. The more cement in the mortar the stronger the mortar and the less flexible. (Kristensen, 1994; Ethical Consumer Research Association, 1995a; Clough and Martyn, 1995). Brick slips will be damaged if attempted to be removed. Brick wall
Contaminants	The main contaminant is cement mortar in bricks. This makes reuse more complex and time consuming.
Material loss through recycling process	Kristensen (1994) suggests that theoretically 100 per cent of the bricks processed to produce brick dust for reprocessing would be reprocessed. This would suggest a zero per cent loss. However, this does not take into account the deconstruction process losses. Furthermore, as mentioned the lack of progress in the area of reprocessing brick dust suggests that the process is not (yet) feasible. Material loss associated with reuse, resulting from brick breakages, is also significant.
Environmental impacts particular to recycling processes	Reuse is not associated with any impacts particular to its process. Recycling brick dust has not been investigated.
Deterioration of material	Clay bricks are extremely durable and resistant to freeze thaw cycles if suitably installed bricks can last hundreds of years, examples of bricks from 1300 BC exist (Doran, 1994). The durability of bricks and brick walls is extended if bricks are kept dry (BS5628 Part3 table13).
Barriers to recycling	Brick dust recycling is limited by technical requirements for firing (Hansen, 1994). Reuse of bricks is hampered by lack of information regarding different types of bricks recovered, that have different performance (Kristensen, 1994; Coventry and Guthrie, 1998). Mortar types (see above).
other	

Fired clay bricks	**Recycling through industrial processes**	x	**Recycling through natural processes**	x
	Infinite recycling	x	Rate and efficiency	x
	Processing efficiency	x	Hazards and quality	x
	Hazards	✓		x

GYPSUM (Cementing and masonry materials)

Building industry uses	wall finishes and wall boards
Recycling statistics	none
Environmental lifecycle impacts	**RESOURCING** - Gypsum is primarily calcium sulphate. Gypsum is both surface mined and deep mined. Gypsum is also a by-product of the electricity industries resulting from flue gas desulphurisation (FGD). FGD requires limestone to be mined, crushed and transported. **natural resource depletion and environmental impact of mining** - Surface extraction temporarily affects the local ecology. However, the areas are normally restored (Clough and Martyn, 1995). The environmental impact of producing FGD is generally associated with the electricity industry. **MANUFACTURING** - The gypsum is crushed, ground and heated. It is aerated and generally bound between two sheets of strong paper. **environmental impact of production** - Main emissions are particulates to air. **EMBODIED ENERGY** - 890 KWh/ tonne (Talbot, 1995), 900 KWh/m^3 (Talbot, 1995), 5 MJ/kg (Berge, 2000) **DISPOSAL** - When gypsum undergoes anaerobic digestion it can result in the production of hydrogen sulphide H_2S, which in turn can form hydrochloric acid. (Beck and SCS Engineers, 2003)
Environmental benefits of recycling	Reduction of all above impacts.
Recycling process	Composting - Gypsum drywall - paper fraction of the drywall should certainly biodegrade. The gypsum itself, will not biodegrade but is used as agricultural soil conditioner. Recycling to form new gypsum - Trommel Screen process - Drywall is first broken up to reduce large elements and then passed through a rotation filter drum (ca 6-7mlong) where most of the drywall is separated from its paper backing due to breakages. The plasterboard dust and elements smaller that 10-25mm dia fall through the filter and are collected. The process is repeated to achieve higher yields. The left over material is mainly paper with still a significant amount of gypsum. 8-10mm gypsum is used for agricultural applications, 18-25mm gypsum is used in the cement industry (Beck and SCS Engineers, 2003) Typically no more than 10 to 20% of the new gypsum boards consists of recycled gypsum (Beck and SCS Engineers, 2003)
Contaminants	paint, especially lead-based paints (Townsend and Cochran, 2003)
Material loss through recycling process	Based on a maximum 10-20% recycled gypsum content in new gypsum boards together with the losses in the recycling process, material loss is estimated above 10%.
Environmental impacts particular to recycling processes	Recycling is not associated with any additional impacts particular to its process.
Deterioration of material	If too much recyclate is included in the manufacture of new plasterboard the quality of material is thought to become fragile (Beck and SCS

	Engineers, 2003) The main danger to the durability of plasterboard is humidity. In appropriate conditions plasterboard can last 30 to 60 years (Shiers, Howard, Sinclair, 1996).
Barriers to recycling	Plasterboard is generally screw fixed to metal or timber stud work. Fixings are normally hidden and joints and edges taped. It is often covered with a skin coat of plaster, painted or covered with wallpaper. Dismantling is difficult and time consuming and the boards are likely to be damaged. There is potential of using new types of wall paper that use adhesives which allows removal of the wall paper with out damaging the substrate Manufacturers many limit the use of recycled gypsum to sources of their own products. Paper content must be kept to less than 2%, metal fragments have to be excluded.
other	Gypsum is a common soil conditioner that provides calcium and sulphur for plants and is used for peanut corps, potatoes and corn. It is particularly appropriate for alkaline soils as it raised the PH; has been used to reinstate salty soils; can flocculate clayey soils. Contaminants from demolition waste should be avoided (Townsend and Cochran, 2003).

Gypsum	Recycling through industrial processes	x	Recycling through natural processes	x
	Infinite recycling	x	Rate and efficiency	
	Processing efficiency	x	Hazards and quality	
	Hazards	✓		

CEMENT (Cementing and masonry materials)

Building industry uses	Binder in concrete and concrete products Render
Recycling statistics	None
Environmental lifecycle impacts	**RESOURCING** - Lime rich material such as limestone or chalk and silica rich material such as clay or shale are the base materials to form Portland cement. **Natural resource depletion -** Limestone and chalk reserves are generally abundant, with the exception of the south-east where 'permitted' reserves are running low. **Environmental impact of mining** - Clay, limestone and chalk are won by surface mineral extraction and temporarily affect the local ecology by occupying large areas of land. However, the areas are normally restored. Main emissions are particulates to air and water, surface or ground water courses can be interrupted (Clough and Martyn, 1995). **MANUFACTURING** - The raw materials of chalk and clay are fired in kilns, the temperature peaks in excess of 1400°C where the calcium carbonate from the limestone or chalk is dissociated into calcium oxide and carbon dioxide and the oxides of calcium, silicon, aluminium and iron are transformed into active ingredients of Portland cement. The resulting clinkers leave the kiln at a temperature of 1000°C and are cooled to 60°C in a controlled manner. The cooled clinkers are ground to a powder with the addition of gypsum (calcium silicate) which controls the rate of hardening. There are four production processes for cement ranging form a dry process to a wet process. **Environmental impact of production** - the process of heating the limestone or chalk given off large amounts of CO_2. The cement industry is responsible for 8-10% of the total global emissions of CO_2 (Ethical Consumer Research Association, 1995a). The heating process is very energy intensive. Major cement manufacturers are experimenting using waste as an alternative cheap fuel. Much of the burnt waste is chemical and produces toxic emissions of dioxins and heavy metals. Emission controls for cement kiln are not as stringent as for incinerators. **Embodied energy** Wet process consumes 6.1GJ/tonne dry process consumes 3.4 GJ/tonne (Clough and Martyn, 1995). 2,200 KWh/ tonne (Talbot, 1995), 2,860 KWh/m³ (Talbot, 1995)
Environmental benefits of recycling	N/A
Recycling process	None available at the moment. Research into the recycling of concrete to extract cement paste have been undertaken but yields are low and the process is experimental (Linß and Mueller, 2003).
Barriers to recycling	Technical. There are currently no effective methods to recycle cement. Issues of contaminants, material loss, material deterioration and additional environmental impacts do not apply
other	

Cement	**Recycling through industrial processes**	x	**Recycling through natural processes**	x
	Infinite recycling	x	Rate and efficiency	
	Processing efficiency	x	Hazards and quality	
	Hazards	✓		

CONCRETE (Cementing and masonry materials)

Building industry uses	In-situ concrete structures, concrete blocks, precast concrete building elements (e.g. stairs, floor panels)
Recycling statistics	Concrete that is sorted, crushed and graded to comply with performance and specification requirements for aggregate for new concrete is approximately 4 per cent.
Environmental lifecycle impacts	**CONCRETE** - concrete is manufactured by mixing cement, aggregate and water. **MANUFACTURE** - Emissions to air of particulates. Emissions to water include particulates and washwater. **EMBODIED ENERGY** - Concrete 1:3:6 – Embodied energy = 275 KWh/ tonne (Talbot, 1995)/ 600 KWh/m³ (Talbot, 1995)/ 1 MJ/kg (Berge, 2000) **ENVIRONMENTAL IMPACTS OF CONSTITUENT PARTS** **Cement** – see cement section. **Natural aggregates** – see ballast section **Sand** - obtained by surface mineral extraction and marine dredging. **Environmental impact of mining** marine dredging can cause damage to flora and fauna / coastal defences can be affected because of beach drawdown (Clough and Martyn, 1995). **Embodied energy** - energy required to win aggregate varies between 0.02 and 0.08GJ/tonne.
Environmental benefits of recycling	Main benefits relate to the recycling of aggregate, which primarily reduces the impact associated with resourcing. Carbon dioxide emissions are mainly associated with the manufacture of cement and are therefore not avoided by the use of recycled aggregate.
Recycling process	Concrete recycling involves crushing, sorting and grading the concrete to extract rubble of adequate size for new uses, aggregate for new concrete being one, hardcore being the most common. (Coventry, Woolveridge, Hillier, 1999). A new method of recycling concrete uses shock waves, which are generated by an electrical discharge under water. The system produces cement paste, free of aggregates. (Linß and Mueller, 2003)
Contaminants	Organic material and secondly metallic material (Collins, 1993). Metal, timber and masonry limit the recyclability of the concrete. Gypsum contamination makes concrete useless (Guthrie, Woolverridge, Patel, 1997) as it can cause a decrease in the strength of new concrete (Sturges and Lowe, 2000a).
Material loss through recycling process	40 per cent of material by volume would be lost if recycled aggregate is used with virgin sand and cement. Using recycled cement substitute e.g. ground blastfurnace slag, which can substitute a maximum of 80 per cent virgin cement or pulverised fuel ash which can substitute up to 60 per cent of cement, both substitutions are governed by British Standards (Coventry, Woolveridge, Hillier, 1999) then additional 10 per cent of recycled content could be envisaged in the best case scenario. Best case scenario would involve recycling 60 per cent, using 10 per cent recycled material and 30 per cent primary material.
Environmental impacts particular to recycling	Noise and dust of crushing. Impacts of extracting cement paste have to be established.

processes	
Deterioration of material	Concrete is essentially a very durable material. Concrete strength peaks @ 20 years (Doran, 1994). The dome of the Pantheon (27BC) was built with light weight concrete, using volcanic pumice as aggregate spans 50m is now over 2000 years old. (It was un-reinforced so steel corrosion is not a problem). Two ways how concrete can deteriorate: 1 concrete itself may suffer spalding and even complete disruption due to frost or chemical action 2 the reinforcement steel may corrode causing spalding and cracking of concrete cover concerns regarding durability include the use of high alumina cement and calcium chloride admixtures and the phenomena of carbonation and alkali silica reaction. The least permeable the concrete mix the more vulnerable the reinforcement. Protective coatings (epoxy/galvanised) to steel help against corrosion.
Barriers to recycling	Technological. Recovering the cement may become feasible with new technologies but recovering the sand which makes up approximately 30% of the product is at the moment unlikely. Recycling aggregate in new concrete has technical difficulties in conforming with existing standards (Coventry and Guthrie, 1998)
other	There are no design and structural testing standards for the re-use of concrete and cost-savings over new products are minimal at present.

Concrete	**Recycling through industrial processes**	x	**Recycling through natural processes**	x
	Infinite recycling	x	Rate and efficiency	
	Processing efficiency	x	Hazards and quality	
	Hazards	✓		

BALLAST (Cementing and masonry materials)

Building industry uses	general fill material and railway ballast
Recycling statistics	Nearly 50 % of aggregate is crushed and screed for reuse (Department for Environment, Food and Rural Affairs, 2007).
Environmental lifecycle impacts	**Natural aggregates – RESOURCING -** gravel is obtained by surface mineral extraction and marine dredging / hard rock quarries extract stone by blasting the rock. **Environmental impact of mining -** quarries occupy large areas of land which temporarily affect the local ecology. However, are normally restored (Clough and Martyn, 1995). The trend towards 'Superquarries' near the coast will result in longer term impact on local ecology (Ethical Consumer Research Association, 1995a). **MANUFACTURE** – the primary material is crushed and screened.
Environmental benefits of recycling	The main environmental impact that would be reduced relates to the local mining impacts on biodiversity, the local landscape, noise, dust and traffic. Most hardcore is resourced from land quarries, but some is resourced from marine dredging. Reduced marine dredging would reduce erosion and related loss of marine biodiversity. (Ethical Consumer Research Association, 1995a).
Recycling process	Screening to select desired grade of material and washing to remove contaminants. Currently good practice in road buildings (Guthrie, Woolverridge, Patel, 1997).
Contaminants	Metals, phenols, sulphates and polyacyclic aromatic hydrocarbons from sidings, fuel oil, lubricating oils, greases and antifreeze, from rail standing locations, herbicides. (Coventry, Woolveridge, Hillier, 1999, pp.161) Maximum allowable contaminants for hardcore include 10 per cent tar or asphalt, 2 per cent wood, 1 per cent clay or other materials (Building Research Establishment, 1998).
Material loss through recycling process	By filtering recovered ballast a high level of product should be attainable even if currently this is not undertaken due to economic reasons.
Environmental impacts particular to recycling processes	Grading and screening is associated with dust and noise. While this is not particularly more intrusive than the process associated with primary material it is often located in populated areas and can become a nuisance to neighbouring communities.
Deterioration of material	Biodegradable material should be excluded.
Barriers to recycling	Mainly economic.

Ballast	**Recycling through industrial processes**	✓	**Recycling through natural processes**	x
	Infinite recycling	✓	Rate and efficiency	
	Processing efficiency	✓	Hazards and quality	
	Hazards	✓		

ROCKWOOL (Cementing and masonry materials)

Building industry uses	Thermal and acoustic insulation.
Recycling statistics	None. The rock fibre recycling schemes that do exist in the UK are not widely publicised. (Steel Construction Institute, 2007)
Environmental lifecycle impacts	Resin bonded rock fibres **RESOURCES** – Diabase and limestone and coke. **Environmental impact of mining -** Quarries occupy large areas of land which temporarily affect the local ecology. However, are normally restored (Clough and Martyn, 1995). **MANUFACTURE** - Rock and coke are heated to 1500°C and the rock fibres are bonded with 2 per cent of phenol glue and made into bats or loose wool. Aliphatic oils are added to reduce dust (Berge, 2000). **Environmental impact of manufacture** – there is evidence of health impacts on worker in factories who appear to have a higher occurrence of cancer. (Ethical Consumer Research Association, 1995a). **EMBODIED ENERGY** - 230 KWh/m³ (Talbot, 1995), 16 MJ/kg (Berge, 2000) **DISPOSAL** – Rockwool does not biodegrade and in landfill has not been found to leach out hazardous substances. (Ethical Consumer Research Association, 1995a).
Environmental benefits of recycling	Reduction of above impacts.
Recycling process	Recycling rock fibre –rock fibre waste is compacted into briquettes that can be introduced into the standard manufacturing process. Currently this is primarily used to recycle manufacturing waste rock fibre and less than 1%, coming from post-consumer or demolition waste sources. (Steel Construction Institute, 2007)
Contaminants	The level of contamination in post-consumer or demolition rock fibre waste that can be considered acceptable has not been established. It is expected that rockwool extracted from metal panels is cleaner than that recovered from wall or roof installations. (Steel Construction Institute, 2007)
Material loss through recycling process	Material loss is expected to occur during the process removal of the insulation from the building installations. Decontamination of rock fibre waste material is considered technically feasible, but economically expensive. (Steel Construction Institute, 2007)
Environmental impacts particular to recycling processes	The impact of transportation of this low density product is significant (Steel Construction Institute, 2007).
Deterioration of material	Deterioration of material is minimal if enclosed.
Barriers to recycling	Economic. (Steel Construction Institute, 2007)
Other	Rockwool Ltd. is a good example of an Industrial Ecology system partner. Through the European funded LIFE programme Rockwool Ltd. has begun using waste products from other industries in their production. (Rockwool International, nd.).

Rockwool	**Recycling through industrial processes**	✓	**Recycling through natural processes**	x
	Infinite recycling	✓	Rate and efficiency	
	Processing efficiency	✓	Hazards and quality	
	Hazards	✓		

PE / EPS (THERMOPLASTICS) (Plastics / oil-based products)

Building industry uses	PE – water pipes, waste water pipes, damp-proof courses and membranes, separating membranes, **vapour control layers** **EPS – thermal insulation**
Recycling statistics	0.5-2% in UK, USA, Canada, France, Italy, Germany (Shent, Pugh, Forssberg, 1999). **Virgin LLDPE pellets c £450/tonne, treated clean LLDPE process scrap costs £400-480/tonne, post-consumer scrap costs £600-680/tonne** (Environmental Resources Management for the Department of Trade and Industry, 2002c). Successful recycling trials have already been conducted on polypropylene breather membranes and polythene vapour control layers but this is not current practice (Steel Construction Institute, 2007). recycled EPS is used to manufacture extrusions for furniture however it is not reformed into its original state.
Environmental lifecycle impacts	**RESOURCING** – crude oil is processed in naphtha which is processed to produce ethylene / crude oil can be separated into groups of chemicals by fractionation. Natural gas can also be processed to give ethylene - **natural resource depletion** - Known reserves of oil are estimated to last 40 years at current consumption, gas reserves 60 years. **environmental impact of mining** - Impact of mining includes pollution form flaring, marine and land pollution from oil spills and leaks (particularly from tanker accidents) affecting the flora and fauna. **MANUFACTURE** – EPS - ethylene and benzene are combined to produce ethylbenzene, which is dehydrogenated to produce styrene. Styrene is polymerised and blown with HCFCs to form expanded polystyrene or with pentane to form beadboards. **Environmental impact of production** - Pollutants to air include VOCs SOx, NOx, COx and particulates. Pollutants to water include sulphides, oil and soluble organic matter. Pollutants to land include spent catalysts, process sludges and sediments, most hazardous are polynuclear aromatics & heavy metals **EMBODIED ENERGY** Energy required to produce 1kg of polystyrene is 30MJ/kg, the calorific value is 66MJ/kg therefore the total energy is 96MJ/kg (Clough and Martyn, 1995a). Embodied energy - 84 MJ/kg (Berge, 2000) Polyethylene (PE) 67 MJ/kg (Berge, 2000) **HEALTH** - Emissions from polystyrene production include SOx, NOx, COx, hydrocarbons and particulates. **DISPOSAL** - Polystyrene present a hazard in case of fire giving off CO, CO_2, smoke and water vapour.
Environmental benefits of recycling	90% energy savings of recycling plastic manufacturing waste compared to landfilling and 66% savings compared to incineration and 97% CO2 savings of recycling plastic manufacturing waste compared to landfilling and 89% savings compared to incineration (Plinke *et al.*, 2000) Resourcing impacts are reduced and possibly obviated totally.
Recycling process	Recycling material is sorted, crushed, cleaned and separated from secondary products before being reprocessed. **Plastics separation** - Plastics flotation is used in separating mixtures of plastics. Automatic sorting, gravity separation and electrostatic separation are alternative methods of separating mixed plastics, but have limitations (Shent, Pugh, Forssberg, 1999). Separating different type of plastics is critical in achieving high quality secondary plastics particularly when recycled by mechanical means. (Environmental Resources Management for the Department of Trade and Industry, 2002c). **Plastics cleaning** - Adhesives are typically alkali- or water-soluble and can easily be removed. Adhesives that are made of the same plastic can be recycled without having to be removed. Almost all bonded materials

	can be removed relatively easily, often by the use of high temperatures, which may damage the material and adds cost. (Environmental Resources Management for the Department of Trade and Industry, 2002c). **Mechanical recycling** involves grinding the waste into pellets or granules for extrusion into new products, typically with an addition of virgin materials, pigments and stabilisers. **Feedstock or chemical recycling**, such as **thermolysis**, can treat mixed plastic waste and decomposes the polymers into individual monomers by depolymerisation. Small amounts of contamination are acceptable (Environmental Resources Management for the Department of Trade and Industry, 2002c).
Contaminants	Dissimilar plastics, paper, metal.
Material loss through recycling process	Mechanical recycling efficiencies are similar in range to UPVC
Environmental impacts particular to recycling processes	Mechanical and chemical recycling should have same impacts as virgin manufacture, no explicit data was available.
Deterioration of material	Excessive heating will degrade the material. EPS insulation is expected to last over 50 years particularly if not exposed (Everett, 1994).
Barriers to recycling	Contamination and cost. The production of high-quality recyclates with defined technical specifications (e.g. strength, elasticity, colour) requires pure recyclate. (Plinke *et al.*, 2000)
Other	Sensitive labels used in the automobile industry or electronic industry. These labels are expected to stick to the surfaces safely for decades, but do not disturb the later material recycling of the construction parts Recycled polyethylene terephthalate (PET) can be used to manufacture carpets, new bottle pre-forms, fibres for clothes, sheets and binders. (Environmental Resources Management for the Department of Trade and Industry, 2002c).

Thermoplastics PE vapour control layer	**Recycling through industrial processes**	✓	**Recycling through natural processes**	x
	Infinite recycling	✓	Rate and efficiency	
	Processing efficiency	✓	Hazards and quality	
	Hazards	✓		

Thermoplastics EPS insulation	**Recycling through industrial processes**	✓	**Recycling through natural processes**	x
	Infinite recycling	✓	Rate and efficiency	
	Processing efficiency	✓	Hazards and quality	
	Hazards	✓		

PVC/ UPVC (THERMOPLASTICS) (Plastics / oil-based products)

Building industry uses	PVC Floor coverings, sarking, water stops, preformed joint seals, clip-on extrusions, electrical cables, coatings UPVC – windows, waste water pipes, rainwater pipes
Recycling statistics and information	None specific - 0.5-2% in UK, USA, Canada, France, Italy, Germany (Shent, Pugh, Forssberg, 1999). little recycling of PVC exists and consists of low grade recycling to produce street furniture
Environmental lifecycle impacts	**RESOURCING** – crude oil is processed in naphtha which is processed to produce ethylene / crude oil can be separated into groups of chemicals by fractionation. Natural gas can also be processed to give ethylene - **natural resource depletion** - known reserves of oil are estimated to last 40 years at current consumption, gas reserves 60 years. **environmental impact of mining** - impact of mining includes pollution form flaring, marine and land pollution from oil spills and leaks (particularly from tanker accidents) affecting the flora and fauna. **MANUFACTURE** – Crude oil is processed in naphtha which is processed to produce ethylene. Crude oil can be separated into groups of chemicals by fractionation. Natural gas can also be processed to give ethylene. Chlorine is produced by electrolysis of sodium chloride solution, which is purified from brine. Purification process removes calcium, magnesium and iron, which are disposed in landfill ethylene is combined with chlorine and hydrogen chloride to produce ethylene dichloride and then is cracked to produce vinyl chloride monomer and hydrogen chloride vinyl chloride monomer is polymerised at high pressure and at 50-60°C in presence of water. PVC pollutants to air include VOCs SOx, NOx, COx and particulates. Pollutants to water include sulphides, oil and soluble organic matter. Pollutants to land include spent catalysts, process sludges and sediments. The most hazardous are polynuclear aromatics and heavy metals. Emissions from electrolysis processes to produce chlorine include chlorine to air and sodium hypochlorite to water and mercury if amalgam cells are used. Waste includes contaminated sludge. Emissions from PVC production include vinyl chloride, ethylene dichloride, particulates and SOx, NOx, COx (Ethical Consumer Research Association, 1995). **EMBODIED ENERGY** The energy to produce 1kg of PVC is 35MJ/kg, the calorific value of 1kg of PVC is 24MJ/kg giving a total energy content of 59MJ/kg (Clough and Martyn, 1995a). **HEALTH** - PVC flooring releases high concentrations of plasticisers and small concentrations of unreacted vinyl chloride. Chlorine is highly toxic , if incinerated PVC can form chlorinated dioxins and furans. **DISPOSAL** - PVC releases chlorinated dioxins and furans when burnt.
Environmental benefits of recycling	90% energy savings of recycling plastic manufacturing waste compared to landfilling and 66% savings compared to incineration and 97% CO2 savings of recycling plastic manufacturing waste compared to landfilling and 89% savings compared to incineration. PVC pipes with 50 per cent recyclate compared with PVC from primary material would save 10 per cent energy, 9 per cent CO2 emissions and 16 per cent emissions (Plinke et al., 2000). Resourcing impacts are reduced and possibly obviated totally, including resource depletion of oil and rocksalt, and impacts on natural environment due to transport of oil. Manufacturing impacts of vinyl chloride monomer are avoided
Recycling process	Recycling material is sorted, crushed, cleaned and separated from secondary products before being reprocessed. Plastics separation - Plastics flotation is used in separating mixtures of plastics. Automatic sorting, gravity separation and electrostatic separation are alternative methods of separating mixed plastics, but have limitations (Shent, Pugh, Forssberg, 1999). Separating different type of plastics is critical in achieving high quality secondary plastics particularly when recycled by mechanical means.

	(Environmental Resources Management for the Department of Trade and Industry, 2002c). Mechanical recycling involves grinding the waste into pellets or granules for extrusion into new products, typically with an addition of virgin materials, pigments and stabilisers. Feedstock or chemical recycling, such as thermolysis, can treat mixed plastic waste and decomposes the polymers into individual monomers by depolymerisation. Small amounts of contamination are acceptable (Environmental Resources Management for the Department of Trade and Industry, 2002c). The Vinyloop® PVC recovery, developed by Solvay, involves first shredding the PVC and then dissolving it in a solvent to separate out its additives after which it is recovered and dried. This does not involve depolymerisation but does result in a pure PVC. This process can be used to recycle cables, pharmaceutical blister packs, floor finishes, car dashboards, etc. and is considered by the company undertaking the recycling as a closed loop system that has no emissions to water (Tukker et al., 1999).
Contaminants	Mixed material can potentially contaminate the recyclate.
Material loss through recycling process	Mechanical recycling of vinyl flooring is limited to 30 per cent due to contaminations like glue, sand or concrete. Mechanical recycling of PVC windows suffers material losses is in the order of 30-40 per cent. Some of the losses are due to the extensive separation process to remove rubber, metals, glass, sorting by colours, etc. Material losses when recycling pipes with mechanical treatment are lower, approximately 10%, and lower again with chemical treatment (Plinke *et al.*, 2000).
Environmental impacts particular to recycling processes	The Vinyloop ® PVC recovery system is said not to have emissions to water, evidence of other emissions was not found.
Deterioration of material	Typical life of a PVC floor is 10 years it is non-degradable (Shiers, Howard, Sinclair, 1996, p.50). Rainwater goods can be expected to remain in good service for 20 years (Everett, 1994).
Barriers to recycling	The production of high-quality recyclates with defined technical specifications (e.g. strength, elasticity, colour) requires pure recyclate. However, PVC waste is often mixed and additives can make up more than 50% of plasticised PVC. UPVC can be 85% (windows) to 98% (pipes) pure PVC. **Consequently 100% substitution of virgin PVC is more likely in UPVC than PVC**. Equally, recycled products are of different colours, so the recycling process must colours or colour must be immaterial to product. Where mixed PVC types cannot be separated the recyclate can only be used for inferior uses (i.e. downcycled) (Plinke *et al.*, 2000)
Other	In some applications, like window frames, PVC wastes of different compositions can be mixed and used as core material covered with virgin PVC.

Thermoplastics PVC	Recycling through industrial processes	x	Recycling through natural processes	x
	Infinite recycling	x	Rate and efficiency	
	Processing efficiency	x	Hazards and quality	
	Hazards	✓		

Thermoplastics UPVC	Recycling through industrial processes	✓	Recycling through natural processes	x
	Infinite recycling	✓	Rate and efficiency	
	Processing efficiency	✓	Hazards and quality	
	Hazards	✓		

PU (THERMOSETTING PLASTICS) (Plastics / oil-based products)

Building industry uses	Thermosetting plastics include: Phenol formaldehyde PF/ Urea formaldehyde UF/ Melamine formaldehyde MF/ Resorcinol formaldehyde RF/ Polyester resin UP/ Epoxide resins EP/ Silicon resins SI **Products include: Insulation (PU**, UF), electrical mouldings (UF), laminates (MF), adhesives for woos (RF), in-situ flooring (EP), sealants (SI), impregnants for building fabrics, adhesives, binders for glass-fibre reinforced plastics, binders in paints and clear finishes (Everett, 1994)
Environmental lifecycle impacts	**RESOURCING** – Oil and gas are the base materials for form two polyethers and isocyanates which are reacted together with a tin catalyst. Phenol propionate is a typical anti oxidant used and a bromine compounds is used as a flame retardant. **Natural resource depletion** - known reserves of oil are estimated to last 40 years at current consumption, gas reserves 60 years. **Environmental impact of mining** - impact of mining includes pollution form flaring, marine and land pollution from oil spills and leaks (particularly from tanker accidents) affecting the flora and fauna. (Ethical Consumer Research Association, 1995). **MANUFACTURE** – Pentane or carbon dioxide is used to foam the plastic to form a rigid structure. **Environmental impact of manufacture** – Chlorinated hydrocarbons, phenolformaldehyde, ammonia and possibly timn and chlorofluorocarbons are emitted to air. (Berge, 2000) **HEALTH** – Workers in factories and during installation may be exposed to isocyanates (Berge, 2000) **EMBODIED ENERGY** - Ureaformaldehyde 40 MJ/kg, Polyurethane 110 MJ/kg (Berge, 2000)
Environmental benefits of recycling	Reduction of embodied energy, resource use and impacts.
Recycling process	Thermosetting plastics undergo a irreversible chemical change. A curing agent make the molecular chain cross link which creates rigid structure. Once set thermosetting plastics cannot be softened with heat and char when heated excessively. (Everett, 1994) Therefore, binders, treatments and paints cannot be separated as a material. Insulation boards can be separated and ground into a powder. This powder can be reprocessed mechanically to make high density boards for use in construction. Reintroducing the powder into the standard manufacturing process have been attempted by Kingspan and the results is technically successful but not economically feasible. However, the recycled powder would only constitute a small percentage of the product. (Steel Construction Institute, 2007)
Contaminants	Thermosetting plastics include fillers, such as wood flour, asbestos, glass, cotton flock, silica and metallic powders.
Material loss through recycling process	Reprocessing the powder into a lower grade board is downcycling. Recyclate content when reintroducing recyclate in standard manufacturing process is very low.
Environmental impacts particular to recycling processes	The dust could have negative impacts on health but no information is available.
Barriers to recycling	Technical.

Thermosetting plastics PU insulation	**Recycling through industrial processes**	x	**Recycling through natural processes**	x
	Infinite recycling	x	Rate and efficiency	
	Processing efficiency	x	Hazards and quality	
	Hazards	x		

GLASS (Plastics / oil-based products)

Building industry uses	**Windows**, rooflights and doors, structural members and floor elements
Recycling statistics	By separating differently coloured glass and aided by quality assurance processes a green glass bottles in Germany consists of more than 90% of used glass, brown and white bottles 50% (Onusseit, 2006)
Environmental lifecycle impacts	**RESOURCES** - Silica(quartz sand), sodium carbonate or lime(calcium oxide) sodium or potassium salts (eg. soda- sodium oxide) are the basic ingredients. Sodium carbonate can be mined as a mineral or produced by the Solvay process, where ammonia is added to brine to from sodium bicarbonate. This is heated to form sodium carbonate. Ammonia is produced form natural gas and brine is produced from mined salt. **Natural resource depletion** limestone and chalk reserves are generally abundant, with the exception of the south-east where 'permitted' reserves are running low. **Environmental impact of mining** - Quartz is extracted by surface mineral extraction and affects the local ecology by occupying large areas of land, which are normally restored. The extraction process results in particulate emissions to the air and water, surface or ground water courses can be interrupted (Clough and Martyn, 1995). **MANUFACTURE** - the silica and the additives are fired at 1500-1600°C, there are three methods of producing glass: 1/vertical drawing produced drawn glass; 2/flat sheet casting and rolling for patterned glass; 3/floating on molten metal for float glass. Some production waste is used in the manufacturing process (Doran, 1994). **Environmental impact of manufacture** - emissions to the air of SOx, NOx, CO, CO2, fluoride, chlorides and particulates. Lead can be emitted through production of lead compounds for lead glass. Waste form the process include organic solvents, alkalis and alkali earth metals and their oxides **EMBODIED ENERGY** 9,200 KWh/ tonne, 23,000 KWh/m³ (Talbot, 1995), 8 MJ/kg (Berge, 2000)
Environmental benefits of recycling	Resource savings are made but not critical as base material is plentiful. The use of recycled cullet reduces the amount of manufacturing energy required (Pilkington Group Limited, 2008). Energy savings of 20 per cent are possible with bottle production (Onusseit, 2006).
Recycling process	Reclaimed glass can be sorted by colour with automated laser sorting machinery. The cullet is then reintroduced in the standard manufacturing process (Environmental Resources Management for the Department of Trade and Industry, 2002d). Glass is recycled by melting it at a temperature of about 1550°C.
Contaminants	The main contaminant is glass of a different colour. Green glass is the majority of recycled glass and if not suitably sorted it will affect the new glass colour. (Environmental Resources Management for the Department of Trade and Industry, 2002d). Adhesives based on casein or synthetic polymers used to label glass bottles, and polysulfide and butyl rubber adhesives in double glazed units burn at high temperatures necessary to melt glass and therefore do not compromise the recycling process (Onusseit, 2006) Building glass may have silicon and mastic contamination. Other contaminants are ceramics and pyrex (Pilkington Group Limited, 2008).
Material loss through recycling process	Glass manufacturing processes for containers (e.g. bottles) can include a high percentage of recycled glass subject to it being of high enough quality. For buildings products and for the car industry, Pilkington uses 15 per cent of recycled glass cullet in the flat glass production (Pilkington Group Limited, 2008). However, this is not necessarily post-consumer waste even

	though the mention by Pilkington of contaminants including ceramics and pyrex would suggest it refers to post-consumer waste.
Environmental impacts particular to recycling processes	None
Deterioration of material	No quality deterioration is experienced using the limited levels of 15 per cent cullet in building products.
Barriers to recycling	Fragility of material. Economic - prices of cullet feedstock is higher than soda ash (Pilkington Group Limited, 2008).

Glass	Recycling through industrial processes	x	Recycling through natural processes	x
	Infinite recycling	x	Rate and efficiency	
	Processing efficiency	x	Hazards and quality	
	Hazards	✓		

STEEL (Metals)

Building industry uses	structural elements, roofing, wall cladding, rainwater goods, curtain walling, windows and doors
Recycling statistics	A study of steel construction in the UK, Netherlands and Sweden concluded that 83% of steel products are recycled, 14% are re-used, and 3% are landfilled (Durmisevic and Noort, 2003). Exceptions are: 59% post coated inner wall components and 53% composite sandwich cladding panels were found to be recycled, 7% and 37% respectively were reused and 34% and 10% respectively were landfilled. (Onusseit, 2006)
Environmental lifecycle impacts	Pig iron is made by mixing iron ore, coke and limestone in a blast furnace. **Natural resource depletion** – 200 years of supply at current rates of consumption. 100 years of supply at exponential growth rates of consumption (Howard, 1995). **Environmental impact of mining** - solid waste arises from mining. Land clearance in Brazil may contribute to rainforest destruction. **MANUFACTURE** – Liquid pig iron and scrap is heated in a blast furnace fired to 1200°C, after the impurities have been eliminated the temperature rises to iron's melting point 1535°C. Deoxydation takes place in a third heating process to produce liquid steel which can be cast in ingots or continuously cast in sections. Steel will corrode in the presence of oxygen and water therefore requires treatment. Stainless steel containing 12 per cent chromium does not need protection. Corten steel containing 1-2 per cent chromium and copper produces a protective layer of rust. Other steel has to be either actively protected with a layer of zinc (galvanisation) where the zinc is anodic and will corrode in preference to steel or protected with a inert barrier such as pitch, tar, bitumen (organic barrier) or enamel or cement (inorganic barrier). Enamels include oil based paints, chlorinated rubber, vinyl paints based on PVC/PVA, epoxy resin, plastic coatings (PVC, polyester, fluorocarbons), plastisol. **Environmental impact of production** - solid waste results from secondary steel-making, toxic and phytoxic metals may enter cleaning waters. Emissions to the air is thought to be a major source of dioxin emissions. Other emissions to the air include iron oxides, lead, cadmium, mercury, cyanide, zinc, copper, nickel, coal dust, oil, carbonyl, fluoride, alkali fumes. The dioxins released during manufacture are thought to be hormone disrupters (Ethical Consumer

	Research Association, 1996). **EMBODIED ENERGY** Primary steel production requires 25-33GJ/tonne (3 tonnes of CO_2 emissions /tonne of steel) / recycled steel production requires 10GJ/tonne (1.6 tonnes CO_2 emissions/tonne recycled steel) (Howard, 1995). Other figures include: 13,200 KWh/ tonne, 103,000 KWh/m³ (Talbot, 1995), 25 MJ/kg (Berge, 2000).
Environmental benefits of recycling	Energy savings reduce the original embodied energy ratings of
Recycling process	most steel frames dismantled using thermal lances or shears steel sections are either bolted or welded together steel is cut or unbolted and transported to the steel work to be recycled Steel can be easily separated magnetically recycling potentially 95 per cent of steel could be recycled / in 1984 15.12 million tonnes of steel were made with 7.86 million tonnes of scrap of which half arises in the steel works themselves, and the rest comes from processing industries and from post consumer scrap (14 per cent) / post consumer scrap can contain contaminants, such as copper or tin, as recycling increases these 'tramp' elements may become problematic (Doran, 1994).
Contaminants	As a consequence of the high temperatures of the metal recycling processes, adhesives used for labelling of cans and for bonding in construction and transportation made of organic polymers incinerate and make recycling possible (Onusseit, 2006) Tin, copper and zinc can drastically reduce the value of recycled iron (Lin and Lin, 2003).
Material loss through recycling process	Stainless steel if virtually completely made of scrap metal and this applies globally to the stainless steel industry, therefore there is no reason to believe that this cannot apply to all steel. (Howard, 1995)
Environmental impacts particular to recycling processes	Transport, however this is not necessarily in excess of that associated with the production with primary materials.
Deterioration of material	no value deterioration no quality deterioration (Onusseit, 2006)
Barriers to recycling	Economic fluctuations of primary material costs
other	The Steel Construction Institute offers guidelines on the appraisal of existing iron and steel structures for structural reuse (Morgan and Stevenson, 2005).

Steel	Recycling through industrial processes	✓	Recycling through natural processes	x
	Infinite recycling	✓	Rate and efficiency	
	Processing efficiency	✓	Hazards and quality	
	Hazards	✓		

TIMBER (Materials of wood and other natural sources)

Building industry uses	structure, stairs, windows, doors, fixtures and fittings, cladding, roof coverings
Recycling statistics	350 - 400 000 tonnes of wood is estimated to be recycled annually
Environmental lifecycle impacts	Timber is a renewable source covering approximately one third of the world's land surface. There is a growing stock of about 300,000 million m³ of timber. 40% of the growing stock is used in the paper industry, 38% is used for sawn timber, 22% for wood panels (Doran, 1994). **Natural resource depletion-** Deforestation remains one of the most pressing environmental problems. **Environmental impact of harvesting -** Deforestation of the old forests results in the destruction of natural habitats and plant and animal species within. (Ethical Consumer Research Association, 1995). A number of managed forests are now established and have been operating in for some time. Managed forests also include plantations that are often monocrop and require insecticide treatments. **embodied energy** the embodied energy of timber depends very much on the distances it has to be transported. Timber trade federation states a figure of 5.3MJ/kg for converting, kiln drying and treating rough sawn timber. (Newton and Venables, 1995). imported softwood - 1,450 KWh/ tonne, 7,540 KWh/m³ (Talbot, 1995), 3 MJ/kg (Berge, 2000). Timber local airdried - 200 KWh/ tonne, 110 KWh/m³ (Talbot, 1995). Timber local green oak - 200 KWh/ tonne, 220 KWh/m³ (Talbot, 1995)
Environmental benefits of recycling	Recycling reduces resource depletion and associated impacts. Composting avoids landfill impacts.
Recycling process	The timber has to be screened to separate the timber with different treatments (e.g. painting, stains, treatments, fixings etc.). Timber waste has to be pre-wetted and then shredded to appropriate sizes to include in a composting process. This may require several shredding processes. Wetting is required during the composting process as well. The composting can take places as windrows, aerated static piles, silos, rotary drums and fixed batch tunnels (ADAS UK Ltd., 2007).
Contaminants	Aggregates, bricks, ceramic tiles, concrete, glass, gypsum, plaster' asbestos, asphalt shingles, carpets, linoleum, dirt, soiling, stones, drywall lining, fibre glass, insulation, metallic (ferrous and non ferrous) compounds, plastic compounds, paper, cardboard, tar paper, wall papers, Creosote, preservatives, waxes, oils, paints, lacquers, glues, adhesives, fire retardants (ADAS UK Ltd., 2007). Physical contaminants need to be removed before reuse or composting. Drum grinders can cope with nails to enable the recycling of timber. Treatments can create a health hazard when timber is reworked. Water can reduce its recyclability and reuse potential (Guthrie, Woolverridge, Patel, 1997) but is irrelevant to biodegradation.
Material loss through recycling process	Timber product can last hundreds of years if detailed appropriately and can then be reused without loss of quality. However, adjustments to enable reuse are typically associated with material loss (Newton and Venables, 1995). Composting recovers 100% of material.
Environmental impacts particular to recycling	Wood or stripping off paint generates a range of toxic and irritant gases. Treated wood can not be burnt in most wood fired plants, treated timber in landfill site can produce contaminated leachate.

processes	Shredding of timber board waste may offgas formaldehyde (ADAS UK Ltd., 2007).
Deterioration of material	Compost produced has to achieve appropriate levels of quality and if not has to be further treated.
Barriers to recycling	Economic related to collection and pre-processing.
other	Timber re-used for structural purposes must be strength-graded to BS4978 (softwood) or BS5756 (hardwood) TRADA can undertake visual inspections to assess strength of timber (Morgan and Stevenson, 2005).

Timber	**Recycling through industrial processes**	x	**Recycling through natural processes**	✓
	Infinite recycling	x	Rate and efficiency	✓
	Processing efficiency	x	Hazards and quality	✓
	Hazards	x		

CELLULOSE FIBRE (Materials of wood and other natural sources)

Building industry uses	Insulation for lofts and timber framed buildings. Can be sprayed, bagged or loose laid.
Recycling statistics	None
Environmental lifecycle impacts	**RESOURCES** - Recycled cellulose fibres are derived from recycled newsprint, which is collected through municipal collection systems. Main impacts are associated with transport. **MANUFACTURE** - Waste paper is processed to a fluffy pulp and treated with borax (sodium tetraborate) for fire and insect resistance. **environmental impact of manufacture** - CO_2, SOx, NOx emissions to air through energy consumption. Borax is moderately toxic, but generally considered an environmentally acceptable pesticide. **EMBODIED ENERGY** 0.48GJ/m³ (Ethical Consumer Research Association, 1995b). 133 KWh/m³ (Talbot, 1995), 21 MJ/kg (Berge, 2000)
Environmental benefits of recycling	Avoidance of landfill.
Recycling process	The insulation has to be collected and contaminants have to be removed. It can then be reintroduced in the manufacturing process. It can also be made to biodegrade or be used as grass seed mulch. (Excel Industries Ltd., nd.)
Contaminants	Extraneous objects such as timber, metal or plastic objects.
Material loss through recycling process	While the recycling process causes a certain degradation of the material, the extent of which is not known, the product can also be made to biodegrade 100 per cent.
Environmental impacts particular to recycling processes	None
Deterioration of material	Some deterioration through recycling. Deterioration irrelevant to biodegradation.
Barriers to recycling	Economic. Collection of loose insulation is time consuming.
other	

Cellulose fibre	**Recycling through industrial processes**	x	**Recycling through natural processes**	✓
	Infinite recycling	x	Rate and efficiency	✓
	Processing efficiency	x	Hazards and quality	✓
	Hazards	✓		

CORK (Materials of wood and other natural sources)

Building industry uses	Insulation, flooring
Recycling statistics	None
Environmental lifecycle impacts	**RESOURCE** - Cork is the bark the cork oak tree grown in Portugal, Spain and North Africa. The cork can be harvested every 9-12 years. **Natural resource depletion** – Harvesting frequencies above those that allow for renewal of the bark would unbalance the industry and could destroy it. **Environmental impact of harvesting** The techniques for harvesting are still low tech and have limited environmental impact. **MANUFACTURE** – The cork granules are cooked at high temperature (250-300°C) and under pressure to form a mat. The corks glue components are released with the heat and bind the granules. (Berge, 2000) **TRANSPORT** – The material has to be transported from relatively far away therefore is associated with emissions of CO_2, NOx and SOx. **EMBODIED ENERGY** - 4 MJ/kg (Berge, 2000) **DISPOSAL** – The material is 100per cent natural and therefore biodegradable.
Environmental benefits of recycling	The reuse of cork will reduce all environmental impacts, particularly beneficial is the avoidance of resource depletion. Despite the material being renewable, it is limited in availability without overharvesting it.
Recycling process	Cork can be made to disintegrate from its board form into granules which can be reformed into new products. It can also be made to biodegrade.
Contaminants	Fixings and other materials used in conjunction with the cork insulation have to be removed before recycling. Cork floor may be glued and would have to have the glue removed before recycling. Subject to using a natural glue the flooring with glue can be composted.
Material loss through recycling process	Minimal through recycling. None through composting.
Environmental impacts particular to recycling processes	None.
Deterioration of material	None.
Barriers to recycling	Technical for floors that are glued. Removable glues would allow for the cork sheets to be reused. No barriers for composting.
other	

Cork	**Recycling through industrial processes**	✓	**Recycling through natural processes**	✓
	Infinite recycling	✓	Rate and efficiency	✓
	Processing efficiency	✓	Hazards and quality	✓
	Hazards	✓		

APPENDIX 11 - CLMC ASSESSMENT: BUILDING ELEMENT SHEETS (RESULTS FROM APPLICATION OF ORIGINAL ASSESSMENT TOOL)

APPENDIX 11 IS RELATED TO SECTION 4.6 'ASSESSMENT CRITERIA FOR CLMC' AND SECTION 5.2 'BUILDING ELEMENT ASSESSMENT'

Appendix 11 represents the results from the process of applying the criteria developed in section 4.6 to a selection of building components. As with the assessment of materials in Appendix 11, the aim was twofold: firstly to establish whether the system of criteria was appropriate for its designated purpose (results are described in section 5.2.1), and secondly to assess a selection of building components that would used in the subsequent whole building assessment. The building component assessment makes use of the material assessments previously competed.

The assessments were based on information on specification for building components installation gained through a literature review of construction products.

A form was devised to record the assessment. The parts of the form that are not to be altered are shaded in grey and the parts to be completed are white. Compliance with the criteria for recycling through natural and industrial processes will be recorded with a tick (✓) and non-compliance with a cross (x). Space on the form is provided to record the amounts of materials of the building component in question. The sheets follow the principle of the beam and block floor table below.

Sample assessment results table for a Beam and Block floor.

Note: for a real assessment the quantities of materials would be included to allow a quantitative assessment of the types of waste associated with the construction.

Beam and block floor with a screed finish Building name or reference	**Overall compliance with closed loop material cycle criteria**	x
Constituent part compliance	Key: compliant = ✓ non-compliant = x Disposal options: RI = Industrial recycling RN = Natural recycling L = Landfill or incineration	
Constituent part description	Quantity	RI/RN/L
Cement screed layer	????	L
Concrete beams and blocks	?????	L

Deconstruction process	x	notes
Ability to access	✓	fully accessible
Accessibility of fixings	x	screed bonded to substrate
Types of connections	x	screed bonding impedes damage-free separation
Durability of fixings		n/a
Information	✓	standard construction

Recycling process				
Cement	**Recycling through industrial processes**	x	**Recycling through natural processes**	x
	Infinite recycling	x	Rate and efficiency	
	Processing efficiency	x	Hazards and quality	
	Hazards	✓		
Concrete	**Recycling through industrial processes**	x	**Recycling through natural processes**	x
	Infinite recycling	x	Rate and efficiency	
	Processing efficiency	x	Hazards and quality	
	Hazards	✓		

Concrete trench foundations House 1				**Overall compliance with closed loop material cycle criteria**	x
Constituent part compliance				Key: compliant = ✓ non-compliant = x Disposal options: RI = Industrial recycling RN = Natural recycling L = Landfill or incineration	
Constituent part description				Quantity	RI/RN/L
Concrete trench foundation				26520 KG	L
Sand blinding				2761 KG	L
Hardcore				6626 KG	RI
Deconstruction process	x	notes			
Ability to access	x	Not accessible			
Accessibility of fixings		n/a			
Types of connections		n/a			
Durability of fixings		n/a			
Information	✓	standard construction			
Recycling process					
Concrete		**Recycling through industrial processes**	x	**Recycling through natural processes**	x
		Infinite recycling	x	Rate and efficiency	
		Processing efficiency	x	Hazards and quality	
		Hazards	✓		
Sand		**Recycling through industrial processes**	x	**Recycling through natural processes**	x
		Infinite recycling	x	Rate and efficiency	
		Processing efficiency	x	Hazards and quality	
		Hazards	✓		
Hardcore – can be recovered after concrete is demolished		**Recycling through industrial processes**	✓	**Recycling through natural processes**	x
		Infinite recycling	✓	Rate and efficiency	
		Processing efficiency	✓	Hazards and quality	
		Hazards	✓		

<table>
<tr><td colspan="3">Concrete ground bearing slab
House 1</td><td colspan="2">Overall compliance with closed loop material cycle criteria</td><td>x</td></tr>
<tr><td colspan="3">Constituent part compliance</td><td colspan="3">Key: compliant = ✓
non-compliant = x
Disposal options:
RI = Industrial recycling
RN = Natural recycling
L = Landfill or incineration</td></tr>
<tr><td colspan="3">Constituent part description</td><td colspan="2">Quantity</td><td>RI/RN/L</td></tr>
<tr><td colspan="3">Concrete ground bearing slab</td><td colspan="2">24102 KG</td><td>L</td></tr>
<tr><td>Deconstruction process</td><td>x</td><td colspan="4">notes</td></tr>
<tr><td>Ability to access</td><td>✓</td><td colspan="4">fully accessible</td></tr>
<tr><td>Accessibility of fixings</td><td></td><td colspan="4">n/a</td></tr>
<tr><td>Types of connections</td><td>x</td><td colspan="4">Inseparable friction fixing linked with foundations</td></tr>
<tr><td>Durability of fixings</td><td></td><td colspan="4">n/a</td></tr>
<tr><td>Information</td><td>✓</td><td colspan="4">standard construction</td></tr>
<tr><td colspan="6">Recycling process</td></tr>
<tr><td colspan="2">Concrete</td><td>Recycling through industrial processes</td><td>x</td><td>Recycling through natural processes</td><td>x</td></tr>
<tr><td colspan="2"></td><td>Infinite recycling</td><td>x</td><td>Rate and efficiency</td><td></td></tr>
<tr><td colspan="2"></td><td>Processing efficiency</td><td>x</td><td>Hazards and quality</td><td></td></tr>
<tr><td colspan="2"></td><td>Hazards</td><td>✓</td><td></td><td></td></tr>
</table>

<table>
<tr><td colspan="3">DPM below ground
House 1</td><td colspan="2">Overall compliance with closed loop material cycle criteria</td><td>✓</td></tr>
<tr><td colspan="3">Constituent part compliance</td><td colspan="3">Key: compliant = ✓
non-compliant = x
Disposal options:
RI = Industrial recycling
RN = Natural recycling
L = Landfill or incineration</td></tr>
<tr><td colspan="3">Constituent part description</td><td colspan="2">Quantity</td><td>RI/RN/L</td></tr>
<tr><td colspan="3">DPM PE</td><td colspan="2">89 KG</td><td>RI</td></tr>
<tr><td>Deconstruction process</td><td>✓</td><td colspan="4">notes</td></tr>
<tr><td>Ability to access</td><td>✓</td><td colspan="4">Accessible after slab is demolished</td></tr>
<tr><td>Accessibility of fixings</td><td></td><td colspan="4">n/a</td></tr>
<tr><td>Types of connections</td><td></td><td colspan="4">n/a</td></tr>
<tr><td>Durability of fixings</td><td></td><td colspan="4">n/a</td></tr>
<tr><td>Information</td><td>✓</td><td colspan="4">standard construction</td></tr>
<tr><td colspan="6">Recycling process</td></tr>
<tr><td colspan="2">DPM PE</td><td>Recycling through industrial processes</td><td>✓</td><td>Recycling through natural processes</td><td>x</td></tr>
<tr><td colspan="2"></td><td>Infinite recycling</td><td>✓</td><td>Rate and efficiency</td><td></td></tr>
<tr><td colspan="2"></td><td>Processing efficiency</td><td>✓</td><td>Hazards and quality</td><td></td></tr>
<tr><td colspan="2"></td><td>Hazards</td><td>✓</td><td></td><td></td></tr>
</table>

EPS Insulation below ground House 1				Overall compliance with closed loop material cycle criteria	✓
Constituent part compliance				Key: compliant = ✓ non-compliant = x Disposal options: RI = Industrial recycling RN = Natural recycling L = Landfill or incineration	
Constituent part description				Quantity	RI/RN/L
EPS insulation below ground				186 KG	RI
Deconstruction process	✓	notes			
Ability to access	✓	Accessible after slab is demolished			
Accessibility of fixings		n/a			
Types of connections		n/a			
Durability of fixings		n/a			
Information	✓	standard construction			
Recycling process					
EPS insulation		**Recycling through industrial processes**	✓	**Recycling through natural processes**	x
		Infinite recycling	✓	Rate and efficiency	
		Processing efficiency	✓	Hazards and quality	
		Hazards	✓		

PU Insulation at perimeter House 1				Overall compliance with closed loop material cycle criteria	x
Constituent part compliance				Key: compliant = ✓ non-compliant = x Disposal options: RI = Industrial recycling RN = Natural recycling L = Landfill or incineration	
Constituent part description				Quantity	RI/RN/L
PU perimeter insulation				87 KG	L
Deconstruction process	✓	notes			
Ability to access	✓	Accessible through digging around foundations			
Accessibility of fixings		n/a			
Types of connections		n/a			
Durability of fixings		n/a			
Information	✓	standard construction			
Recycling process					
PU insulation		**Recycling through industrial processes**	x	**Recycling through natural processes**	x
		Infinite recycling	x	Rate and efficiency	
		Processing efficiency	x	Hazards and quality	
		Hazards	✓		

<table>
<tr><td colspan="3">Wall construction: external cladding elements timber
House 1</td><td colspan="2">Overall compliance with closed loop material cycle criteria</td><td>✓</td></tr>
<tr><td colspan="3">Constituent part compliance</td><td colspan="3">Key: compliant = ✓
non-compliant = x
Disposal options:
RI = Industrial recycling
RN = Natural recycling
L = Landfill or incineration</td></tr>
<tr><td colspan="3">Constituent part description</td><td colspan="2">Quantity</td><td>RI/RN/L</td></tr>
<tr><td colspan="3">Timber cladding</td><td colspan="2">222 kg</td><td>RN</td></tr>
<tr><td colspan="3">Cladding fixings</td><td colspan="2">3 kg</td><td>RI</td></tr>
<tr><td colspan="3">Timber battens</td><td colspan="2">104 kg</td><td>RN</td></tr>
<tr><td>Deconstruction process</td><td>✓</td><td colspan="4">notes</td></tr>
<tr><td>Ability to access</td><td>✓</td><td colspan="4">Scaffolding would be required</td></tr>
<tr><td>Accessibility of fixings</td><td>✓</td><td colspan="4"></td></tr>
<tr><td>Types of connections</td><td>✓</td><td colspan="4">Screws</td></tr>
<tr><td>Durability of fixings</td><td>✓</td><td colspan="4">Depends on the actual screw type. A good quality is assumed</td></tr>
<tr><td>Information</td><td>✓</td><td colspan="4">Standard construction</td></tr>
<tr><td colspan="6">Recycling process</td></tr>
<tr><td colspan="2">Timber</td><td>Recycling through industrial processes</td><td>x</td><td>Recycling through natural processes</td><td>✓</td></tr>
<tr><td colspan="2"></td><td>Infinite recycling</td><td>x</td><td>Rate and efficiency</td><td>✓</td></tr>
<tr><td colspan="2"></td><td>Processing efficiency</td><td>x</td><td>Hazards and quality</td><td>✓</td></tr>
<tr><td colspan="2"></td><td>Hazards</td><td>✓</td><td></td><td></td></tr>
<tr><td colspan="2">Stainless steel</td><td>Recycling through industrial processes</td><td>✓</td><td>Recycling through natural processes</td><td>x</td></tr>
<tr><td colspan="2"></td><td>Infinite recycling</td><td>✓</td><td>Rate and efficiency</td><td>x</td></tr>
<tr><td colspan="2"></td><td>Processing efficiency</td><td>✓</td><td>Hazards and quality</td><td>x</td></tr>
<tr><td colspan="2"></td><td>Hazards</td><td>✓</td><td></td><td></td></tr>
</table>

Wall construction: external cladding brick House 1				Overall compliance with closed loop material cycle criteria		x
Constituent part compliance				Key: compliant = ✓ non-compliant = x Disposal options: RI = Industrial recycling RN = Natural recycling L = Landfill or incineration		
Constituent part description				Quantity		RI/RN/L
Brick				26438 kg		L
Deconstruction process	✓	notes				
Ability to access	✓	good				
Accessibility of fixings	✓	good				
Types of connections	✓	lime mortar				
Durability of fixings	✓	good				
Information	✓	standard construction				
Recycling process						
Bricks		**Recycling through industrial processes**	x	**Recycling through natural processes**		x
		Infinite recycling	x	Rate and efficiency		
		Processing efficiency	x	Hazards and quality		
		Hazards	✓			

Wall construction: external PU insulation House 1				Overall compliance with closed loop material cycle criteria		x
Constituent part compliance				Key: compliant = ✓ non-compliant = x Disposal options: RI = Industrial recycling RN = Natural recycling L = Landfill or incineration		
Constituent part description				Quantity		RI/RN/L
PU insulation				188 kg		L
Deconstruction process	✓	Notes				
Ability to access	✓	Once cladding is removed				
Accessibility of fixings	✓					
Types of connections	✓	Screws				
Durability of fixings	✓	Depends on the actual screw type. A good quality is assumed.				
Information	✓	standard construction				
Recycling process						
PU insulation		**Recycling through industrial processes**	x	**Recycling through natural processes**		x
		Infinite recycling	x	Rate and efficiency		
		Processing efficiency	x	Hazards and quality		
		Hazards	x			

Wall construction: internal plasterboard lining with skim coat House 1					Overall compliance with closed loop material cycle criteria	x
Constituent part compliance			Key: compliant = ✓ non-compliant = x Disposal options: RI = Industrial recycling RN = Natural recycling L = Landfill or incineration			
Constituent part description			Quantity		RI/RN/L	
internal lining with skim coat			2930 kg		L	
Deconstruction process	x	notes				
Ability to access	✓	Direct access				
Accessibility of fixings	x	Covered by plaster				
Types of connections	x	Nails are assumed				
Durability of fixings	x	Likely to be damaged through removal of plaster				
Information	✓	Standard construction				
Recycling process						
Gypsum		**Recycling through industrial processes**	x	**Recycling through natural processes**	x	
		Infinite recycling	x	Rate and efficiency		
		Processing efficiency	x	Hazards and quality		
		Hazards	✓			

<table>
<tr><td colspan="3">Wall construction: timber frame
House 1</td><td colspan="2">Overall compliance with closed loop material cycle criteria</td><td>✓</td></tr>
<tr><td colspan="3">Constituent part compliance</td><td colspan="3">Key: compliant = ✓
non-compliant = x
Disposal options:
RI = Industrial recycling
RN = Natural recycling
L = Landfill or incineration</td></tr>
<tr><td colspan="3">Constituent part description</td><td colspan="2">Quantity</td><td>RI/RN/L</td></tr>
<tr><td colspan="3">Panel line</td><td colspan="2">796kg</td><td>RN</td></tr>
<tr><td colspan="3">Timber frame</td><td colspan="2">2580kg</td><td>RN</td></tr>
<tr><td colspan="3">Frame fixings</td><td colspan="2">3 kg</td><td>RI</td></tr>
<tr><td colspan="3">Rockwool</td><td colspan="2">563 kg</td><td>RI</td></tr>
<tr><td colspan="3">Panelvent</td><td colspan="2">999kg</td><td>RN</td></tr>
<tr><td colspan="3">vapour control PE</td><td colspan="2">17 kg</td><td>RI</td></tr>
<tr><td colspan="3">Internal battens</td><td colspan="2">224 kg</td><td>RN</td></tr>
<tr><td colspan="3">Rockwool in service gap</td><td colspan="2">84 kg</td><td>RI</td></tr>
<tr><td colspan="3">Batten and lining fixings</td><td colspan="2">39 kg</td><td>RI</td></tr>
<tr><td>Deconstruction process</td><td></td><td colspan="4">notes</td></tr>
<tr><td>Ability to access</td><td>✓</td><td colspan="4">Each layer will expose the next</td></tr>
<tr><td>Accessibility of fixings</td><td>✓</td><td colspan="4">Good</td></tr>
<tr><td>Types of connections</td><td>✓</td><td colspan="4">Screws are assumed</td></tr>
<tr><td>Durability of fixings</td><td>✓</td><td colspan="4">Depends on the actual screw type. A good quality is assumed.</td></tr>
<tr><td>Information</td><td>✓</td><td colspan="4">Standard construction</td></tr>
<tr><td colspan="6">Recycling process</td></tr>
<tr><td colspan="2">Steel</td><td>Recycling through industrial processes</td><td>✓</td><td>Recycling through natural processes</td><td>x</td></tr>
<tr><td colspan="2"></td><td>Infinite recycling</td><td>✓</td><td>Rate and efficiency</td><td>x</td></tr>
<tr><td colspan="2"></td><td>Processing efficiency</td><td>✓</td><td>Hazards and quality</td><td>x</td></tr>
<tr><td colspan="2"></td><td>Hazards</td><td>✓</td><td></td><td></td></tr>
<tr><td colspan="2">Timber products</td><td>Recycling through industrial processes</td><td>x</td><td>Recycling through natural processes</td><td>✓</td></tr>
<tr><td colspan="2"></td><td>Infinite recycling</td><td>x</td><td>Rate and efficiency</td><td>✓</td></tr>
<tr><td colspan="2"></td><td>Processing efficiency</td><td>x</td><td>Hazards and quality</td><td>✓</td></tr>
<tr><td colspan="2"></td><td>Hazards</td><td>✓</td><td></td><td></td></tr>
<tr><td colspan="2">Rockwool insulation</td><td>Recycling through industrial processes</td><td>✓</td><td>Recycling through natural processes</td><td>x</td></tr>
<tr><td colspan="2"></td><td>Infinite recycling</td><td>✓</td><td>Rate and efficiency</td><td>x</td></tr>
<tr><td colspan="2"></td><td>Processing efficiency</td><td>✓</td><td>Hazards and quality</td><td>x</td></tr>
<tr><td colspan="2"></td><td>Hazards</td><td>✓</td><td></td><td></td></tr>
<tr><td colspan="2">PE membrane</td><td>Recycling through industrial processes</td><td>✓</td><td>Recycling through natural processes</td><td>x</td></tr>
<tr><td colspan="2"></td><td>Infinite recycling</td><td>✓</td><td>Rate and efficiency</td><td>x</td></tr>
<tr><td colspan="2"></td><td>Processing efficiency</td><td>✓</td><td>Hazards and quality</td><td>x</td></tr>
<tr><td colspan="2"></td><td>Hazards</td><td>✓</td><td></td><td></td></tr>
</table>

Roof: concrete tile covering House 1			**Overall compliance with closed loop material cycle criteria**		x
Constituent part compliance			Key: compliant = ✓ non-compliant = x Disposal options: RI = Industrial recycling RN = Natural recycling L = Landfill or incineration		
Constituent part description			Quantity		RI/RN/L
Roof slates			1320 kg		L
Deconstruction process	✓	notes			
Ability to access	✓	accessible with scaffolding			
Accessibility of fixings	✓	good			
Types of connections	✓	good			
Durability of fixings	✓	good			
Information	✓	standard construction			
Recycling process					
Concrete		**Recycling through industrial processes**	x	**Recycling through natural processes**	x
		Infinite recycling	x	Rate and efficiency	
		Processing efficiency	x	Hazards and quality	
		Hazards	✓		

Roof: rainwater goods PVC House 1			**Overall compliance with closed loop material cycle criteria**		✓
Constituent part compliance			Key: compliant = ✓ non-compliant = x Disposal options: RI = Industrial recycling RN = Natural recycling L = Landfill or incineration		
Constituent part description			Quantity		RI/RN/L
Rainwater PVC			18 kg		RI
Deconstruction process	✓	notes			
Ability to access	✓	accessible with scaffolding			
Accessibility of fixings	✓	good			
Types of connections	✓	good			
Durability of fixings	✓	good			
Information	✓	standard construction			
Recycling process					
UPVC		**Recycling through industrial processes**	✓	**Recycling through natural processes**	x
		Infinite recycling	✓	Rate and efficiency	
		Processing efficiency	✓	Hazards and quality	
		Hazards	✓		

Roof: timber frame and fixings House 1				**Overall compliance with closed loop material cycle criteria**	✓
Constituent part compliance				Key: compliant = ✓ non-compliant = x Disposal options: RI = Industrial recycling RN = Natural recycling L = Landfill or incineration	
Constituent part description				Quantity	RI/RN/L
Slates fixings				43 kg	RI
Timber battens				323 kg	RN
Timber battens				147 kg	RN
Panelvent				287kg	RN
Rockwool				458 kg	RI
Frame fixings				1 kg	RI
Timber frame				527 kg	RN
vapour control PE				52 kg	RI
lining fixings				6 kg	RI
Deconstruction process	✓	notes			
Ability to access	✓	Scaffolding will be required			
Accessibility of fixings	✓	Each layer will be accessed in sequence			
Types of connections	✓	Screws			
Durability of fixings	✓	Good quality screws are assumed			
Information	✓	standard construction			
Recycling process					
Steel	**Recycling through industrial processes**	✓	**Recycling through natural processes**	x	
	Infinite recycling	✓	Rate and efficiency	x	
	Processing efficiency	✓	Hazards and quality	x	
	Hazards	✓			
Timber products	**Recycling through industrial processes**	x	**Recycling through natural processes**	✓	
	Infinite recycling	x	Rate and efficiency	✓	
	Processing efficiency	x	Hazards and quality	✓	
	Hazards	✓			
Rockwool insulation	**Recycling through industrial processes**	✓	**Recycling through natural processes**	x	
	Infinite recycling	✓	Rate and efficiency	x	
	Processing efficiency	✓	Hazards and quality	x	
	Hazards	✓			
PE membrane	**Recycling through industrial processes**	✓	**Recycling through natural processes**	x	
	Infinite recycling	✓	Rate and efficiency	x	
	Processing efficiency	✓	Hazards and quality	x	
	Hazards	✓			

Roof: internal plasterboard lining with skim coat House 1			**Overall compliance with closed loop material cycle criteria**	x
Constituent part compliance			Key: compliant = ✓ non-compliant = x Disposal options: RI = Industrial recycling RN = Natural recycling L = Landfill or incineration	
Constituent part description			Quantity	RI/RN/L
internal plasterboard lining with skim coat			755 kg	L
Deconstruction process	x	notes		
Ability to access	✓	fully accessible		
Accessibility of fixings	x	Plaster over fixings		
Types of connections	x	Nails would be reasonable if accessible		
Durability of fixings	x	Likely to be damaged through removal of plaster		
Information	✓	standard construction		
Recycling process				
Gypsum	**Recycling through industrial processes**	x	**Recycling through natural processes**	x
	Infinite recycling	x	Rate and efficiency	
	Processing efficiency	x	Hazards and quality	
	Hazards	✓		

Floor: ceiling plasterboard lining with skim coat House 1			**Overall compliance with closed loop material cycle criteria**	x
Constituent part compliance			Key: compliant = ✓ non-compliant = x Disposal options: RI = Industrial recycling RN = Natural recycling L = Landfill or incineration	
Constituent part description			Quantity	RI/RN/L
ceiling plasterboard lining with skim coat			876 + 108	L
Deconstruction process	x	notes		
Ability to access	✓	fully accessible		
Accessibility of fixings	x	Plaster over fixings		
Types of connections	x	Nails would be reasonable if accessible		
Durability of fixings	x	Likely to be damaged through removal of plaster		
Information	✓	standard construction		
Recycling process				
Gypsum	**Recycling through industrial processes**	x	**Recycling through natural processes**	x
	Infinite recycling	x	Rate and efficiency	
	Processing efficiency	x	Hazards and quality	
	Hazards	✓		

Floor: intermediate floor structure House 1			**Overall compliance with closed loop material cycle criteria**		✓
Constituent part compliance			Key: compliant = ✓ non-compliant = x Disposal options: RI = Industrial recycling RN = Natural recycling L = Landfill or incineration		
Constituent part description			Quantity		RI/RN/L
floor lining chipboard			526		RN
I joists			833		RN
insulation between studs Rockwool			284		RI
lining fixings +frame fixings			9+1		RI
skirtings total			46		RN
Deconstruction process	x	notes			
Ability to access	✓	fully accessible			
Accessibility of fixings	✓	Layer are accessed in sequence			
Types of connections	✓	Screws			
Durability of fixings	✓	Good quality screws are assumed			
Information	✓	standard construction			
Recycling process					
Steel	**Recycling through industrial processes**	✓	**Recycling through natural processes**		x
	Infinite recycling	✓	Rate and efficiency		x
	Processing efficiency	✓	Hazards and quality		x
	Hazards	✓			
Timber products	**Recycling through industrial processes**	x	**Recycling through natural processes**		✓
	Infinite recycling	x	Rate and efficiency		✓
	Processing efficiency	x	Hazards and quality		✓
	Hazards	✓			
Rockwool insulation	**Recycling through industrial processes**	✓	**Recycling through natural processes**		x
	Infinite recycling	✓	Rate and efficiency		x
	Processing efficiency	✓	Hazards and quality		x
	Hazards	✓			

Secondary building elements- plasterboard lining with skim coat House 1			Overall compliance with closed loop material cycle criteria		x
Constituent part compliance			Key: compliant = ✓ non-compliant = x Disposal options: RI = Industrial recycling RN = Natural recycling L = Landfill or incineration		
Constituent part description			Quantity		RI/RN/L
int partitions plaster boarding			2339		L
int partition finish skim coat			287		L
Deconstruction process	x	notes			
Ability to access	✓	Fully accessible			
Accessibility of fixings	x	Plaster over fixings			
Types of connections	x	Nails would be reasonable if accessible			
Durability of fixings	x	Likely to be damaged through removal of plaster			
Information	✓	Standard construction			
Recycling process					
Gypsum		**Recycling through industrial processes**	x	**Recycling through natural processes**	x
		Infinite recycling	x	Rate and efficiency	
		Processing efficiency	x	Hazards and quality	
		Hazards	✓		

Secondary building elements – doors and windows House 1			Overall compliance with closed loop material cycle criteria		x
Constituent part compliance			Key: compliant = ✓ non-compliant = x Disposal options: RI = Industrial recycling RN = Natural recycling L = Landfill or incineration		
Constituent part description			Quantity		RI/RN/L
door leaves			62		RN
door frames			89		RN
entrance door leaf			31		RN
entrance door frame			11		RN
Timber window frames			249		RN
Glass in windows			266		L
Deconstruction process	x	notes			
Ability to access	✓	fully accessible			
Accessibility of fixings	✓	Bead fixings accessible with appropriate tools			
Types of connections	✓	screws			
Durability of fixings	✓	good			
Information	✓	standard construction			
Recycling process					
Timber products		**Recycling through industrial processes**	x	**Recycling through natural processes**	✓
		Infinite recycling	x	Rate and efficiency	✓
		Processing efficiency	x	Hazards and quality	✓
		Hazards	✓		

Glass	**Recycling through industrial processes**	x	**Recycling through natural processes**	x
	Infinite recycling	x	Rate and efficiency	x
	Processing efficiency	x	Hazards and quality	x
	Hazards	✓		

Secondary building elements – timber frame with insulation House 1		**Overall compliance with closed loop material cycle criteria**	x
Constituent part compliance		Key: compliant = ✓ non-compliant = x Disposal options: RI = Industrial recycling RN = Natural recycling L = Landfill or incineration	
Constituent part description		Quantity	RI/RN/L
int partitions framing		608	RN
int partitions insulation Rockwool		231	RI
internal partitions fixings		5	RI

Deconstruction process	x	notes
Ability to access	✓	Accessible after lining is removed
Accessibility of fixings	✓	Good
Types of connections	✓	Screws
Durability of fixings	✓	Good quality screws are assumed
Information	✓	Standard construction

Recycling process

Steel	**Recycling through industrial processes**	✓	**Recycling through natural processes**	x
	Infinite recycling	✓	Rate and efficiency	x
	Processing efficiency	✓	Hazards and quality	x
	Hazards	✓		
Timber products	**Recycling through industrial processes**	x	**Recycling through natural processes**	✓
	Infinite recycling	x	Rate and efficiency	✓
	Processing efficiency	x	Hazards and quality	✓
	Hazards	✓		
Rockwool insulation	**Recycling through industrial processes**	✓	**Recycling through natural processes**	x
	Infinite recycling	✓	Rate and efficiency	x
	Processing efficiency	✓	Hazards and quality	x
	Hazards	✓		

Floor: PVC floor finish fixed with adhesive House 1	**Overall compliance with closed loop material cycle criteria**	x
Constituent part compliance	Key: compliant = ✓ non-compliant = x Disposal options: RI = Industrial recycling RN = Natural recycling L = Landfill or incineration	

Constituent part description	Quantity	RI/RN/L
flexible floor finish ground fl. + first fl. PVC	30+22 KG	L

Deconstruction process	x	notes
Ability to access	✓	fully accessible
Accessibility of fixings	x	bonded to substrate
Types of connections	x	adhesive
Durability of fixings		n/a
Information	✓	standard construction

Recycling process				
PVC	**Recycling through industrial processes**	x	**Recycling through natural processes**	x
	Infinite recycling	x	Rate and efficiency	
	Processing efficiency	x	Hazards and quality	
	Hazards	✓		

Floor: synthetic carpet floor finish fixed with adhesive House 1	**Overall compliance with closed loop material cycle criteria**	x
Constituent part compliance	Key: compliant = ✓ non-compliant = x Disposal options: RI = Industrial recycling RN = Natural recycling L = Landfill or incineration	

Constituent part description	Quantity	RI/RN/L
carpet floor finish ground + first floor	610+565	L

Deconstruction process	x	notes
Ability to access	✓	fully accessible
Accessibility of fixings		n/a
Types of connections	x	adhesive
Durability of fixings		n/a
Information	✓	standard construction

Recycling process				
Mixed plastics	**Recycling through industrial processes**	x	**Recycling through natural processes**	x
	Infinite recycling	x	Rate and efficiency	
	Processing efficiency	x	Hazards and quality	
	Hazards	✓		

APPENDIX 12 – CLMC WHOLE BUILDING ASSESSMENT: BUILDING QUANTITIES (PRIMARY DATA USED IN APPLICATION OF ORIGINAL ASSESSMENT TOOL)

APPENDIX 12 IS RELATED TO SECTION 5.3 'WHOLE BUILDING ASSESSMENT'

Appendix 12 includes the raw data related to the whole building assessments discussed in section 5.3.

The whole building assessment is based on three building design options. The selection rational and process is outlined in Sections 1.5.4 and 5.3.

The construction for each design option was detailed and the materials used in each case measured. The material quantities measured were used for each of the three whole building assessments to establish the total amounts of the different types of materials including: non-CLMC materials and CLMC materials. The material quantities are set out is in Excel worksheets format organised into sections including foundations, walls, roofs, floors and partitions. A summary sheet for each building option is used to show the total material quantities for each building and convert the volume of materials into weight, the latter used to relate the waste to potential disposal costs.

The results regarding the design and specification options and the resulting CLMC compliance are discussed in Section 5.3.

Foundation option 1

concrete floor thickness	concrete floor volume	perimetre insulation depth	perimetre insulation width	perimetre insulation cross-section	perimetre insulation linear metre	perimetre insulation volume	insulation under slab area	insulation under slab thickness	insulation under slab volume
0.2	10.2562	1.2	0.08	0.096	32.52	3.12192	46.014	0.15	6.9021

dpm area	dpm thickness	dpm volume	sand blinding area	sand blinding thickness	sand blinding volume	hardcore area	hardcore thickness	hardcore volume
66	0.0015	0.099	46.014	0.05	2.3007	46.014	0.15	6.9021

Foundation option 2

	cross-section	linear metre	volume	total volume concrete foundations	I joist linear metres (area=0.008 754)	number	subtotal I joist linear metres	I joists volume
					0.008754			
concrete foundation	0.658	3.6	2.3688	2.3688				1.21015296
					5.12	27	138.24	1.21015296

insulation between studs area (with timber)	insulation between studs depth	insulation between studs volume (with timber)	insulation between studs volume (without timber)	dpm area	dpm thickness	dpm volume	area ext lining	ext lining volume
								0.009
			10.959347	0.0612	0.001	0.0000612		0.438102
48.678	0.25	12.1695					48.678	

area int lining	int lining volume	area vapour control	vapour control volume	area perimeter timbers	linear metres perimeter timbers	perimeter timbers volume
	0.018		0.00023			
	0.876204		0.01119594			1.65375
48.678		48.678		0.0525	31.5	

Foundation option 3

	cross-section	linear metre 8x1.3	volume	total volume concrete foundations	I joist linear metres (area=0.008754) 0.008754	number	subtotal I joist linear metres	I joists volume	insulation between studs area (with timber)	insulation between studs depth	insulation between studs volume (with timber)	insulation between studs volume (without timber)
timber piles	0.12	10.4	1.248	1.248				1.21015296				10.95534704
					5.12	27	138.24	1.21015296	48.678	0.25	12.1695	

area ext lining	ext lining volume 0.009	area int lining	int lining volume 0.018	area perimeter timbers	linear metres perimeter timbers	perimeter timbers volume
	0.438102		0.876204			1.65375
48.678		48.678		0.0525	31.5	

Wall option 1

	building element	length	width	cross-section	linear metre	number	total linear metres	total volume	total volume timber framing per wall	area of internal lining	volume of internal lining 9mm	area of external lining	volume of external lining 6.5mm
						95	575.674	4.81533					
frame fixings (nails)						570							
frame panel fixings (nails)							5756.74						
batten fixings - nails													
cladding fixings - screws													
[illegible]									[illegible]		[illegible]		[illegible]
WEST WALL	vertical grd timber stud wall west	0.05	0.175	0.00875	2.086	21	43.806	0.3833025					
	horizontal timber stud wall west	0.05	0.175	0.00875	11.01	3	33.03	0.2890125					
	noggings grd	0.05	0.175	0.00875	9.486	2	18.972	0.166005					
	horizontal roof timber stud wall west	0.05	0.175	0.00875	11.37	1	11.37	0.0994875					
	4.99						0	0					
	6.48						0	0					
	noggings 1st	0.05	0.175	0.00875	9.536	2	19.072	0.16688					
	noggings 1st	0.05	0.175	0.00875	4.948	1	4.948	0.043295					
	vertical first fl timber stud wall west	0.05	0.175	0.00875	64.076	1	64.076	0.560665					
	2.129												
	2.325												
	2.542												
	2.762												
	2.98												
	3.199												
	3.417												
	3.617												
	3.846												
	4.053												
	4.071												
	4.27												
	4.106												
	3.82												
	3.52												
	3.2												
	2.96												
	2.651												
	2.389												
	2.22									58.323		66.556	
	total wall								1.7086475		0.524907		[illegible]
EAST WALL	as west wall						195.274	1.464655					
										58.323		63.006	
	total wall								1.7086475		0.524907		0.4095585
SOUTH WALL	vertical grd timber stud wall south	0.05	0.175	0.00875	2.047	8	16.376	0.14329					
	noggings grd	0.05	0.4	0.02	1.98	1	1.98	0.0396					
	vertical 1st timber stud wall south	0.05	0.175	0.00875	1.912	12	22.944	0.20076					
	horizontal timber stud wall south	0.05	0.175	0.00875	5.034	8	40.272	0.35238					
	noggings 1st	0.05	0.175	0.00875	2.85	1	2.85	0.0249375		12		14.671	
	total wall								[illegible]		[illegible]		[illegible]
NORTH WALL	vertical grd timber stud wall north	0.05	0.175	0.00875	2.332	12	27.984	0.24486					
	horizontal grd timber stud wall north	0.05	0.175	0.00875	5.223	2	10.446	0.0914025					
	noggings grd	0.05	0.175	0.00875	8.734	1	8.734	0.0764225					
	vertical 1st timber stud wall north	0.05	0.175	0.00875	1.977	9	17.793	0.15568875					
	vertical 1st timber stud wall north	0.05	0.175	0.00875	2.933	7	20.531	0.17964625					
	horizontal st timber stud wall north	0.05	0.175	0.00875	5.223	2	10.446	0.0914025					
	noggings 1st	0.05	0.175	0.00875	4.77	1	4.77	0.0417375		19.316		22.467	
	total wall								[illegible]		0.173844		[illegible]

Wall option1 cont.

insulation between studs area (with timber)	insulation between studs depth	insulation between studs volume (with timber)	insulation between studs volume (without timber)	area of vapour control layer	volume of vapour control layer	area of external insulation	volume of external insulation	timber battens section	timber battens length	timber battens volume	timber edge trims crossection	timber edge trims length	timber edge trims volume	timber cladding crossection	timber cladding length	timber cladding volume
									74.54			41.686			136.457	
									372.7							
												125.058			409.371	
						167.5028										
			20.8330275		0.019420013		0.760112			0.0998856			[illegible]			[illegible]
58.323	0.175	10.20653		58.323		66.559										
			8.4976775		0.007654894		2.66236									
58.323	0.175	10.20653		58.323		63.009										
			8.4976775		0.007654894		2.52036									
									13						36.67	
									29						10.577	
															10.17	
12	0.175	2.1		12		15.0678		0.00134	42		0.002209	21.145		0.0028	57.417	
			1.3390325		0.001575		0.602712			0.05628			0.046709505			0.1607670
															17.072	
															17.53	
															20.33	
															24.108	
19.316	0.175	3.3803		19.316		22.867		0.00134	32.54		0.002209	20.541		0.0028	79.04	
			2.49914		0.002535225		0.91468			0.0436036			0.045375069			0.221312

Wall option1 cont.

render area	render volume	timber int lining battens section	timber lining battens length	number	timber lining battens volume	area lining insulation	volume lining insulation	area lining board	volume lining board	total frame fixing nails	total panel fixing and batten fixing nails	total cladding fixing screws	volume cu m - total frame fixing nails	volume cu m - total panel fixing and batten fixing nails	volume cu m - total cladding fixing screws
			166.264												
										670			0.001600125		
											7782.98			0.021889631	
			1653.54												
												534.429			0.001503
182.4684						135.626		136.626							
	15.5517768				0.479[illegible]		2.983772		2.09[illegible]						
		GROUND WALLS													
		0.0011	2.622	53	0.1528626										
		FIRST FL WALLS													
		0.0011	61.216	1	0.0673376										
		0.0011	53.8	1	0.05918										
		0.0011	2.927	5	0.0160985										
		0.0011	2.033	8	0.0178904										
		0.0011	1.956	9	0.0193644										
		0.0011	30.8	4	0.13552										
		0.0011	10	1	0.011										
67.872						50.07		50.07							
	6.922944						1.10154		0.75105						
64.363						54.24		54.24							
	6.565026						1.19328		0.8136						
6.8334						12		12							
	0.6970068						0.264		0.18						
13.4						19.316		19.316							
	1.3668						0.424952		0.28974						

Wall option 2

	building element	length	width	cross-section	linear metre	number	total linear metres	total volume	total volume timber framing per wall	area of internal lining with skim coat painted	volume of internal lining 9mm	area of external lining	volume of external lining 6.5mm
						95	575.674	4.81533					
frame fixings (nails)						570							
frame panel fixings (nails)							5756.74						
batten fixings - nails													
cladding fixings - screws													
all stud walls									[illegible]		[illegible]		[illegible]
WEST WALL	vertical grd timber stud wall west	0.05	0.175	0.00875	2.086	21	43.806	0.383303					
	horizontal timber stud wall west	0.05	0.175	0.00875	11.01	3	33.03	0.289013					
	noggings grd	0.05	0.175	0.00875	9.486	2	18.972	0.166005					
	horizontal roof timber stud wall west	0.05	0.175	0.00875	11.37	1	11.37	0.099488					
	4.89						0	0					
	6.48						0	0					
	noggings 1st	0.05	0.175	0.00875	9.536	2	19.072	0.16688					
	noggings 1st	0.05	0.175	0.00875	4.948	1	4.948	0.043295					
	vertical first fl timber stud wall west	0.05	0.175	0.00875	64.076	1	64.076	0.560665					
	2.129												
	2.325												
	2.542												
	2.762												
	2.98												
	3.199												
	3.417												
	3.617												
	3.845												
	4.053												
	4.071												
	4.27												
	4.106												
	3.82												
	3.52												
	3.2												
	2.96												
	2.651												
	2.389												
	2.22									58.323		66.559	
	total wall								1.708648		0.699876		0.432634
EAST WALL	as west wall						195.274	1.464555					
										58.323		63.009	
	total wall								1.708648		0.699876		0.409559
SOUTH WALL	vertical grd timber stud wall south	0.05	0.175	0.00875	2.047	8	16.376	0.14329					
	noggings grd	0.05	0.4	0.02	1.98	1	1.98	0.0396					
	vertical 1st timber stud wall south	0.05	0.175	0.00875	1.912	12	22.944	0.20076					
	horizontal timber stud wall south	0.05	0.175	0.00875	5.034	8	40.272	0.35238					
	noggings 1st	0.05	0.175	0.00875	2.85	1	2.85	0.024938		12		14.671	
	total wall								0.760968		0.144		0.095362
NORTH WALL	vertical grd timber stud wall north	0.05	0.175	0.00875	2.332	12	27.984	0.24486					
	horizontal grd timber stud wall north	0.05	0.175	0.00875	5.223	2	10.446	0.091403					
	noggings grd	0.05	0.175	0.00875	8.734	1	8.734	0.076423					
	vertical 1st timber stud wall north	0.05	0.175	0.00875	1.977	9	17.793	0.155689					
	vertical 1st timber stud wall north	0.05	0.175	0.00875	2.933	7	20.531	0.179646					
	horizontal st timber stud wall north	0.05	0.175	0.00875	5.223	2	10.446	0.091403					
	noggings 1st	0.05	0.175	0.00875	4.77	1	4.77	0.041738		19.316		22.467	
	total wall								0.88116		0.231792		0.146036

Wall option 2 cont.

insulation between studs area (with timber)	insulation between studs depth	insulation between studs volume (with timber)	insulation between studs volume (without timber)	area of vapour control layer	volume of vapour control layer	area of external insulation	volume of external insulation	timber battens section	timber battens length	timber battens volume	timber edge trims crossection	timber edge trims length	timber edge trims volume	timber cladding crossection	timber cladding length	timber cladding volume
									74.54			41.686			136.457	
									372.7			125.088			409.371	
			20.83393		0.038733		13.04287924			0.367348			0.092084			0.36206
58.323	0.175	10.20653		58.323		66.559										
			8.497878		0.014085		5.32472									
58.323	0.175	10.20653		58.323		63.009										
			8.497878		0.014085		5.04072									
									13						36.67	
									29						10.577	
															10.17	
12	0.175	2.1		12		15.0678		0.004794	42		0.002209	21.145		0.0026	57.417	
			1.330032		0.002898		1.205424			0.201348			0.046709			0.160758
															17.872	
															17.63	
															20.33	
															24.108	
19.316	0.175	3.3803		19.316		22.867		0.004794	32.54		0.002209	20.541		0.0026	79.04	
			2.49914		0.004668		1.82936			0.155997			0.045378			0.221312

Wall option 2 cont.

render area	render volume	int lining timber battens section	int lining timber battens length	number	int lining timber battens volume	area lining insulation	volume lining insulation	area lining board	volume lining board	total frame fixing nails	total panel fixing and batten fixing nails	total cladding fixing screws	volume cu m - total frame fixing nails	volume cu m - total panel fixing and batten fixing nails	volume cu m - total cladding fixing screws
			165.354												
										570			0.001603		
											7782.98			0.02189	
			1653.54												
												534.429			0.001503
	1.219747				0.958507		5.009037		1.35626						
		GROUND WALLS													
		0.0022	2.622	53	0.3057252										
		FIRST FL WALLS													
		0.0022	61.216	1	0.1346752										
		0.0022	53.8	1	0.11836										
		0.0022	2.927	5	0.032197										
		0.0022	2.033	8	0.0357808										
		0.0022	1.956	9	0.0387288										
		0.0022	30.8	4	0.27104										
		0.0022	10	1	0.022										
67.872						50.07		50.07							
	0.542976						2.20308		0.5007						
64.363						54.24		54.24							
	0.514904						2.38656		0.5424						
6.8334						12		12							
	0.054667						0.528		0.12						
13.4						19.316		19.316							
	0.1072						0.849904		0.19316						

Wall option 3

	building element	length	width	cross-section	linear metre	number	total linear metres	total volume	total volume timber framing per wall	area of internal lining	volume of internal lining 9mm	area of external lining
						95	575.674	6.70743				
frame fixings (nails)						570						
frame panel fixings (nails)							5756.74					
batten fixings - nails												
cladding fixings - screws												
all stud walls									7.927893		1.331658	
WEST WALL	vertical grd timber stud wall west	0.05	0.275	0.01375	2.086	21	43.806	0.602333				
	horizontal timber stud wall west	0.05	0.275	0.01375	11.01	3	33.03	0.454163				
	noggings grd	0.05	0.275	0.01375	9.486	2	18.972	0.260865				
	horizontal roof timber stud wall west	0.05	0.275	0.01375	11.37	1	11.37	0.156338				
		4.89	0.275				0	0				
		6.48	0.275				0	0				
	noggings 1st	0.05	0.275	0.01375	9.536	2	19.072	0.26224				
	noggings 1st	0.05	0.275	0.01375	4.948	1	4.948	0.068035				
	vertical first fl timber stud wall west	0.05	0.275	0.01375	64.076	1	64.076	0.881045				
		2.129										
		2.325										
		2.542										
		2.762										
		2.98										
		3.199										
		3.417										
		3.617										
		3.845										
		4.053										
		4.071										
		4.27										
		4.106										
		3.82										
		3.52										
		3.2										
		2.96										
		2.661										
		2.389										
		2.22								58.323		66.559
	total wall								2.685018		0.524907	
EAST WALL	as west wall						195.274	1.464555				
										58.323		63.009
	total wall								2.685018		0.524907	
SOUTH WALL	vertical grd timber stud wall south	0.05	0.275	0.01375	2.047	8	16.376	0.22517				
	noggings grd	0.05	0.4	0.02	1.98	1	1.98	0.0396				
	vertical 1st timber stud wall south	0.05	0.275	0.01375	1.912	12	22.944	0.31548				
	horizontal timber stud wall south	0.05	0.275	0.01375	5.034	8	40.272	0.55374				
	noggings 1st	0.05	0.275	0.01375	2.85	1	2.85	0.039188		12		14.571
	total wall								1.173178		0.108	
NORTH WALL	vertical grd timber stud wall north	0.05	0.275	0.01375	2.332	12	27.984	0.38478				
	horizontal grd timber stud wall north	0.05	0.275	0.01375	5.223	2	10.446	0.143633				
	noggings grd	0.05	0.275	0.01375	8.734	1	8.734	0.120093				
	vertical 1st timber stud wall north	0.05	0.275	0.01375	1.977	9	17.793	0.244654				
	vertical 1st timber stud wall north	0.05	0.275	0.01375	2.933	7	20.531	0.282301				
	horizontal st timber stud wall north	0.05	0.275	0.01375	5.223	2	10.446	0.143633				
	noggings 1st	0.05	0.275	0.01375	4.77	1	4.77	0.065588		19.316		22.467
	total wall								1.38468		0.173844	

Wall option 3 cont.

volume of external lining 6.5mm	insulation between studs area (with timber)	insulation between studs depth	insulation between studs volume (with timber)	insulation between studs volume (without timber)		timber edge trims crosssection	timber edge trims length	timber edge trims volume	timber cladding crosssection	timber cladding length	timber cladding volume	timber cladding area	timber cladding volume
							41.686			136.457			
							125.058			409.371		3513.192	
1.083586				29.80242				0.092084			0.38208		3.2789792
	58.323	0.255	14.87237									67.872	
0.432634				12.18735									1.289568
	58.323	0.255	14.87237									64.363	
0.409559				12.18735									1.222897
										36.67			
										10.577			
										10.17			
	12	0.255	3.06			0.002209	21.145		0.0028	57.417		6.8334	
0.095362				1.886823				0.046709			0.160768		0.1298346
										17.072			
										17.53			
										20.33			
										24.108			
	19.316	0.255	4.92558			0.002209	20.541		0.0028	79.04		13.4	
0.146036				3.5409				0.045375			0.221312		0.2546

Wall option 3 cont.

timber int lining battens section	timber lining battens length	number	timber lining battens volume	area lining insulation	volume lining insulation	area lining board	volume lining board	total frame fixing nails	total panel fixing and batten fixing nails	total cladding fixing screws	volume cu m - total frame fixing nails	volume cu m - total panel fixing and batten fixing nails	volume cu m - total cladding fixing screws
	165.354							570			0.001603		
									7410.28			0.020841	
	1653.54									4047.621			0.011384
			0.958507		5.009037		1.627512						
GROUND WALLS													
0.0022	2.622	53	0.3057252										
FIRST FL WALLS													
0.0022	61.216	1	0.1346752										
0.0022	53.8	1	0.11836										
0.0022	2.927	5	0.032197										
0.0022	2.033	8	0.0357808										
0.0022	1.956	9	0.0387288										
0.0022	30.8	4	0.27104										
0.0022	10	1	0.022										
				50.07		50.07							
					2.20308		0.60084						
				54.24		54.24							
					2.38656		0.65088						
				12		12							
					0.528		0.144						
				19.316		19.316							
					0.849904		0.231792						

Roof option 1

	area of internal lining	internal lining 9mm volume	area of vapour control	vapour control volume	area of external lining	external lining 6.5mm volume	roof I beams linear metres (area=0.008754)	I beam volume	insulation between studs area (with timber)	insulation between studs depth	insulation between studs volume (with timber)	insulation between studs volume (without timber)	roof battens linear metres (area=0.002446)	battens volume
		0.009		0.001		0.0065	0.008754						0.002446	
		0.52425		0.05825		0.389994		1.0325343				16.96717		0.288506
SOUTH ROOF														
	-4.2		-4.2		-4.2									
	35.25		35.25		36.099									
	31.05		31.05		31.899		66.34		31.899	0.3	9.5697		66.34	
		0.27945		0.03105		0.207344		0.5807404				8.98896		0.162268
NORTH ROOF														
	27.2		27.2		28.1		51.61		28.1	0.3	8.43		51.61	
		0.2448		0.0272		0.18265		0.4517939				7.978206		0.126238
							117.95							
fixing lining							1179.5							
fixings frame					10 x	12	120							
fixing tiles														
fixing lining volume								0.0033173						
fixings frame volume								0.0003375						
fixing tiles volume														

roof countre battens linear metres (96no) (area=0.002446)	counter battens volume	roof slates 96x.17x5.44 (3mm)	roof slates volume	linear metre downpipe 75mm dia (circumference 235mm)	linear metre gutter (304mm folded)	area of flat downpipe 75mm dia (circumference 235mm)	area of flat gutter (304mm folded)	area of gutter and downpipe	volume of gutter and downpipe (thickness2.2pvcmm)
0.001223		0.005							
518.4	0.634003	88.16	0.4408						0.012578
				5.137	5.44	1.207195	1.65376		
								2.860955	0.006294
				5.117	5.44	1.202495	1.65376		
								2.856255	0.006284

8640
96 x

45 x

2

0.0243

Roof option 2

	area of internal lining	internal lining 9mm volume	area of vapour control	vapour control volume	area of external lining	external lining 6.5mm volume	roof I beams linear metres (area=0.008754)	I beam volume	insulation between studs area (with timber)	insulation between studs depth	insulation between studs volume (with timber)	insulation between studs volume (without timber)	roof battens linear metres (area=0.002446)	battens volume
		0.009		0.00023		0.0065	0.008754						0.002446	
		0.52425		0.013398		0.389994		1.032534				16.96717		0.288506
SOUTH ROOF														
	-4.2		-4.2		-4.2									
	35.25		35.25		36.099									
	31.05		31.05		31.899		66.34		31.899	0.3	9.5697		66.34	
		0.27945		0.007142		0.207344		0.58074				8.98896		0.162268
NORTH ROOF														
	27.2		27.2		28.1		51.61		28.1	0.3	8.43		51.61	
		0.2448		0.006256		0.18265		0.451794				7.978206		0.126238

			117.95	
fixing lining			1179.5	
fixings frame	10 x	12	120	
fixing tiles				
fixing lining volume				0.003317
fixings frame volume				0.000338
fixing tiles volume				

roof countre battens linear metres (96no) (area=0.002446)	counter battens volume	roof slates 96x.17x5.44 (3mm)	roof slates volume	linear metre downpipe 75mm dia (circumference 235mm)	linear metre gutter (304mm folded)	area of flat downpipe 75mm dia (circumference 235mm)	area of flat gutter (304mm folded)	area of gutter and downpipe	volume of gutter and downpipe (thickness 2mmaluminium)
0.001223		0.005							
516.4	0.634003	88.16	0.4408						0.011434
				5.137	5.44	1.207195	1.65376		
								2.860955	0.005722
				5.117	5.44	1.202495	1.65376		
								2.856255	0.005713

8640
96 x

45 x

2

0.0243

Roof option 3

	area of internal lining	internal lining 9mm volume	area of vapour control	vapour control volume	area of external lining	external lining 6.5mm volume	roof I beams linear metres (area=0.008754)	I beam volume	insulation between studs area (with timber)	insulation between studs depth	insulation between studs volume (with timber)	insulation between studs volume (without timber)	roof battens linear metres (area=0.002446)	battens volume
		0.009		0.001		0.0065	0.008754						0.002446	
		0.52425		0.05825		0.389904		1.032534				16.96717		0.288506
SOUTH ROOF														
	-4.2		-4.2		-4.2									
	35.25		35.25		36.099									
	31.05		31.05		31.899		66.34		31.899	0.3	9.5697		66.34	
		0.27945		0.03105		0.207344		0.58074				8.98896		0.162268
NORTH ROOF														
	27.2		27.2		28.1		51.61		28.1	0.3	8.43		51.61	
		0.2448		0.0272		0.18265		0.451794				7.978206		0.126238

				117.95
fixing lining				1179.5
fixings frame	10 x		12	120
fixing tiles				
fixing lining volume				0.003317
fixings frame volume				0.000338
fixing tiles volume				

roof countre battens linear metres (96no) (area=0.002446)	counter battens volume	timber 100x15 roofing boarding 2 layers	roof timber boards volume	linear metre downpipe 75mm dia (circumference 235mm)	linear metre gutter (304mm folded)	area of flat downpipe 75mm dia (circumference 235mm)	area of flat gutter (304mm folded)	area of gutter and downpipe	volume of gutter and downpipe (thickness 15mm)
0.001223		0.03							
516.4	0.6340032	65.5	1.965						0.085758
				5.137	5.44	1.207195	1.65376		
								2.860955	0.042914
				5.117	5.44	1.202495	1.65376		
								2.856255	0.042844

72.24
12.04 x

3 x

2

0.0002032

Floor option 1

	area of ceiling lining	internal ceiling volume	area of floor lining	floor lining volume	I joist linear metres (area=0.008754)	number	subtotal I joist linear metres	I joists volume	insulation between studs area (with timber)	insulation between studs depth	insulation between studs volume (with timber)	insulation between studs volume (without timber)
		0.0125		0.018	0.008754							
		0.608475		0.876204				1.63283985				10.53666015
FLOORS	48.678		48.678		5.12	26	133.12	1.16533248	48.678	0.25	12.1695	
					4.067	7	28.469	0.249217626				
					3.176	1	3.176	0.027802704				
					10.88	2	21.76	0.19048704				
total linear metres joists						36	186.525					
fixings linings							1865.25					
fixings frame						288						
fixings linings volume								0.005246016				
fixings frame volume							0.00081					

area of wet floor finish grd	wet floor finish (ceramic tiles) grd volume	area of carpet floor finish grd	floor finish (carpet) grd volume	area of wet floor finish first	wet floor finish first volume	area of carpet floor finish first	floor finish (carpell) first volume	skirtings linear metres	skirtings volume	area of ceiling slim finish	volume of ceiling slim finish
	0.003		0.01		0.003		0.01	60.453	0.0015		0.003
	0.021441		0.35964		0.015957		0.33343		0.09068		0.146034
7.147		35.964		5.319		33.343		27.756 grd fl 32.697 first fl		48.678	

Floor option 2

	area of ceiling lining	ceiling lining volume	area of floor lining	floor lining volume	I joist linear metres (area=0.008754)	number	subtotal I joist linear metres	I joists volume	insulation between studs area (with timber)	insulation between studs depth	insulation between studs volume (with timber)	insulation between studs volume (without timber)
		0.0125		0.018	0.008754							
		0.608475		0.876204				1.63283985				10.53666015
FLOORS	48.678		48.678		5.12	26	133.12	1.16533248	48.678	0.25	12.1695	
					4.067	7	28.469	0.24921762				
					3.176	1	3.176	0.0278027				
					10.88	2	21.76	0.19048704				
total linear metres joists						36	186.526					
fixings linings							1865.25					
fixings frame						288						
fixings linings volume								0.00524602				
fixings frame volume							0.00081					

Floor option 2 cont.

area of wet floor finish grd	wet floor finish (linoleum) grd volume	area of carpet floor finish grd	floor finish (carpet) grd volume	area of wet floor finish first	wet floor finish (linoleum) grd volume	area of carpet floor finish first	floor finish (carpet) first volume	skirtings linear metres	skirtings volume	area of ceiling skim finish painted	volume of ceiling skim finish painted
	0.003		0.01		0.003		0.01	60.453	0.0015		0.003
	0.021441		0.35964		0.015957		0.33343		0.09068		0.146034
7.147		35.964		5.319		33.343		27.756 grd fl 32.697 first fl		48.678	

Floor option 3

	area of ceiling lining	ceiling lining volume	area of floor lining	floor lining volume	I joist linear metres (area=0.008754)	number	subtotal I joist linear metres	I joists volume	insulation between studs area (with timber)	insulation between studs depth	insulation between studs volume (with timber)	insulation between studs volume (without timber)
		0.0125		0.018	0.008754							
		0.608475		0.876204				1.63283985				10.53666015
FLOORS	48.678		48.678		5.12	26	133.12	1.16533248	48.678	0.25	12.1695	
					4.067	7	28.469	0.24921763				
					3.176	1	3.176	0.0278027				
					10.88	2	21.76	0.19048704				
total linear metres joists						36	186.525					
fixings linings							1865.25					
fixings frame						288						
fixings linings volume								0.00524602				
fixings frame volume							0.00081					

area of wet floor finish grd	wet floor finish (linoleum) grd volume	area of carpet floor finish grd	floor finish (cork) grd volume	area of wet floor finish first	wet floor finish (linoleum) grd volume	area of carpet floor finish first	floor finish (cork) first volume
	0.003		0.01		0.003		0.01
	0.021441		0.35964		0.015957		0.33343
7.147		35.964		5.319		33.343	

Partitions option 1

	wall lining volume	volume of skim finish painted
TOTAL BLD	1.62415205	0.389796492

	area of wall lining	area of doors	wall lining volume	volume of skim finish painted	number of studs	length of studs	linera metres of studs	studs volume
			0.0125	0.003				0.00375
			0.67294955	0.161507892				0.3120975
PARTITONS GRD	33.31798	-6.4	53.835964		33	2.522	83.226	

total linear metres wall
total linear metres joists
fixings linings
fixings frame

	area of wall lining	area of doors	wall lining volume	volume of skim finish painted	number of studs	length of studs	linear metres of studs	studs volume
			0.0125	0.003				0.00375
			0.9512025	0.2282886				0.497475
PARTITONS FIRST	9.9036	-6.4	76.0962				132.66	
	15.3745				20	3.78	75.6	
	19.17				18	3.17	57.06	
							0	

total linear metres wall
total linear metres joists
fixings linings
fixings frame

fixings linings volume
fixings frame volume

	area if door leaf	volume of door leaf	area of section of architrave, lining, stops	linear metres of architrave, lining, stops	volume of architrave, lining, stops
8 DOORS		0.1208			0.173536
INTERNAL DOORS cardboard with tot 10mm panels	1.51	0.0151	0.004384	4.948	0.021692
1 DOORS EXTERNAL DOORS	1.51	0.0604	0.004384	4.948	0.021692

Partitions option 1 cont.

				volume of all framing			volume of insulation without studs
				1.19223			8.5526823

length of horizontal sections	number of horizontal sections	linear metres of horizontal sections	volume of horizontal sections	volume of all framing	area of insulation with studs	volume of insulation with studs	volume of insulation without studs
			0.00375				
			0.1623075	0.474405			3.5632923
		43.282			53.835964	4.0376973	
4.93	3	14.79					
2.84	6	17.04					
1.884	3	5.652					
3	3	9					
		-3.2					
12.654	15						
95.88							
958.8							
144							

length of horizontal sections	number of horizontal sections	linear metres of horizontal sections	volume of horizontal sections	volume of all framing	area of insulation with studs	volume of insulation with studs	volume of insulation without studs
			0.00375				
			0.22035	0.717825			4.98939
		58.76			76.0962	5.707215	
5.4	4	21.6					
2.62	8	20.96					
4.85	4	19.4					
		-3.2					
12.87	16						
88.47							
884.7							
108							

0.002488

0.000304

area of window section	linear metres	volume of window sections		area of glass	volume of glass 6-12-6
0.007168	68	0.487424		8.65	0.1038

Partitions option 2

	wall lining volume	volume of skim finish painted
TOTAL BLD	1.62415205	0.389796492

	area of wall lining	area of doors	wall lining volume	volume of skim finish painted	number of studs	length of studs	linera metres of studs	studs volume
			0.0125	0.003				0.00375
			0.67294955	0.161507892				0.3120975
PARTITONS GRD	33.31798	-6.4	53.835964		33	2.522	83.226	

total linear metres wall
total linear metres joists
fixings linings
fixings frame

	area of wall lining	area of doors	wall lining volume	volume of skim finish painted	number of studs	length of studs	linear metres of studs	studs volume
			0.0125	0.003				0.00375
			0.9512025	0.2282886				0.497475
PARTITONS FIRST	9.9036	-6.4	76.0962				132.66	
	15.3745				20	3.78	75.6	
	19.17				18	3.17	57.06	
							0	

total linear metres wall
total linear metres joists
fixings linings
fixings frame

fixings linings volume
fixings frame volume

	area if door leaf	volume of door leaf	area of section of architrave, lining, stops	linear metres of architrave, lining, stops	volume of architrave, lining, stops
8 DOORS		0.1208			0.173536
INTERNAL DOORS cardboard with tot 10mm panels	1.51	0.0151	0.004384	4.948	0.021692
1 DOORS EXTERNAL DOORS	1.51	0.0604	0.004384	4.948	0.021692

Partitions option 2 cont.

				volume of all framing			volume of insulation without studs
				1.19223			8.5526823

length of horizontal sections	number of horizontal sections	linear metres of horizontal sections	volume of horizontal sections	volume of all framing	area of insulation with studs	volume of insulation with studs	volume of insulation without studs
			0.00375				
			0.1623075	0.474405			3.5632923
		43.282			53.835964	4.0376973	
4.93	3	14.79					
2.84	6	17.04					
1.884	3	5.652					
3	3	9					
		-3.2					
12.654	15						
95.88							
958.8							
144							

length of horizontal sections	number of horizontal sections	linear metres of horizontal sections	volume of horizontal sections	volume of all framing	area of insulation with studs	volume of insulation with studs	volume of insulation without studs
			0.00375				
			0.22035	0.717825			4.98939
		58.76			76.0962	5.707215	
5.4	4	21.6					
2.62	8	20.96					
4.85	4	19.4					
		-3.2					
12.87	16						
88.47							
884.7							
108							

0.002488

0.000304

area of window section	linear metres	volume of window sections		area of glass	volume of glass 6-12-6
0.007168	68	0.487424		8.65	0.1038

Partitions option 3

	wall lining volume
TOTAL BLD	1.62415205

	area of wall lining	area of doors	wall lining volume	number of studs	length of studs	linera metres of studs	studs volume
			0.0125				0.00375
			0.67294955				0.3120975
PARTITONS GRD	33.31798	-6.4	53.835964	33	2.522	83.226	

total linear metres wall
total linear metres joists
fixings linings
fixings frame

	area of wall lining	area of doors	wall lining volume	number of studs	length of studs	linear metres of studs	studs volume
			0.0125				0.00375
			0.9512025				0.497475
PARTITONS FIRST	9.9036	-6.4	76.0962			132.66	
	15.3745			20	3.78	75.6	
	19.17			18	3.17	57.06	
						0	

total linear metres wall
total linear metres joists
fixings linings
fixings frame

fixings linings volume
fixings frame volume

	area if door leaf	volume of door leaf	area of section of architrave, lining, stops	linear metres of architrave, lining, stops	volume of architrave, lining, stops
8 DOORS		0.4832			0.173536
INTERNAL DOORS cardboard with tot 10mm panels	1.51	0.0604	0.004384	4.948	0.021692
1 DOORS EXTERNAL DOORS	1.51	0.0604	0.004384	4.948	0.021692

Partitions option 3 cont.

				volume of all framing			volume of insulation without studs
				1.19223			8.5526823

length of horizontal sections	number of horizontal sections	linear metres of horizontal sections	volume of horizontal sections	volume of all framing	area of insulation with studs	volume of insulation with studs	volume of insulation without studs
			0.00375				
			0.1623075	0.474405			3.5632923
		43.282			53.835964	4.0376973	
4.93	3	14.79					
2.84	6	17.04					
1.884	3	5.652					
3	3	9					
		-3.2					
12.654	15						
95.88							
958.8							
144							

length of horizontal sections	number of horizontal sections	linear metres of horizontal sections	volume of horizontal sections	volume of all framing	area of insulation with studs	volume of insulation with studs	volume of insulation without studs
			0.00375				
			0.22035	0.717825			4.98939
		58.76			76.0962	5.707215	
5.4	4	21.6					
2.62	8	20.96					
4.85	4	19.4					
		-3.2					
12.87	16						
88.47							
884.7							
108							
	0.002488						
	0.000304						

area of window section	linear metres	volume of window sections			area of glass	volume of glass 6-12-6
0.007168	68	**0.487424**			8.65	**0.1038**

House 1 – total material quantities

Key to references:
1 - (Hornbostel, 1978)
2 - (Illston and Domone, 2001)
3 - (Doran, 1994)
4 - (Baden-Powell, 2001)
5 - (Simmons, 2001)
6 - measured
7 - (Excel Industries ltd., 2002).
8 - (pro clima, 2008).
9 - (Visqueen, 2007, 2008)
10 - (Burlington Slate Ltd., 2001)
11 - 14 (Everett, 1994)

	House 1 - Non-recyclable waste VOL	density (kg/cum)	ref	House 1 - Non-recyclable waste total weight (kg)	House 1 industrially recyclable waste VOL	density (kg/cum)	ref	House 1 - industrially recyclable waste total weight (kg)	House 1 - Biodegradable waste VOL	density (kg/cum)	ref	House 1 - Biodegradable waste total weight (kg)
TOTAL SUM	63			96926	67			2003	16			8683
TOTAL LANDFILL INERT				85007								
TOTAL LANDFILL OTHER				11919								
foundations / grd fl.	34			60192	7			186	0			0
hardcore	7	960	3	6626								
sand blinding	2	1200	3	2761								
concrete foundation	11	2350	2	26520								
concrete slab	10	2350	2	24102								
perimetre insulation	3	28	1	87								
insulation under slab EPS					7	27	3	186				
dpm(virgin PE)	0	900	9	89								
fixings as floors	0	1778	6	6								
walls	24			29656	24			[illegible]	9			4346
timber framing (softwood)									5	510	3	2580
internal lining									1	750	7	999
external lining									1	735	7	796
insulation between studs (rockwool)					21	27	3	563				
vapour control(PE)					0	900	9	17				
external insulation (extruded polyurethane)	7	28	1	188								
timber battens									0	510	3	51
timber edge battens									0	580	3	53
timber cladding									0	580	3	222
brick volume	16	1700	11	26438								
internal battens									0	510	3	244
internal insulation rockwool					3	28	1	84				
internal lining(plasterboard with skim coat painted)	2	1440	14	2930								
frame fixings(nos.)					0	1778	6	3				
external cladidng fixings(nos.)					0	1778	6	3				
batten and lining fixings(nos.)					0	1778	6	39				
roof	1			2075	17			578	2			1284
internal lining	1	1440	14	755								
vapour control PE					0	900	9	52				
external lining									0	735	7	287
timber I beams									1	510	3	527
insulation between studs rockwool					17	27	3	458				
battens									0	510	3	147
counter battens									1	510	3	323
roof slates	0	2996	10	1320								
rainwater goods - pvc					0	1410	3	18				
frame fixings					0	1778	6	1				
tile fixings					0	1778	6	43				
internal lining fixings					0	1778	6	6				
floors	1			2211	11			291	3			1405
ceiling lining	1	1440	14	876								
floor lining chipboard									1	600	2	526
I joists									2	510	3	833
insulation between studs rockwool					11	27	3	284				
carpet floor finish grd	0	1695	5	610								
rigid floor finish grd fl.pvc	0	1410	3	30								
carpet floor finish first	0	1695	5	565								
rigid floor finish first fl.pvc	0	1410	3	22								
skirtings total									0	510	3	46
ceiling finish - skim coat plus paint	0	737	13	108								
frame fixings					0	1778	6	1				
lining fixings					0	1778	6	6				
secondary bld elements	2			2892	9			236	2			1049
int partitions framing									1	510	3	606
int partitions boarding	2	1440	14	2339								
int partitions insulation					9	27	3	231				
int partition finish	0	737	13	287								
internal partitions fixings					0	1778	6	5				
door leaves									0	510	3	62
door frames									0	510	3	89
entrance door leaf									0	510	3	31
entrance door frame									0	510	3	11
windows									0	510	3	249
glass	0	2560	11	266								

House 2 – total material quantities

building elements	House 2 - Non-recyclable waste VOL	density (kg/cum)	ref	House 2 - Non-recyclable waste total weight (kg)	House 2 - industrially recyclable waste VOL	density (kg/cum)	ref	House 2 - industrially recyclable waste total weight (kg)	House 2 - Biodegradable waste VOL	density (kg/cum)	ref	House 2 - Biodegradable waste total weight (kg)
	9			14369	0			181	108			15616
				5567								
				8803								
foundations / grd fl.	2.37			5567	0.01			15	15.14			3010
concrete foundation	2.37	2350	2	5567								
timber I joists									1.21	510	3	617
insulation between joists									10.96	52	7	570
external lining									0.44	735	7	322
internal lining									0.88	750	7	657
vapour control PE					0.01	804	8	9				
dpm(recycled PP)												
perimetre timbers									1.65	510	3	843
fixings as floors					0.00	1778	6	6				
walls	2.58			2852	0.06			73	48.59			7065
timber framing (softwood)									5.06	510	3	2580
internal lining (Paneline no glue)									1.78	750	7	1332
external lining (Panelvent no glue)									1.08	735	7	796
insulation between studs (cellulose fibre)									20.83	52	7	1083
vapour control (PE- Proclima)					0.04	804	8	29				
external insulation									13.04			0
timber battens									0.36	510	3	182
timber edge battens									0.09	580	3	53
timber cladding									0.38	580	3	222
render volume	1.22	737	13	899								
internal battens									0.96	580	3	556
internal insulation									5.01	52	7	260
internal lining plasterboard with	1.36	1440	14	1953								0
frame fixings(nos.)					0.00	1778	6	3				
external cladidng fixings(nos.)					0.00	1778	6	3				
batten and lining fixings(nos.)					0.02	1778	6	39				
roof	0.97			2075	0.05			77	19.31			2166
internal lining	0.52	1440	14	755								
vapour control					0.01	804	8	11				
external lining									0.39	735	7	287
timber I beams									1.03	510	3	527
insulation between studs									16.97	52	7	882
battens									0.29	510	3	147
counter battens									0.63	510	3	323
roof slates	0.44	2995	10	1320								
rainwater goods					0.01	1410	3	16				
frame fixings					0.00	1778	6	1				
tile fixings					0.02	1778	6	43				
internal lining fixings					0.00	1778	6	6				
floors	0.75			984	0.01			11	13.87			2489
ceiling lining	0.61	1440	14	876								
floor lining chipboard									0.88	600	2	526
I joists									1.63	510	3	833
insulation between studs									10.54	52	7	548
ash timber floor finish grd									0.36	710	4	255
ash timber floor finish grd									0.02	710	4	15
ash timber floor finish grd									0.33	710	4	237
ash timber floor finish grd									0.02	710	4	11
skirtings total									0.09	710	4	64
ceiling finish - skim coat plus p	0.15	737	13	108								
frame fixings					0.00	1778	6	1				
lining fixings					0.01	1778	6	9				
secondary bld elements	2.12			2892	0.00			5	10.61			885
int partitions framing									1	510	3	0
int partitions boarding	2	1440	14	2339								
int partitions insulation									9	52	7	445
int partition finish	0	737	13	287								
internal partitions fixings					0	1778	6	5				
door leaves									0	510	3	62
door frames									0	510	3	89
entrance door leaf									0	510	3	31
entrance door frame									0	510	3	11
windows									0	510	3	249
glass	0	2560	11	266								

House 3 – total material quantities

building elements	House 3 - Non-recyclable waste VOL	density (kg/cum)	ref	House 3 - Non-recyclable waste total weight (kg)	House 3 - industrially recyclable waste VOL	density (kg/cum)	ref	House 3 - industrially recyclable waste total weight (kg)	House 3 - Biodegradable waste VOL	density (kg/cum)	ref	House 3 - Biodegradable waste total weight (kg)
	0			266	0			89	116			25522
				0								
				266								
foundations / grd fl.	0			0	0			6	16			3871
timber piles									1	690	4	861
timber I joists									1	510	3	617
insulation between joists									11	52	7	570
external lining									0	735	7	322
internal lining									1	750	7	657
perimetre timbers									2	510	3	843
fixings as floors					0	1778	6	6				
walls	0			0	0			60	51			13233
timber framing (softwood)									8	510	3	4043
internal lining (Paneline no glue)									1	750	7	999
external lining (Panelvent no glue)									1	735	7	796
insulation between studs									30	52	7	1550
timber battens included in framing												
timber edge battens									0	580	3	53
timber cladding									3	580	3	1902
internal battens									1	510	3	489
internal insulation									5	510	3	2555
internal lining ply with natural glue									2	520	2	846
frame fixings(nos.)					0	1778	6	3				
external cladidng fixings(nos.)					0	1778	6	20				
batten and lining fixings(nos.)					0	1778	6	37				
roof	0			0	0			7	22			3605
internal lining									1	750	7	393
external lining									0	735	7	287
timber I beams									1	510	3	527
insulation between studs									17	52	7	882
battens									0	510	3	147
counter battens									1	510	3	323
roof timber boarding									2	510	3	1002
rainwater goods - timber									0	510	3	44
frame fixings					0	1778	6	1				
tile fixings					0	1778	6	0				
internal lining fixings					0	1778	6	6				
floors	0			0	0			11	14			2290
ceiling lining ply natural glue									1	520	2	316
floor lining									1	510	3	447
I joists									2	510	3	833
insulation between studs									11	52	7	548
cork floor finish grd									0	200	4	72
cork floor finish grd									0	200	4	4
cork floor finish first									0	200	4	67
cork floor finish first									0	200	4	3
frame fixings					0	1778	6	1				
lining fixings					0	1778	6	9				
secondary bld elemei	0			266	0.00			5	13			2523
int partitions framing									1	510	3	606
int partitions boarding ply with natural glues									2	520	2	845
int partitions insulation									9	52	7	445
internal partitions fixings					0	1778	6	5				
door leaves									0	510	3	246
door frames									0	510	3	89
entrance door leaf									0	510	3	31
entrance door frame									0	510	3	11
windows									0	510	3	249
glass	0	2560	11	266								

APPENDIX 13 - CLMC WHOLE BUILDING ASSESSMENT: BUILDING DRAWINGS (PRIMARY DATA USED IN APPLICATION OF ORIGINAL ASSESSMENT TOOL)

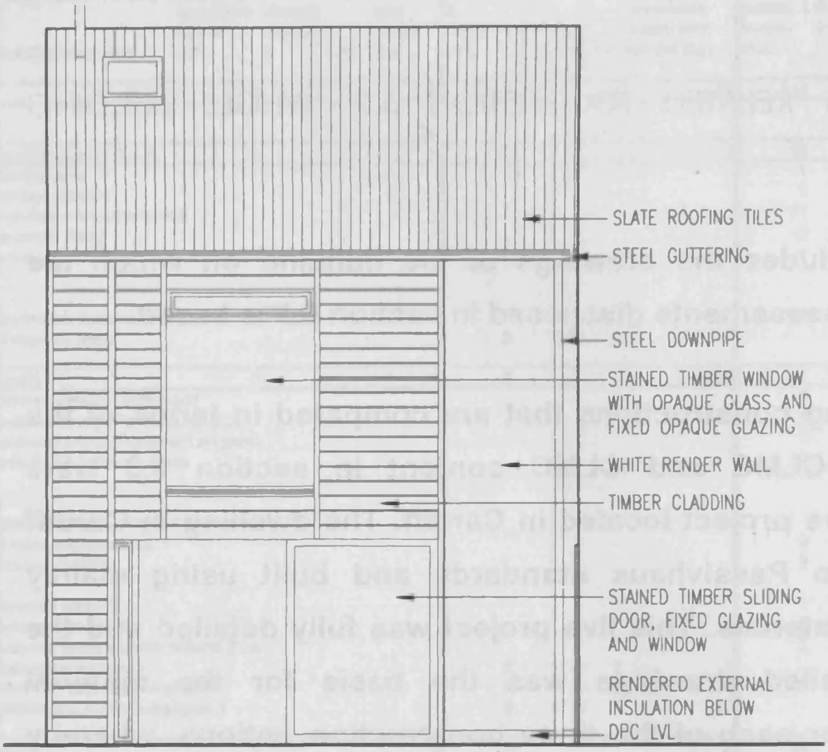
APPENDIX 13 IS RELATED TO SECTION 5.3 'WHOLE BUILDING ASSESSMENT'

Appendix 13 includes the drawings of the building on which the whole building assessments discussed in section 5.3 is based.

The three building constructions that are compared in terms of the amount of non-CLMC and CLMC content in section 5.3 were modelled on a live project located in Cardiff. The dwelling in Cardiff was designed to Passivhaus standards and built using mainly biodegradable materials. This live project was fully detailed and the full set of detailed drawings was the basis for the material measurements for each of the three construction options, whereby the construction was altered to accommodate the specification changes for each option.

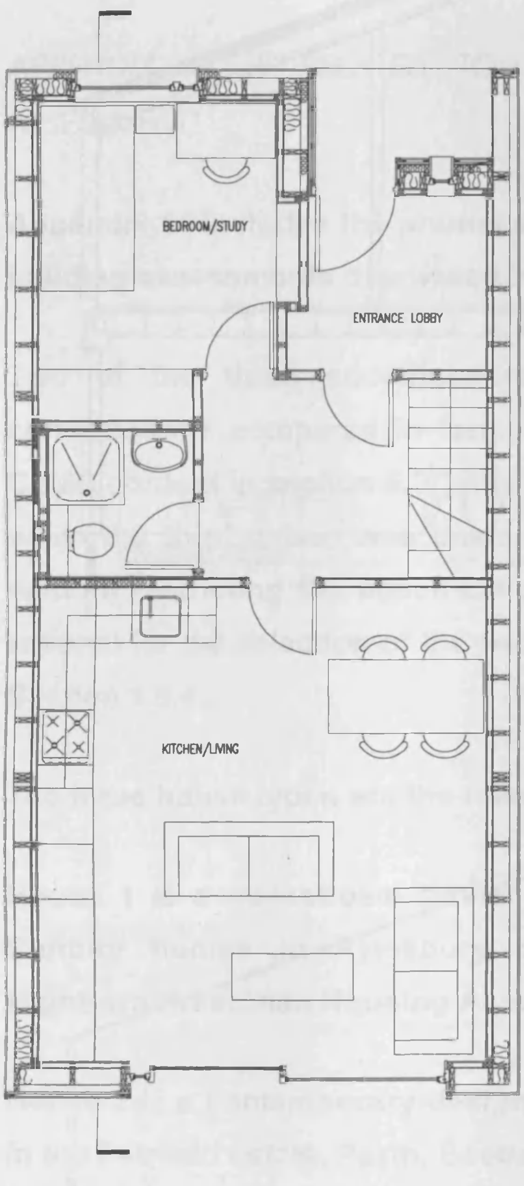
The following drawings show the house configuration with the original specification.

SOUTH ELEVATION

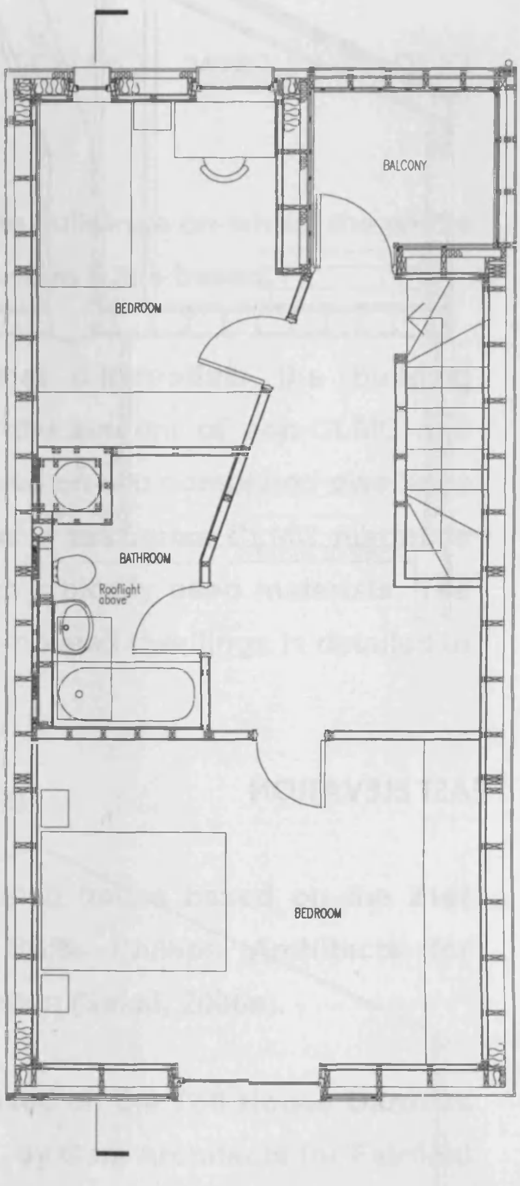


NORTH ELEVATION

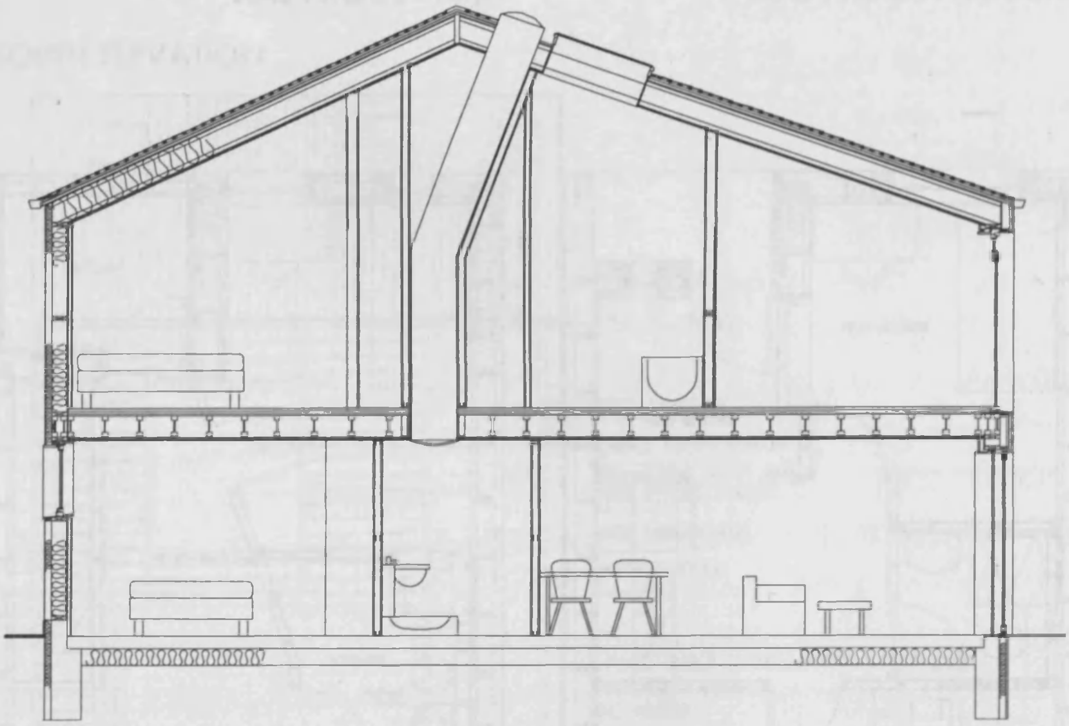
GROUND FLOOR PLAN



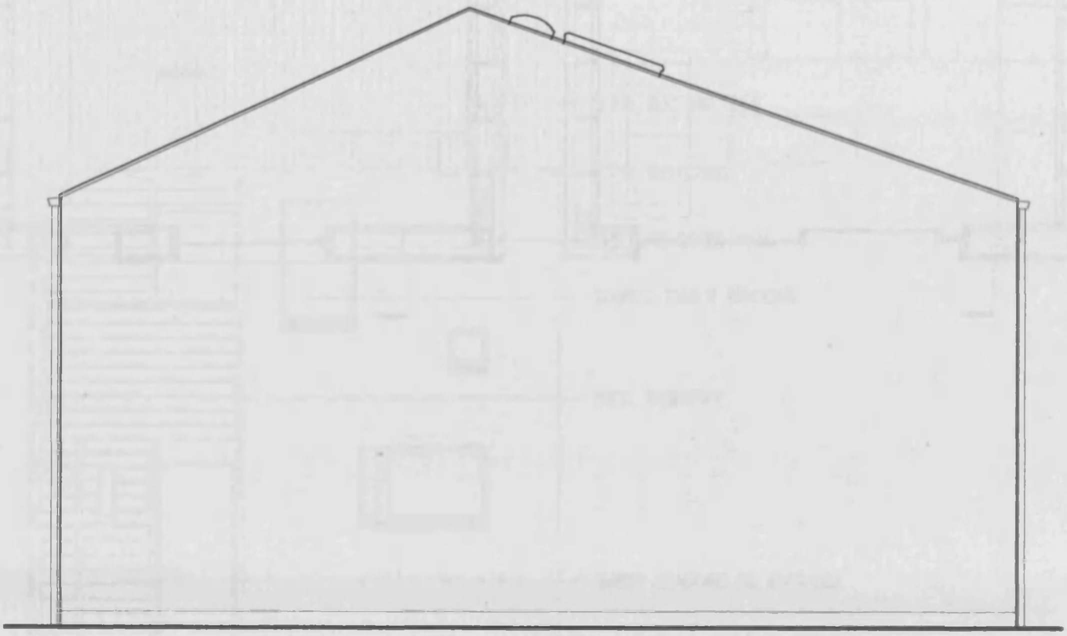
FIRST FLOOR PLAN



SECTION



EAST ELEVATION



APPENDIX 14 - CLMC WHOLE BUILDING ASSESSMENT: BUILDING TYPES (SECONDARY DATA USED IN APPLICATION OF ORIGINAL ASSESSMENT TOOL)

APPENDIX 14 IS RELATED TO SECTION 5.3 'WHOLE BUILDING ASSESSMENT'

Appendix 14 includes the photos of the buildings on which the whole building assessments discussed in section 5.3 is based.

Two of the three specifications that differentiate the building constructions compared in terms of the amount of non-CLMC and CLMC content in section 5.3, were based on two completed dwellings while the third option was developed to maximise CLMC materials without restricting the specification to typically used materials. The rational for the selection of the two completed dwellings is detailed in Section 1.5.4.

The three house types are the following.

House 1 is a mainstream timber framed house based on the 21st Century homes in Aylesbury by Briffa Phillips Architects for Hightown Preatorian Housing Association (Sassi, 2006a).

House 2 is a contemporary design based on the Toll House Gardens in the Fairfield estate, Perth, Scotland, by Gaia Architects for Fairfield Housing Co-operative (Sassi, 2006a).

House 3 is not based on an existing example of a building but simply maximises the use of biodegradable materials.

House 1 is a mainstream timber framed house based on the 21st Century homes in Aylesbury by Briffa Phillips Architects for Hightown Preatorian Housing Association (Sassi, 2006a).

House 2 is a contemporary design based on the Toll House Gardens in the Fairfield estate, Perth, Scotland, by Gaia Architects for Fairfield Housing Co-operative (Sassi, 2006a).

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