October

2012

Design for Deconstruction: An Appraisal

Danielle Densley Tingley

Thesis submitted in partial fulfilment of the degree in
Doctor of Philosophy

Civil and Structural
Engineering Department

The University of Sheffield

Declaration

All work presented within this thesis is my own work, except where specific reference has been made to the work of others.

Danielle Densley Tingley

Date

Summary

This thesis contains an assessment and discussion of the sustainability of design for deconstruction. As a basis for the work, existing literature was reviewed and the gaps in existing knowledge highlighted. Environmental assessment methods were identified as a way to incentivise design for deconstruction.

An analysis of LEED demonstrated minimal achievement of reuse credits, likely due to limited availability of reused materials. The supply chain can be developed in the future through the design for deconstruction of all new buildings.

Quantifying the environmental benefits of design for deconstruction was underlined as a key strategy to encourage designers to consider the incorporation of design for deconstruction. A methodology was developed to account for designed-in future reuse at the initial design stage. This is based on a PAS2050 methodology (2008) which shares the environmental impact of an element over the number of predicted lives. In the course of this work it has been assumed that the typical building has a fifty year life span, a conservative estimate. Studies in this thesis limit analysis to a hundred year period, giving a possible two lives for the majority of elements.

The methodology was used as a basis for the calculation of savings that occur by designing for deconstruction. Initial feasibility studies estimated that a 49% saving in embodied carbon is accomplished by designing for deconstruction. Having demonstrated the potential scope of savings, a tool, Sakura, was developed to enable designers to investigate the savings in embodied energy and carbon for their own schemes. Sakura was used to assess the savings that could be achieved for a range of case studies. Steel and timber frame structures demonstrated the greatest potential savings from design for deconstruction. School projects exhibited the highest savings when the building types were compared.

Acknowledgements

First and foremost, thanks must go to Buick Davison for supervising this project, for his support, wisdom and patience throughout. Not to mention letting me go to a conference in New York!

To the EPSRC, for the doctoral training grant which enabled me to carry out this work

To all of 'Team Awesome', for keeping me sane and reminding me to take lunch breaks

To my 'Morning Motivator', for making me laugh and weeks of texts to wake me up – this never would have been handed in on time(ish) without you

To TM for the support and boring yourself with the proof reading

And to anyone else I've forgotten.....

Table of Contents

List of Tables:

List of Figures:

1 Introduction

With increasing urbanisation and resource consumption, a different approach to the built environment needs to be taken to ensure sustainability. When concerns about carbon emissions and the quantities of waste sent to landfill are added to this, the problems seem insurmountable. These issues and their connection with the built environment are introduced and discussed through this chapter. Tactics such as deconstruction, design for deconstruction and material reuse are introduced as positive steps that can be taken to combat carbon emissions, reduce resource consumption and avoid waste to landfill. This thesis reviews the strategy of design for deconstruction in particular, examines its potential and explores how this method could contribute to a sustainable future.

1.1 Environmental background

Climate change is an unavoidable issue and, irrespective of to what extent humans have accelerated the process or to what degree it is a natural cycle, it is a topic for serious discussion. It would seem to be irrefutable that the earth is getting warmer (UNEP, 2007) and that this is going to have serious implications for the planet and all organisms that inhabit it. Even though it is too late to completely reverse the effects (UNEP, 2007) the prevailing opinion is that action should be taken now to minimise temperature increases and the associated changes to the Earth.

The recent Earth Summit in Rio de Janeiro gathered heads of state and government from around the globe to discuss the implications of climate change on the world population and future generations. Whilst a common vision for the future was presented (UN 2012), there was a significant lack of binding commitments that will turn these ideas into reality, which has led to criticism from some Non Governmental Organisations (NGOs) (UKGBC, 2012a).

If an optimistic view is taken that governments, NGOs, businesses and individuals will work together in pursuit of this 'vision', then it is important to examine and define several crucial related issues: a definition for sustainability, arguments for and against climate change, the effects of climate change and the potential for combating and minimising these consequences. The work presented in this thesis explores opportunities within the built environment to help attain this vision.

1.1.1 A definition for Sustainability

Many documents and papers remain quite vague or ambiguous on what is actually meant by sustainability. Often it is discussed in terms of sustainable development or environmental sustainability without these terms being clearly defined. Indeed according to Johnston, et al. (2007) there are as many as three hundred different definitions for sustainability and sustainable development. Referring to the dictionary is not particularly helpful either. The Oxford dictionary defines sustainable as 'able to be sustained' with the secondary meaning 'of industry, development, or agriculture avoiding depletion of natural resources' (Oxford English Dictionary, 2008). From this one might conclude that to be sustainable involves being able to indefinitely continue behaving in a certain way without depleting natural resources. However, it could be argued that sustainability involves more than not depleting natural resources. The *Global Environmental Outlook* report from the UN comments on 'the need for a sustainable way of life which not only addresses current environmental challenges but also ensures a secure society well into the future' (UNEP, 2007, p.4). This alludes to the dual considerations of protecting/maintaining the environment whilst also considering the development of society. Johnston et al. (2007), base their argument for sustainability around the TNS system conditions (named after The Natural Step organisation that is promoting these ideas). These four system conditions are outlined as follows:

"in the sustainable society, nature is not subject to systematically increasing…

1. ….concentrations of substances extracted from the Earth's crust
2. ….concentrations of substances produced by society
3. ….degradation by physical means and
4. People are not subject to conditions that systematically undermine their capacity to meet their needs" (Johnston et al, 2007, p.3).

This is not to say that humans can no longer extract natural resources from the Earth, but that it should be done at a rate which can be maintained without causing permanent damage to the planet. This definition seems to be a fairly concise summary for what can be considered to be sustainable development; this also draws parallels with the often quoted definition for sustainable development from the Brundtland Report (1987, chapter 1, point 49): 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'. In addition to these thoughts on sustainable development, the author feels that it is important to consider the preservation of the huge range of other species that inhabit the planet and the adverse affects human actions often have on these. The human race is reliant on biodiversity for survival and should not treat the environment and those species that reside within it as expendable resources.

1.1.2 The Argument for action

The Brundtland Report was the first major document to turn peoples' attention to the potential effects of climate change; written over two decades ago, it highlighted key issues that the planet and its inhabitants would potentially face in the future if the human race continued to live in an unsustainable manner. However, the resulting action by governments, businesses and the general population has been slow to produce a unified result. Some progress has been made, particularly with regards to the emission of pollutants that cause acid rain and the reduction of the use of substances that cause depletion of the ozone layer. The success of the latter, following the Montreal protocol (UNEP, 2007), is considered a good example of how international cooperation can be achieved with the desired results. However, achieving this level of agreement has proved to be more problematic with the Kyoto Protocol – which predominately addresses carbon dioxide and other greenhouse gas (GHG) emissions. Continuing meetings and discussions by world leaders, both at the Copenhagen convention and Rio+20 have resulted in suggestions and ideas but no measurable targets to build on the Kyoto Protocol (UN, 2012). Change is needed as the general consensus of scientists is that it is the build up of greenhouse gases in the atmosphere that is causing global warming and the associated climate change effects. According to the Global Environmental Outlook report from the UNEP (2007) the average temperature of the Earth has risen by 0.74°C during the last century; with predictions for a future rise of 4°C if green house gas emissions are not addressed immediately.

1.1.3 Global Warming

This is the term used to describe the effects when GHG gases (main examples include carbon dioxide, methane, nitrous oxide and water vapour) become trapped in the atmosphere (IPCC 2001). These gases absorb radiation that is trying to escape the Earth, thus trapping it within the atmosphere which then slowly increases the temperature of the planet. It is also thought that once temperature increases start to occur this can trigger further releases of carbon dioxide from natural reservoirs. In addition, the warmer the atmosphere is, the more water vapour (a GHG) it can hold, further increasing the global warming effect.

The energy sector is a major producer of carbon dioxide and although an increased use of renewable technologies and the use of carbon capture and storage techniques within power stations that burn fossil fuels has reduced the CO_2 emitted per amount of energy produced, the total energy requirements are high and predicted to continue to rise. With populations at an all time peak (UNFPA, 2011), energy usage is at a premium. According to the UNEP report (2007) the global population has risen by 1.7 billion between the time of the Brundtland report (1987) and the publication of the UNEP report (2007) – with the largest increases in Asia and Africa. Not only is the population increasing, but peoples' pattern of living is changing, with increasing urbanisation. This in itself is causing further problems as 'cities create heat islands that alter regional meteorological conditions and affect atmospheric chemistry and climate' (UNEP, 2007, p.50).

1.1.4 The Argument against action

Whilst the majority of scientists seem to have now come to the conclusion that climate change and global warming are at least being accelerated by human emissions/pollution, some still disagree that the human impacts in this area are significant. Florides and Christodoulides (2008), argue that the temperature increases that the planet is currently experiencing are nothing more than natural fluctuations and that similar spikes have happened in the past. Their paper on 'Global Warming and Carbon Dioxide through Sciences' goes further, arguing that there is no significant evidence to link increases in the concentration of carbon dioxide to global warming.

1.1.5 The potential effects of Climate Change on the environment

Having briefly examined the arguments for and against human influence on climate change, this thesis adopts the position that human emissions are accelerating if not causing global warming and that the only responsible course of action for the well-being of the planet and future generations is to significantly reduce impact on the Earth, by among other things reducing green house gas emissions. The following paragraphs outline some of the potential effects as presented in the Global Environmental Outlook from the UNEP; emphasising the importance of taking action now, before the effects are completely irreversible.

Increasing temperatures will cause ice in the Polar Regions to melt as these areas are susceptible to the slightest temperature increase. This in turn produces rising sea levels, by up to 0.59m in a worst case scenario (BBC, 2009). A rise in sea levels will instigate wide spread flooding to low-lying regions, displacing thousands of people from their homes and destroying the natural habitat of many species. Global warming could also change circulation currents within the ocean, alterations for example to the movement of the Gulf Stream would cause climates within Europe to dramatically change. In addition, changes in water temperature will affect the ecosystems that reside within, potentially disturbing these to a point from which they cannot recover; wiping out species and causing further poverty in developing nations which rely on these as a food source.

Other effects include the alteration of precipitation patterns, increasing drought and flooding which not only cause large problems themselves, but when combined with land degradation can trigger an escalation of desertification and mudslides. Not only humans will feel these effects, many species are suffering from increased risk of extinction, with biodiversity in some areas seriously threatened.

The effects of Global Warming across the world differ, with the Polar Regions seeing temperature increases that are over double the global average, this has a knock-on effect with rising sea levels for the rest of the planet. The UN report suggests that those already in the worst position will be most affected, stating that 'poverty and environmental degradation have a cause-and–effect relationship, and can fall into a cycle that is difficult to reverse' (UNEP, 2007, p.201).

1.2 Reducing greenhouse gas emissions

Given the predictions for the planet if business as usual continues, strategies need to be devised to limit GHG emissions and mitigate the damage already caused. A move towards renewable energy sources would help, but it would seem highly unlikely that renewable sources alone can supply current energy demands, let alone the increases in demand that will occur. Furthermore, many renewable sources are not yet economically viable for large scale use. David MacKay's book 'Sustainable Energy – without the hot air' (2008) examines this issue with remarkable clarity, looking at the areas within Britain that would be required for wind farms, solar panels etc. and then comparing the potential energy that could be produced, with an estimated energy demand per person in Britain, and concludes that renewable energy is only part of the answer. Nuclear powered energy plants are likely to also become part of the solution, although whilst these do not produce carbon dioxide there is the radioactive waste produced that must be dealt with, some of which must be contained and stored for a thousand years before it may be safe. Ground source heat pumps could become an efficient way to heat buildings, thus reducing the electricity/gas required to do this. However, it will take time and substantial funding to attain these goals. Carbon capture and storage may effectively buy more time to continue using fossil fuels whilst reducing carbon dioxide emissions and making the transition to more sustainable energy sources. MacKay (2008) also suggests that tax incentives may help encourage the transition to sustainable energy production / product design. The idea of a carbon tax is also raised, – designed to make it too expensive to continue emitting current levels of carbon dioxide. The concept of a carbon tax is increasingly debated (Bordigoni et al., 2012; Tolis & Rentizelas, 2011) and looks likely to become a reality in the future.

Making the move to sustainable energy sources seems possible, particularly with the appropriate incentives and funding in place. This has strong implications for the building sector - which accounts for 30 – 40% of global energy use according the Global Environmental Outlook report from the UNEP (2007). MacKay (2008) demonstrates that energy usage within buildings can be reduced, (with corresponding reductions in carbon dioxide emissions) either with increased insulation, double/triple glazing, and reducing draughts in old buildings or simply designing and building new, more energy efficient ones. One can also reduce personal energy usage within buildings by sensible practices like turning lights off, or not leaving electronic appliances on standby. However, what about the energy embodied within the building and the carbon dioxide emissions associated with that? 3.2% of global emissions are from the manufacture of iron and steel, whilst 4% are from cement factories (Fachinger, 2012) and much of these materials will go into the built environment. There are design techniques and strategies that can be introduced to target the impact these have and these are areas that can be influenced by a Structural Engineer when specifying materials.

1.3 Embodied energy versus operational energy

Whilst there are large amounts of energy and carbon dioxide emissions associated with building materials, and there are increasing amounts of research work on reducing embodied carbon, the government's main focus is on reducing the operational energy of buildings. There are targets for new build homes to meet the zero carbon standard by 2016 (Communities and local government, 2008 a, p. 77) and new non-domestic buildings to do the same by 2019 (Communities and local government, 2008 a, p. 65), although there is debate about the latter. The zero carbon standard is not truly zero carbon but targets only those emissions that are within the purview of building regulations (Shapps, 2011). This regulated energy use includes that for lighting, heating, ventilation and water heating. Unregulated emissions, which are outside the current scope, include the energy used for household electrics and for cooking. These are estimated to account for one third of emissions from the home (Zero Carbon Hub, 2011).

This new definition is a significant step backwards from the original aims of a zero carbon home, where the predicted energy use of appliances in the home was to be accounted for, potentially through the provision or connection of on-site low/zero carbon technologies (Communities and local government, 2008a). Instead building regulations will focus on the energy efficiency of the building fabric, with higher standards to occur in 2013 and 2016 (Target Zero Report, 2010). This also means that homes will be designed to this standard from 2016 but will not be performing at this level until a year or so later when the new homes have been built.

Ideally, this standard should be considered in conjunction with embodied energy and the impacts it may have on it. In many cases achieving zero carbon emissions will result in increased embodied energy of the building (Brocklesby, 1998); this emphasises the importance of considering these two issues in unison for the optimal outcome. Whilst some consider the embodied energy of a building to only be 8-10% of the total energy usage in the whole building's life (Kingspan, 2010), other studies (Sturgis & Roberts, 2010) estimate for some building types that the embodied carbon could contribute up to 60% of the whole life carbon. There is a growing awareness in this area, for example mgb Architecture + Design state that 'the effects of embodied energy in structures are significant, and they will command our attention more as buildings become increasingly energy efficient (thereby changing the operating versus embodied energy ratio)' (p.26 2012). Furthermore, recommendations were made to the government by the Innovation and Growth Team (a steering group, with experts from industry) that standardised methods of assessing embodied carbon should be developed so that this can be included within feasibility studies (IGT, 2010).

There is a strong argument that the embodied energy should be included in the definition of zero carbon buildings. The Green Building Council Australia state that 'buildings need to have zero emissions in their construction, operation and embodied energy to be truly carbon neutral' (2008). It seems likely then that it is not a question of *if* embodied energy and carbon should be minimised but a case of *when* legislation will dictate that this must be done. It would therefore seem sensible to start considering ways in which this might be achieved now.

One way in which the embodied energy of building could be reduced is to minimise the energy required to make 'new' materials in the first place. Researching different ways of manufacturing materials, ways that are less energy intensive, is one option. Developing current processes to be more energy efficient is another choice, and changing the source of the energy used in the manufacture to renewable energy forms would also minimise the embodied carbon of products. However, detailed consideration of these issues is outside the scope of this thesis.

An alternative to the above approach is to reduce the embodied energy of materials through recycling and material reuse. Recycling materials, rather than creating them from raw materials, is often less energy intensive and so the resulting materials will have a lower embodied energy. Material reuse would reduce embodied energy even more. This can occur when building materials have been salvaged so that they can be reused again in their current form – some repair or repainting may be required, but overall the process would require significantly less energy than the manufacturing of 'new' material. According to Edmonds and Gorgolewski 'reuse of components allows for complete retention of embodied energy, requiring energy only for transportation to their next use' (Unknown date, p.1). An important issue involved in material reuse is ensuring that the materials do not get damaged during the demolition of the original building. Ideally for maximum material recovery the building should be deconstructed rather than demolished; this involves the systematic taking apart of the building piece by piece, and therefore minimises damage to materials. Further to this, where buildings have been designed for deconstruction an even greater material yield may be achieved.

1.4 Responsibility of products/materials at end of life

In order for materials to be reused or recycled at the end of their useful life, one needs to question whose responsibility it is to take charge of this. Current practices imply that for most packaging containers it is the consumer who has this duty: to recycle the glass, cardboard and plastics that the product they bought was stored in. Generally if electronic products break, either the owner gets them repaired or will take them to the tip. It is not normally possible for the owner of the product to take it apart and recognise what parts can be reused, which should be recycled and which materials are potentially hazardous. In these cases a consensus seems to be forming that the manufacturer or producer is the most appropriate person to take responsibility. Given they designed the product in the first place, they are potentially best equipped to disassemble it for reuse or recycling, and legislation is moving in this direction (Europa 2009).

This kind of practice is becoming increasingly important within the product design world. Some companies have introduced voluntary reuse/recycling schemes. For example, Kodak pays film developing companies to return their single use cameras to them so that they can be taken apart and the parts either reused or recycled (Rose et al., 2001, p.189). Assessments can be carried out on products to investigate what the best end of life scenario is, either for the whole product, or for the component parts, as different parts may have different life-spans. Rose et al (2001) outline a tool (ELDA – End-of-Life Design Advisor) to help identify the best practice at the end of life of products. This recommends whether reuse, remanufacture, recycling with disassembly, recycling without disassembly or disposal is the most appropriate scenario. Using this kind of practice can enable companies to achieve higher levels of eco-efficiency in the manufacturing of their products.

This type of practice and thinking is being encouraged by the EU, which has passed legislation (directive 2002/96/EC, - the waste electrical and electronic equipment directive, WEEE, to minimise electrical and electronic equipment waste (Europa, 2008)), with the aim to improve recycling and reuse of these products or the components of these products. The producers, or in some cases retailers, have to fund take back programs, providing information to consumers on how and where to take their products back to, and this must be free of charge for the consumer. The idea is that this will encourage the producers to design and manufacture equipment that can be easily recycled or reused, thus minimising the amount of electronic equipment reaching the waste stream (Europa, 2009). In many cases designing for disassembly can facilitate this type of practice, as it enables products to be easily taken apart so that the components can be reused or recycled depending on their useful life span.

This idea of using valuable resources again and again without down-cycling them is an important issue. It can result in less extraction of natural resources being required, less waste sent to landfill and is likely to be of economic benefit to the manufacturer. It essentially uses the idea of cradle to cradle design rather than cradle to grave i.e. what could be regarded as a waste product is seen as the raw material for another process. Braungart and McDonough (2008) present this idea in their book 'Cradle to Cradle – re-making the way we make things' and explore the concept of fundamentally changing the way products are designed so that they can either be safely reused/recycled or disposed of in a way that is beneficial to the environment. They also explore the idea of leasing a product for a set period of time rather than buying it outright. This means that the manufacturer retains ownership for the materials of the product and gets the product back once the customer no longer has use for it, these materials can then be used as the feedstock for a new product. The WEEE directive from the EU potentially encourages this type of design. However the manufacturers need to fully exploit this to their advantage, recovering the maximum amount of materials for reuse and not just those that it is convenient to do so. In many cases this will require a complete re-visitation to the design process, but if it results in true cradle to cradle design, it could be beneficial both economically and for the environment.

1.5 LCAs – life cycle assessments

Life cycle assessments (LCAs) are becoming an important environmental measure of products that are designed for cradle to grave use. These can be used to shape manufacturing or construction processes by identifying areas that have the largest environmental impact. A major challenge in conducting an LCA is defining and limiting the scope of the project, which is the first of four main phases of a study, the goal and scope definition phase. After this is the inventory analysis phase, which is followed by the impact assessment phase and finally the interpretation phase concludes the study (BS EN ISO 14040: 2006). An LCA considers the whole life of a product, from the extraction of raw materials through to its disposal at end of life. It is the system boundaries that define what is included in the assessment and according to BS EN ISO 14044:2006 any aspect that could significantly influence the outcome of the study should be included. It can however be challenging to decide this and an important part of the study is to explain the cut-off criteria. Increasing numbers of products give their LCI (life cycle information) data as part of their product specifications – enabling consumers to choose materials or products with lower environmental impacts.

1.6 Dependency on natural resources (closing the material loop)

It is widely accepted that there is too much dependence on natural resources to supply energy needs and that a move away from coal, oil and natural gas is essential. This does however raise the question as to whether the human race is too dependent on natural resources for all the materials that are used in everyday life. Remembering the earlier definition of sustainability as: nature not being 'subject to systematically increasing concentrations of substances extracted from the Earth's crust' (Johnston et al, 2007, p.3), it would seem that continued extraction of natural materials is unsustainable. Indeed, Brocklesby (1998) identifies the depletion of resources as a key point of concern in terms of the impact of human activities on the environment. However, natural materials play a crucial part in every industry; the building industry for example, is extremely reliant on them. Without iron there would be no steel; without trees, no timber; without aggregate, no concrete, which does not leave many structural materials! If the human race is to minimise its extraction of natural resources then the solutions seem to be to either stop using natural materials (which would appear to be impossible) or to reuse the materials that have already been extracted. This ideology is known as closing the material loop. The concept being that at the end of a building's life the materials contained within are separated out, so that they can either be reused in their current form or recycled into another form. Steel provides a good example; it is easy to separate from other construction materials due to its magnetic properties and can be reused or recycled. Generally, large amounts of structural steel are recycled; in Australia 97% of all structural steel is reused or recycled (ASI, 2010) but this input of recycled steel cannot meet the demands for new steel, so raw materials still need to be extracted, as is the case for most developed countries. Similar practice should be able to be implemented in the concrete sector. Estevez et al (2003), as part of CIB report 287, conclude that crushing and recycling old, already used concrete for aggregate has less of an environmental impact than quarrying and crushing natural aggregates, particularly in terms of CO_2 emissions. It has the added advantage of reusing a material that otherwise might go to landfill, and reducing dependence on natural resources. Reducing demolition waste is an integral part of closing the material loop.

1.7 Importance of reducing CDW & associated legislation

The construction and demolition sectors produce the most waste compared to any other sector. With less and less space for landfill and the need to preserve natural resources, it is important that increased reuse and recycling of building materials is not only encouraged but enforced.

According to a report on the Management of Construction and Demolition Waste by the SCI (2009), around 90 million tonnes of non-hazardous construction and demolition waste (CDW) is produced per year. The industry also produces the largest amount of hazardous waste compared to any other sector. It can therefore be seen that the industry as a whole needs to make a concerted effort to reduce CDW. The EU and UK government recognise this and legislation is starting to come into place, alongside waste prevention programs. The EU Waste Framework Directive (European Parliament, 2008) gives the UK the target of reusing and recycling at least 70% of CDW by 2020. Whilst this may sound challenging, some EU member states like the Netherlands, Belgium and Denmark already recycle around 90% of their CDW, much of it as a road-base in new road construction (Dorsthorst & Kowalczyk, 2003). In recent years Germany has also managed to dramatically increase the amount of CDW that is reused or recycled. This is the direction the UK needs to be heading in to meet EU targets. According to an SCI report (2009), the government has a series of goals with regards to CDW: to help the construction industry improve its economic efficiency by reducing waste from every stage of the construction process, to encourage the sector to close the resource loop by reusing and recycling CDW and finally to increase sector demand for reused/recycled materials, therefore improving the chances of contractors salvaging materials as there are potentially economic benefits.

Examples in the Netherlands and Germany have shown that strict legislation from the Government can make a significant difference in this area. Both countries have a ban on CDW that can be recycled or reused being taken to landfill. Only hazardous or non-recyclable materials may be disposed of in this way. The difference this strength of legislation can make can be seen in the reuse/recycling percentages for CDW in Germany before and after the legislation came into place. According to a WRAP report (2009) of the legislation and planning developments concerning demolition in selected European Countries, Germany now recycles or reuses 80% of CDW. A significant difference can be seen if this is compared to the 17% that was being recycled before the new legislation came into place (Dorsthorst & Kowalczyk, 2003). It would be interesting to see if similar legalisation within the UK would produce similar results or would also increase fly-tipped waste – according to the SCI report construction waste is already thought to account for a third of fly-tipped waste. Currently, within the UK, landfill tax is the main incentive to recycle or reuse CDW but it is debatable whether this will sufficiently reduce CDW, or whether stricter legislation or a higher tax would be more effective. Nevertheless, it is also possible that encouraging reuse and recycling of CDW and emphasising the potential economic benefits of this might result in a significant reduction in CDW taken to landfill.

1.7.1 Ways to reduce CDW – Delft Ladder, recycling vs. reuse

There are a series of methodologies that look at waste management and the reduction of CDW. At the most basic level there is the principle of the three R's – reduction, reuse and recovery (the final R is sometimes altered to recycle). First the amount of waste produced should be reduced; next, objects that can be reused should be; and finally that the waste should be sorted so that items are recycled, composted or as a final option incinerated to generate energy. The three R's are a principle employed in Japan and in South Korea according to the UNEP report (2007). In the Netherlands a more complex and detailed waste management strategy has been developed, called the Delft Ladder. This has also been adopted in the UK, although it has been simplified and renamed as the Waste Management Hierarchy.

1.7.1.1 The Delft Ladder

This outlines a waste management strategy that can be applied not only to waste from the construction and demolition industries but as a general waste management strategy. It is a ten step hierarchy that was developed from the Ladder of Lansink (Dorsthorst & Kowalczyk, 2003) and should be considered at the design stage of buildings/products as well at the end of life. The Delft ladder is outlined as follows:

1. **Prevention** (essentially the same as reduction in the three R's principle) - future waste can be reduced at the design stage, by careful consideration of material choices and fixtures.
2. **Construction Reuse / Object renovation** – the principle behind this step is to renovate and improve existing structures/objects rather than demolishing them/taking them to landfill, to improve the existing product model or building rather than buying a new product or constructing a new building.
3. **Element Reuse** – considers taking apart a building/product and reusing the individual component parts, rather than letting them go to waste. Designing the building/product for deconstruction will maximise the output of useful elements.
4. **Material Reuse / Recycling** – separating materials out after deconstruction of the building/product, those materials that cannot be reused in their current form should be recycled.
5. **Useful New Application** – this is often called down-cycling, reusing the element or material for a new purpose, for example crushing concrete and reusing it as a road-base.
6. **Immobilisation with useful application** – turning a potentially polluting or harmful material into a harmless new material, for example the use of pulverised fuel ash in concrete.
7. **Immobilisation** – rendering a potentially dangerous material harmless before sending it to landfill.
8. **Incineration with energy recovery** – burning combustible waste materials and recovering the energy produced.
9. **Incineration** – burning combustible waste materials.
10. **Landfill** – waste materials taken to landfill – this should be a last resort (Dorsthorst & Kowalczyk, 2003; Addis & Schouten, 2004).

1.8 Why deconstruct – a broad overview

Burgan and Sansom state that 'sustainable development requires that the end of life impact of buildings is minimised' (2006, p.1182) Deconstruction is a very good way of minimising the end of life impact of a building. Step 3 on the Delft ladder, 'element reuse', can be achieved by deconstructing buildings rather than demolishing them, as deconstruction involves taking the building apart piece by piece which means the parts are much more likely to be reusable. This tactic can be used for both existing buildings and in the design of new buildings. Deconstruction of existing buildings can be difficult and may not yield high recovery rates. Analysis of the building techniques and the site conditions can help assess whether it is worth deconstructing an existing building. Guy (2001) presents a piece of software that can assist in deciding if it is worth deconstructing an existing building. This tool was mainly developed for wood structures, and assesses the economics as well as the practicality of deconstruction for specific projects. The potential difficulties in deconstructing existing buildings demonstrate the importance of considering deconstruction at the design stage; this concept is known as design for deconstruction or DFD for short. If the buildings are designed with deconstruction in mind, then they should be easier to take apart, yield higher material recovery rates, and less material damage should be incurred. As Gorgolewski (2006, p.493) says 'it is desirable that as many components of a building as possible be extracted from the waste stream for reuse at the end of their useful life.’

Deconstruction as opposed to demolition can have a number of benefits that are built on the idea of reusing materials. According to Chini and Nguyen (2003) the benefits of deconstruction can be split into three main categories: social, economic and environmental. The social benefits are that deconstruction will provide employment opportunities, as well as further training prospects for those already involved in the construction industry. It will also produce materials which should be low cost and good quality, these should ideally be used within the community in which the deconstruction takes place. Deconstruction may also generate other benefits for those sectors that support it e.g. if large amounts of materials are salvaged then it may provide the possibility of a local shop that specialises in reused materials. A number of studies have been done to assess the potential of reused material shops. Odom (2003) concluded that reused material shops can be successful if there is sufficient deconstruction in the area or if the company is affiliated with a deconstruction company. Odom states that ‘wherever building material waste is generated, used building material stores also need to exist’ (2003, p.185). This idea of selling the salvaged materials links back into Chini and Nguyen’s thoughts on the economic benefits of deconstruction, selling the materials is one benefit – if the contractor sells these themselves then the return is additional profit for the job. Some older materials that can only be found in existing buildings may also be of higher quality or have better workmanship than new materials and so these old materials may sell for a higher price. Deconstruction can also allow demolition contractors to expand their business and potentially employ more labourers. Finally, the environmental benefits of deconstruction according to Chini and Nguyen (2003) are that it allows reuse of materials which both saves energy and minimises the waste sent to landfill, it preserves natural materials (to some extent) and potentially can decrease disturbance to the site. According to Kestner and Webster, design for deconstruction ‘is arguably the most important green design strategy for achieving material sustainability through closing the materials loop’ (2010). This in combination with the potential energy savings makes design for deconstruction a very important sustainability strategy for future buildings.

A WRAP report has put figures to the potential environmental savings that can occur when elements are reused stating that there is a ‘96% environmental impact saving by reclaiming and reusing 99 tonnes of steel’ (WRAP, 2008, p.5) [when compared to new steel]. Even if the new steel section has 60% recycled steel within it, the component will still have twenty-five times the environmental impact of a reused section. Perhaps more surprisingly, there is a 79% environmental impact saving when reclaiming and reusing timber (WRAP, 2008, p.5).

1.8.1 Key terms relating to deconstruction

Hobbs and Hurley (2001) identify and define certain key terms associated to deconstruction. Demolition is described ‘as a process of intentional destruction’ (Hobbs & Hurley, 2001, p.98). Disassembly and deconstruction are both explained as processes which systematically take apart components, trying not to damage them, with deconstruction having the specific intention of reusing the components after recovery. Refurbishment is the process of upgrading or the replacement of a number of components or services with the intention of improving building performance. Retrofit is predominantly an American term, which describes a ‘change of use or purpose after construction from which a building was designed’ (Hobbs & Hurley, 2001, p.98). The final term described by Hobbs and Hurley (2001) is an adaptable building, which is a structure designed for flexible use – it can be easily changed to accommodate different purposes.

1.9 Deconstruction of existing buildings

The current building stock is substantial and contains lots of valuable and potentially salvageable materials. Many of the buildings in the UK in particular are also very old, not very energy efficient and therefore cost large amounts of money and energy to maintain. There comes a point when it is necessary to question whether one should continue to maintain and renovate existing buildings, as point 1 of the Delft ladder suggests should be done. When does it become better for the environment to remove the existing buildings and rebuild? This topic is suggested as an area for further work, see Recommendation 5. If one is to only consider demolishing, then there is the significant issue of the large amounts of waste that are likely to go to landfill. However, deconstruction provides a valid alternative that can potentially make the removal of existing, non-efficient buildings a lucrative and environmentally friendly option. If the deconstruction is carefully planned, then large amounts of material can be salvaged and potentially sold, and the building components can often be reused, thus significantly reducing the amount of waste sent to landfill. Potentially, new buildings on the same site could reuse the materials/components from the earlier structure, therefore minimising transport costs. There would however, need to be a specific design intention to do this and it would need to be considered at an early stage. The replacement of an old building for a new energy efficient structure can have significant energy savings in the operation of the building and if the new building is reusing components then it can also be said to have a minimised embodied energy. However, deconstruction is not a feasible option for all existing structures because it will depend on materials choices and the type of fixings/jointing and connections used throughout the project. Work has been done to develop a number of tools to help assess the feasibility of the deconstruction of existing buildings.

1.10 Conclusions

This initial chapter sets the scene for the work contained in this thesis. Major topics of concern are discussed, highlighting why new attitudes towards building design are required.

Aims of work are now discussed and an outline of the thesis given to guide readers to key areas of interest.

1.11 Aims and outline of thesis

Conducting an extensive literature review (Chapter 2) was the first step to ascertain gaps in the work on design for deconstruction. It was once this was conducted that specific targets were set for the PhD. These targets form the agenda for the rest of the work. Aims of the PhD include:

- Development of a methodology to account for designed-in future benefits
- Utilisation of this methodology to quantify the environmental savings that result from design for deconstruction and subsequent material reuse. The methodology will be applied to case studies. Initial investigations will explore potential savings within a single structural bay. Further studies will analyse the impacts of incorporating design for deconstruction into a series of structures. The work aims to identify materials and building types that may be best suited to design for deconstruction and future material reuse.
- Creation of a tool, based on the above methodology, will allow designers to explore potential benefits of design for deconstruction within their own schemes.

The aims of the PhD build on each other and are addressed throughout the thesis. The following paragraph outlines the contents of the thesis, within which the aims are dealt with.

Chapter 2 contains the literature review, which encompasses the environmental background and outlines work already conducted in design for deconstruction and material reuse. A study exploring LEED, an environmental assessment method, is discussed in Chapter 3. This includes an analysis of why material reuse credits appear hard to achieve. A methodology is proposed for how to account for designed-in future benefits, this is outlined in Chapter 4 and forms the foundation for the rest of the work. A number of feasibility studies are conducted based on this methodology, exploring the benefits of design for deconstruction for three different structural bay types. These studies are debated in Chapter 5. A tool, Sakura, was developed to allow designers to explore the benefits of design for deconstruction within their own projects; this is described in Chapter 6. Sakura was utilised to calculate the energy and carbon savings from designing for deconstruction for a number of different case studies projects. These included a range of building types and materials. The case studies and results are examined in Chapter 7. Chapter 8 ties the work together, discussing the sustainability of design for deconstruction and debates how uptake of the strategy might be increased. Finally conclusions and recommendations for further work are presented in Chapter 9.

2 Literature Review

2.1 Introduction

This chapter builds upon the background set out in the introduction chapter where environmental concerns were set out and the idea of deconstruction was introduced. In this chapter, current literature on the topics of deconstruction, design for deconstruction and material reuse is reviewed. Different structural materials are considered for their suitability in deconstruction. The concept and role of environmental assessment methods are discussed and the implications these could have for design for deconstruction and material reuse are debated. This chapter identifies gaps in existing knowledge and therefore sets the agenda for the rest of the work within this thesis. Work in this area is fast moving and this literature review is current at the time of writing on 01/09/12.

The relevance and potential of design for deconstruction was explored in the introduction, the work presented here focuses more on the practicality and implementation of the approach.

2.2 Software to assess the feasibility and potential economic benefits of deconstruction

For designers to alter their approach it is important to have firm reasons why deconstruction might be preferable to demolition. Various different research groups have developed software to assess the benefits of deconstruction as opposed to demolition. A tool of this kind, to estimate the cost and revenue potential from deconstruction is outlined by Guy and Ohlsen (2003) as part of the CIB 287 publication. This software was developed with the intention that it could be used to assess which existing buildings were most suitable for deconstruction as well as being an educational tool about deconstruction. It is also hoped that it could be used at the design stage of new structures to help maximise the incorporation of salvageable materials. Details of the current (or future) building are input into the software which assesses these details on their suitability for deconstruction and gives detailed output on the potential value of the salvageable materials including estimates for the labour time and therefore costs to deconstruct. The software can potentially be used to enable deconstruction contractors to give a more competitive bid for the removal of a building, thus hopefully enabling more buildings to be deconstructed rather than demolished.

Another piece of software is the deconstruction material estimation tool (DEMT) developed at the National Defence Centre for Environmental Excellence (NDCEE). This tool is intended to be used to reduce construction and demolition waste within the Department of Defence, in the USA. It is essentially a spreadsheet, where the user inputs details about the existing building and the spreadsheet estimates the feasibility of deconstruction and the potential quantities of materials to be salvaged. It also estimates the labour hours that will be required, the potential cost, and the potential revenue from the salvaged materials (NDCEE, 2005).

The Building Research Establishment (BRE) has developed software that minimises waste from demolition and encourages deconstruction. SMARTWaste^{TM} is an analysis tool designed to help reduce waste generation; it can also be used to provide pre-demolition audits, which assess the materials/components within the building looking at their suitability for reuse or recycling and therefore determining whether it is worth deconstructing the building for maximum material recovery (Hobbs & Hurley, 2001). As part of later work, BRE looked at six case studies (covering various building types), carrying out pre-demolition audits, reclamation valuation surveys and an environmental quantification of structure and contents. SMARTWaste^{TM} was used as part of this analysis; the material type of potential waste output is tabulated, showing large amounts of concrete waste in most building types (hospitals being the exception). A further table shows the potential for reuse, recycling or where landfill is the only option. Large percentages of the materials recovered could be reused or recycled, with pre-fabricated housing showing particularly high reuse values (Hurley, 2003). However, unless this type of analysis is carried out, the true potential of the materials within existing buildings is unlikely to be fully recognised, resulting in large amounts of waste unnecessarily going to landfill. Hurley (2003) suggests that a pre-demolition audit and associated analysis should be included within tender documents for demolition/deconstruction projects. This would however be dependent on the client being conscious of the need for this type of analysis. Perhaps demolition contractors should be made more aware of the potential economic benefits of material recovery, so that pre-demolition audits become an integrated part of the demolition work.

Another piece of software, aimed more at being deployed at the design stage to optimise building's end of life potential is BELCANTO – Building End of Life ANalysis Tool (Dorsthorst, & Kowalczyk, 2002)). This tool was being developed to help analyse which end of life approach is best suited to a particular building, as described in Dorsthort & Kowalczyk's paper 'Design for Recycling'. The software will help target whether reuse of the construction (DFA), reuse of the elements (DFDc) or recycling of the materials (DFDm) is the most appropriate end of life scenario. The idea was that a designer can use BELCANTO to help optimise their building design in terms of end of life considerations. Once materials choices and other associated decisions have been input into the program, BELCANTO will give the environmental load and life cycle costs for these choices and therefore give the most appropriate end of life scenario. However, it does not seem that further developments have been made on this program since the Dorsthorst & Kowalczyk's paper in 2002, or it may be that the tool has been given a different name, so cannot be identified as the same tool.

2.3 Deconstruction feasibility of specific construction materials

There are a number of different construction techniques, and deconstruction will be more appropriate for some of these compared to others. This part of the thesis will look at timber, masonry, concrete and steel as the major construction techniques and assess the suitability of deconstruction for existing buildings built in these ways.

2.3.1 Timber

Deconstruction of timber buildings on a domestic scale is quite common in many countries. Much of the recovered timber is also reused – although there can be problems with re-certifying structural timber, so it is not always reused for a structural purpose. It is generally thought that larger timber components are easier to salvage, as they can be deconstructed with minimal damage to them (Webster & Costello, 2005). Crowther (2003) states that older timber structures (those about 70 -100 years old) are often ideal for deconstruction as they use simple construction techniques, and the timber is generally in standard sizes, making it ideal for recovery and reuse. It is suggested that on projects of this kind an eighty percent recovery rate can be achieved, with these materials recycled or reused, depending on their condition. The type of timber originally used may also dictate whether it is economical to deconstruct. In the USA, higher values are placed on rarer species, softwoods such as Douglas Fir, Southern Yellow Pine, Cedar and some hardwoods (Neun & Grothe, 2001), and so buildings containing these are more likely to be deconstructed for maximum salvage.

A major factor in the deconstruction of timber structures is the type of jointing that has been used. The use of bolts or metal plate connectors are ideal for deconstruction as these can normally be easily removed with minimal damage to the timber, allowing for maximum material recovery and reuse. Screws, nails, staples and adhesives in joints should be avoided as they make deconstruction difficult and limit future reuse. In the cases where the timber cannot be reused in its current form, it can normally be recycled. However, in some cases where the timber is damaged or weathered it can be reprocessed before reuse, but it is not always economical to do. If large amounts of low quality or smaller sections of timber are recovered then these could be laminated together to produced longer, more usable lengths of timber (Grantham, 2002).

One of the biggest problems with deconstructing existing timber structures is that recovery rates can be significantly reduced if damp has penetrated the building envelope. Damp can cause serious lasting damage to the timber components, rendering them unsuitable for reuse (Guy, B. et al. Unknown date). Insect infestations can also be a problem. In a study of deconstruction in different US cities it was found that much of the timber in Miami was unsuitable for reuse due to termite damage (Neun & Grothe, 2001). Both of these issues demonstrate the importance of assessing the state of the building before deciding whether to deconstruct or not.

2.3.2 Masonry

Masonry encompasses brick construction, stone and block buildings. Bricks and blocks are generally made in standard sizes, which makes them convenient to reuse, however a major factor in the recovery of these types of components is how they are fixed together. Traditionally, bricks were joined using lime mortar, this was weaker than the bricks, so the bricks could be easily separated, cleaned and then reused – as is often the case when projects use traditional bricks to match with existing buildings, there is a large market for traditional bricks. However, in newer constructions cement mortar is used, this is stronger than the bricks, which means it is difficult to separate the bricks without breaking them – often the only reuse for bricks fixed in this way is to crush them and reuse them as a road base or as fill material. In brick and block construction the wall ties can also cause further damage to the bricks; however the wall ties can be recycled after use (Garrod, 2002). Traditionally built stone buildings can often be deconstructed as these either use no mortar or lime mortar, the stone can then be recovered and reused – it is considered a valuable material. Even if cement mortars are used it is sometimes possible to recover at least pieces of stone if large pieces were used in the first place. Blocks are generally jointed using cement mortars which makes recovery very difficult, they are generally crushed and recycled (Garrod, 2002).

2.3.3 Concrete

Reinforced concrete structures are generally not suitable for deconstruction, particularly those that are cast in-situ. These structures are fundamentally difficult to take apart without damaging the components, therefore reuse is generally not possible, there have however been some cases with pre-cast elements where it has been possible to deconstruct the building and then reuse the components. Nonetheless in most cases the best scenario for reinforced concrete buildings is to separate the reinforcement steel from the concrete so that this can be recycled and then the concrete is often crushed and used as a road bed (Futaki, Deconstruction in Japan, 2003, p.6), developments also suggest that the crushed concrete can be reused as aggregate in the production of new concrete (Elske Linb et al., 2003). It is important that the concrete has not been contaminated; for example if polystyrene boards are used within the concrete structure to create voids or forms, it is difficult to separate these out from the concrete, and therefore it is can be very challenging to reuse the concrete, which potentially results in large amounts of material being sent to landfill (Fletcher, 2001).

Whilst concrete structures are generally not suitable for reuse, other concrete products like paving slabs and roof tiles can be reused (Goodier, 2002, p.156). Goodier, (2002) also states that some concrete flooring systems could be reused depending on the type of jointing, those joined in-situ are unlikely to be suitable for reuse. However, the biggest barrier for the deconstruction of concrete structures is economic – there is often no or minimal economic gain for reusing concrete products (Goodier, 2002) and while this is the case it will be difficult to make the case for the reuse of concrete products. There are also a number of physical barriers for the deconstruction of existing concrete buildings: elements that have been pre/post tensioned are dangerous to de-stress, joints between units or elements are generally mortared, glued or tied with reinforcement which makes them difficult to separate.

There are, however, a few cases where reinforced concrete buildings have been deconstructed and the elements reused. In Middelburg in the Netherlands, the top seven floors of an apartment building were deconstructed and then reused to build two new, smaller apartment blocks. Deconstruction was possible due to the dry mounting jointing methods used (either steel strips or bolted connections) between all the concrete elements except the floor. The floor to floor joints were grouted but these could be cut through once the wall elements above were lifted. Once the elements were removed some repair work was carried out on them before they were used in the construction of the new apartment buildings (Dorsthorst & Kowalczyk, 2003, pp.8-10).

2.3.4 Steel

Few existing steel buildings seem to have been deconstructed, this may because steel construction is a newer technique and therefore the majority of buildings that have been built in this manner have not yet reached the end of their useable life and so have not been deconstructed. The lack of deconstruction of steel buildings may also be due to the ease of separating steel from other construction materials and then recycling it. If the main aim is to recycle the steel then consideration does not need to be given to not damaging the steel elements – so the steel structure can be cut out and then taken apart using a hydraulic compressive smash machine (Futaki, 2003, p.7). Indeed recycling steel is such a standard procedure that according to Futaki (2003) deconstruction for reuse is not considered in Japan. However, reuse of steel elements does occur with thirteen percent of structural steel sections being recycled, compared to the eighty-six percent that are recycled (Dowling, 2010). It is hoped that this reuse number can increase, according to Burgan and Sansom, ‘the potential for re-use of steel components has been enhanced by the standardization of components and connections’ (2006, p.1182).

If existing steel buildings are to be deconstructed with reuse of elements as an aim, then the connection types between elements becomes important. Bolted connections are easiest to take apart without damage to the steel. Where steel is used in composite construction with concrete, deconstruction can be difficult – as it can be very challenging to separate the steel from the concrete without damaging it. Contamination from fire protection can also be a problem in the reuse of steel structural components, where fire protection is sprayed onto the elements, removal of this can be uneconomical, particularly when potentially hazardous materials have been used (Lennon, 2002). Fletcher (2001) states that the use of intumescent paint or cementitious slurry as fire protection methods are not only difficult to remove from the steel but also add to the environmental impact of the reused steel. He goes on further to say that encasing steel in fire resistant materials is more suitable if reuse of the steel is desired, as the encasing materials can be easily removed and the steel then deconstructed and reused.

There are, however, some examples of existing steel structures that have been deconstructed and the component parts reused. In 1979, after a peace agreement between Egypt and Israel, all the army camps in the Sinai Peninsula had to be relocated. Within the camps were a series of permanent steel structures, these were deconstructed and the majority of the components taken to new sites and reused in the construction of similar structures (Katz, 2003, p.2). According to Katz (2003), a standard procedure was followed: an initial survey was carried out to assess which structures would be suitable for deconstruction and reuse, then a detailed program for deconstruction was outlined, as well as the formulation of a list of items that could be reused. Then the deconstruction was carried out, the components relocated, and finally construction reusing the elements was carried out.

The 2012 London Olympic stadium is a prime example of a current structure that has been designed for deconstruction. The upper tier of the Stadium was designed to be demountable (Figure 2.1), so that after the games are completed, it can be down-scaled to a 25,000 seat stadium for athletics and other sports. This capacity change was considered a key challenge of the design (UKGBC, 2012b) and is important to the legacy aims of the games (Brown, J. 2012).

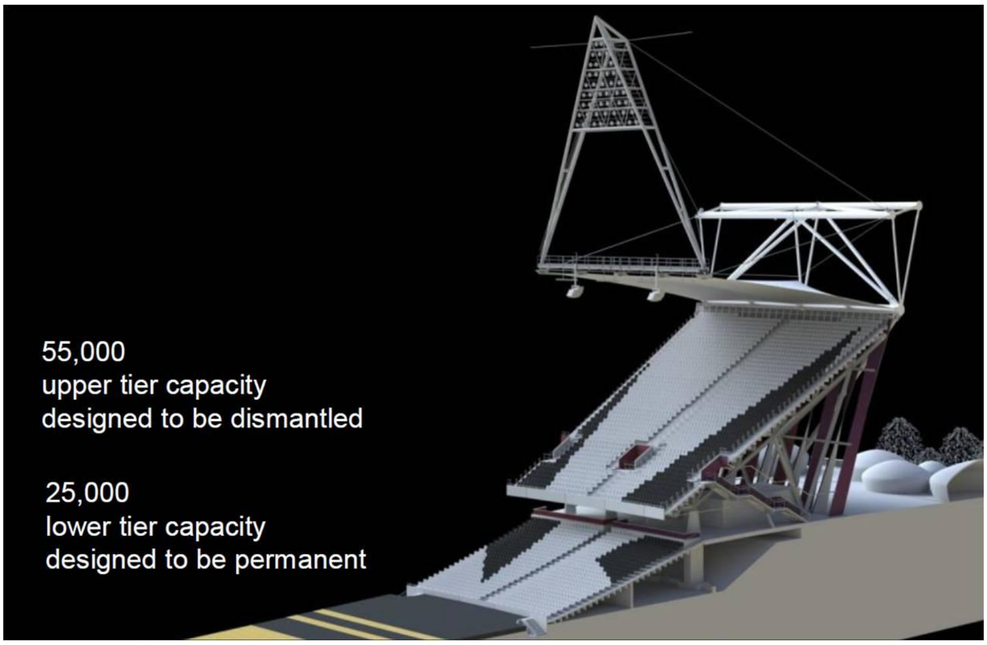


Figure 2.1: 2012 Olympic Stadium, top tier designed for deconstruction (UKGBC, 2012b)

Not only is the upper tier designed for deconstruction but the roof trusses contain reused steel elements, the roof design was adapted to incorporate these (UKGBC, 2012). It is assumed that the steel would be reused after deconstruction, but an NSC article states that 'the majority of London's steelwork is demountable and can be recycled at a later date' (Cooper, 2009, p.16). Whilst it is important that the upper tier can be easily removed – to provide a more flexible stadium, the valuable resource of (what it is assumed will be) predominately undamaged tubular steelwork should also be recognised. These elements could be reused in another project – thus dramatically reducing the embodied energy of the new structure – a truly sustainable use for London's Olympic Stadium's (Figure 2.1) unwanted steelwork.

Figure 2.2: 2012 London Olympic Stadium (UKGBC, 2012b)

Another newly built project that has been built for deconstruction is Vulcan House (Figure 2.3) in Sheffield. Designed as offices for the UK border agency, it is made up of two buildings, both of which achieved BREEAM excellent ratings. The buildings incorporate a series of strategies to make them environmentally efficient, as well as user friendly. Both buildings use steel frame construction, with approximately 980 tonnes of structural steelwork being used (Corus, 2008). An important aspect of the design that is not mentioned in the Corus document, but is commented on in the OGC (Office of Government Commerce) case study is that the frame is designed to be deconstructable. 'In its design and construction the potential future removal of Vulcan House has been considered through use of a bolted demountable steel frame the material of which is recyclable' (OGC, 2009, p.1). As with the Olympic stadium, the full potential of design for deconstruction does not seem to have been realised – that it allows for the reuse of steel sections, as a demountable structure allows the individual sections to be separated with minimal damage, making them ideal for reuse.

Figure 2.3: Vulcan House, Sheffield (Photo credit, David Millington)

2.4 Design for deconstruction in general terms – basic tactics to be applied

Having looked at the deconstruction of existing buildings it can be seen that deconstruction of most structures would be much easier if it had been considered at the design stage and therefore inherently designed into the building. This tactic towards design is often known as DfD for short, and is considered in product design as well as building design as a way to maximise the separation of materials at the end of life, the materials can then be easily recycled or ideally reused in their current form. A number of papers examine possible design strategies for DfD, the subsequent sections outline the key points from these.

According to the report 'Design for Deconstruction' (Guy, B. et al. Unknown date) there are a number of basic steps that can be implemented at the design stage that facilitate deconstruction. Maximising the simplicity and clarity of the construction and the design is the first step. The next consideration is to minimise the number of different materials used on the project, this should minimise the different types of connections required. Using mechanical connections as opposed to chemical ones will enable components to be separated more easily; the connections should also be simplified wherever possible. Silverstein states that 'as an overriding principle, the best connection design strategies preserve the independence of the members, enhancing both deconstructability and reusability' (2009, p.28). The use of hazardous materials should be avoided if at all possible, and if they are used, their position should be recorded so that they can be easily found when it is time to deconstruct. The use of composite materials that cannot be reused or recycled should also be avoided. Generally when material decisions are made, consideration should be given to whether the intention is to reuse the material in its current form, if the material is durable enough for this, or if the material is not to be reused, it should be easily recycled. The building should ideally be designed in layers, so for example that the services are not tangled up with the structure. According to the SEDA report on Design for Deconstruction (2005), building in layers also allows for consideration of different life spans of materials, and therefore considers the importance of access to these individual layers so items such as cladding can be replaced without disturbing any of the other layers. The layers described within the SEDA report (2005) are as follows: site, structure, skin, services, space plan and finally 'stuff'; with the 'stuff' being most frequently altered and the structure considered the most permanent of the layers. The SEDA report (2005) also states that the building components should be designed to be as independent as possible – so that individual sections can be replaced with ease and minimal propping. There are a number of other papers which also present strategies to best design for deconstruction, these are: Addis & Schouten, 2004; Chini & Balachandram, 2002; Crowther, 2001; Guy & Ciarimboli, unknown date; and Webster & Costello, 2005. The main strategies from these papers are summarised in table 1.

Strategies for design for deconstruction	A&S	C&B	G&C	M&S	PC	W&C
Ensure there is an integrated set of 'as built' drawings	🟩	🟩	🟩	🟩		🟩
Design building so elements are layered according to anticipated lifespan		🟩	🟩	🟩	🟩	🟩
Use connections that can be easily removed	🟩	🟩	🟩	🟩	🟩	
Avoid use of adhesives, resins & coatings which compromise reuse potential		🟩	🟩	🟩	🟩	🟩
Develop a deconstruction plan during the design process	🟩	🟩	🟩	🟩		
Design components and joints to be durable, so that they can be reused	🟩		🟩	🟩	🟩	
Provide identification of component types		🟩	🟩		🟩	🟩
Use a standard structural grid		🟩	🟩		🟩	🟩
Design for maximum flexibility - to preserve the building as a whole		🟩		🟩	🟩	
Whole design team, client & contractor need to be on board	🟩		🟩	🟩		
Ensure structural systems can be easily deconstructed	🟩		🟩	🟩		
Identify the design life of different elements	🟩		🟩	🟩		
Provide access to all parts & connection points		🟩	🟩		🟩	
Use the minimum number of connectors and limit the different types			🟩		🟩	🟩
Minimise the different number of materials used		🟩	🟩			🟩
Design the geometry to be simple		🟩	🟩			🟩
Allow extra time to ensure DfD is incorporated			🟩	🟩		
Train contractors in DfD, where required			🟩	🟩		
Establish targets for the percentage of the building that can be reused			🟩	🟩		
Where possible design in passive measures instead of active service elements			🟩	🟩		
Provide a full inventory of all materials and components used in the building			🟩	🟩		
Size components to suit the means of handling			🟩		🟩	
Use prefabrication and mass production where possible			🟩		🟩	
Select easily separable materials, with good reuse potential			🟩			🟩
Avoid composite systems			🟩			🟩
Plan service routes so that they can be easily accessed and maintained				🟩		
Designation of 'fixing free zones' to maximise lengths of material for reuse				🟩		
Use modular design					🟩	
Design for locally produced materials		🟩				
Allow for safe deconstruction			🟩			
Provide adequate tolerances for disassembly			🟩			
Provide spare parts & storage for them			🟩			
Avoid secondary finishes that cover connections			🟩			

Table 2.1: Summary of strategies to be employed when designing for deconstruction

References:
A&S: Addis & Schouten, 2004.
C&B: Chini & Balachandram, 2002.
G&C: Guy & Ciarimboli, unknown date.
M&S: Morgan & Stevenson, (SEDA Guide), 2005.
PC: Crowther, P. 2001
W&C: Webster & Costello, 2005.

2.5 Other Systems Developed to Promote the Reuse of Materials

GAIA architects in Norway developed a building system called 'Building System for Reuse' which was based on three main ideas: build in separate layers, components within each layer should be able to be easily dismantled and replaced, and finally use predominately mono-materials (avoid the use of composite materials). This system was made up of eighty-eight timber and concrete components that were specially designed for use in combination with standard components to produce a series of different constructions that can be easily deconstructed. Using this earlier system as a basis, a simpler system (Assemble for DIS-Assembly, ADISA) was developed containing only forty-five standard components that can be used to construct a variety of structures with flexible space plans (Myhre, 2003, pp.8-9). This system was piloted in the construction of nineteen houses in the eco-village Prestheia (Kibert, 2000) but at the time of writing no further published uses of the ADISA system could be found.

2.6 Environmental Assessment Methods – scope within them for rewarding material reuse and/or design for deconstruction

2.6.1 BREEAM

BREEAM (Building Research Establishment Environmental Assessment method) was one of the earliest environmental assessment methods, first launched in 1990 (Parker, 2009), and is now one of the most widely used assessment methods. It is the main tool used in the UK and is used increasingly across the world. A number of alternative schemes for different building types have been developed and implemented, examples of some of these are: BREEAM: healthcare, offices, industrial, multi-residential, education, prisons, courts, and the code for sustainable homes (BRE, 2010 b). These different tools are based on the same assessment criteria, but highlight and assess key areas that are applicable to some buildings, but not others. Schemes that specifically address environmental issues in other countries or areas have also been developed by BRE global e.g. BREEAM Europe and BREEAM Gulf schemes. BRE are currently assessing the need in other areas, but in many countries BREEAM International standard schemes can be used or BREEAM Bespoke International can assess building projects that do not fall under these schemes (BRE, 2010 c).

There are five different levels of rating within the BREEAM assessments: pass, good, very good, excellent and outstanding. The points to obtain these ratings can be earned from ten different categories: management, health & wellbeing, energy, transport, water, materials, waste, land use & ecology, pollution and innovation. These categories each address key environmental concerns. The stated issues that the materials category deals with are: embodied life cycle impact of materials, materials re-use, responsible sourcing and robustness (BRE, 2010 a).

As yet, it does not seem that there are specific points to be gained in BREEAM for designing for deconstruction. There are however parts of the point system where credit may be gained if deconstruction is considered to be appropriate. When looking at BREEAM's education assessment criteria, there are six credits available for material specification of the major building elements (MAT 1); the idea of this is to encourage the use of materials that have a low environmental impact over their life cycle (BRE, 2010a. p. 212). A structure that has been designed to be deconstructable may fulfil this criterion as the embodied impact of the structural material would be spread out over several lifecycles. Each of the major building elements (external walls, windows, roof, upper floor slabs, internal walls and floor finishes/coverings) are assessed using BRE's Green Guide rating system which allocates points per element depending on its environmental impact. The total amount of points achieved equates to the amount of BREEAM credits that can be earned (BRE, 2010a. p. 212-213). In the case where reused materials are specified as part of a new element (for example reclaimed bricks), the guide suggests that the assessor contact BRE to help ascertain a rating (BRE, 2010a. p. 214).

BRE has published a guide for the methodology for environmental profiles of construction products (BRE, 2007), this does give some guidance on how allocation of environmental impact may be given to products that are recycled or reused. This allocation procedure is discussed within Section 4.3.5.2.

There is also some other scope within BREEAM for material reuse. One point (MAT 3) is available for the reuse of facades – this is specific to the reuse of existing facades in-situ (BRE, 2010 a. p.220). There is also one point that can be achieved for the reuse of an existing structure on the same site (BRE, 2010 a. p.222). Neither of these give a lot of scope as the credit is only awarded if components are reused on the same site, no mention is given of credit for reusing structures on another site.

2.6.2 The Code for Sustainable Homes

The Code for Sustainable Homes was also developed by BRE, and became operational in 2007. From May 2008, all new build homes in England have to have a code rating (BRE, 2010 d). Credits can be achieved within the code in nine different categories: energy & CO_2 emissions, water, materials, surface water runoff, waste, pollution, health & wellbeing, management and ecology. Weightings are applied to these categories to adjust the relative values of credits in them. Dwellings can achieve levels of certification from one to six, where six is the highest level. There are certain mandatory standards that must be achieved for each level of certification (Communities & local government, 2008 b).

Within the code for sustainable homes, there is some scope for gaining credits for material reuse, but little for design for deconstruction. There are fifteen credits available for the environmental impact of materials (MAT 1), there are also mandatory standards that must be achieved in this area. These credits are assessed in the same way as described for BREEAM education projects – using the green guide to rate the materials used. There are also six credits that can be gained for responsible sourcing of materials – basic building elements (MAT 2), credit is given within this for re-used materials and for recycled materials (Communities & local government, 2008 b).

2.6.3 LEED

LEED is an environmental assessment method developed by the US Green Building Council; it stands for Leadership in Energy and Environmental Design. It is used throughout the United States of America and increasingly on an international scale, with many countries developing their own versions. The first pilot version of LEED for New Construction and Major Renovations was launched in 1998, and since then it has undergone various updates, as well as the addition of assessment methods for specific building types, for example schools (USGBC, 2009a). The current, 2009 version, has one hundred and ten points that can be obtained, with four levels of certification: certified, silver, gold and platinum. The points in the 2009 version are split into seven different categories: sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, innovation in design and regional priority. Fourteen out of the one hundred and ten points are awarded in the materials and resources category, which is the area where embodied energy is addressed (USGBC, 2009b).

Within LEED for New Construction there are specific points awarded for reusing parts of existing buildings on site and for general material reuse, all these points can be found within the Materials and Resources category. Three points are awarded for reuse of an existing building: 1.1 Building Reuse, is given if 75% of existing walls, floors & roof are maintained; 1.2 Building Reuse, is awarded if 95% of the existing walls, floors & roof are maintained; and finally 1.3 Building Reuse, is achieved if 50% of the non-structural, interior elements of the building are maintained. There are two points that can be attained for material reuse – 3.1 and 3.2, the first of these is given where 5% of the project’s materials are reused and the second point awarded when 10% of the materials are reused. There are also points awarded for the use of recycled materials, and for sourcing materials locally (USGBC, 2009b). A more extensive description and exploration of the achievement of LEED credits can be found in chapter 3.

2.6.4 Green Star

Green Star is an environmental assessment method that is mainly used in Australia, although some other countries like New Zealand and South Africa also use it (GBCA, 2009c), or are developing it for their use. The method was built on existing systems like BREEAM and LEED (GBCA, 2009a), and so is younger than these other two methods, with the initial pilot rating tool being released in 2003 by the Green Building Council Australia (GBCA). There are three different ratings that are certified by the GBCA: a four star rating which signifies 'best practice', a five star rating which represents 'Australian Excellence' and a six star rating to demonstrate 'World Leadership'. There are nine different categories in which points can be earned: management, indoor environmental quality, energy, transport, water, materials, land use & ecology, emissions and innovation. Environmental weighting factors are applied to each category, before the total number of points achieved is calculated. These weighting factors vary depending on the state in which the project is located, this enables the assessment to take into account different sustainability concerns depending on the climate and location (GBCA, 2009b). There are twenty-two points available within the materials group – although not all of these may be considered to be applicable to the project, in which case the credit option will be removed (GBCA, 2010).

Green Star seems to address and reward the minimisation of the embodied energy of materials more than both BREEAM and LEED. There are six points available for building reuse (within Mat 2) – the amount of points gained being dependant on how much of the existing building is reused. There is one point (Mat 3) that can be earned when the value of reused materials included in the project, is 2% (or more) of the total project value. This credit is new to version three of Green Star for offices. Three points are available if when using concrete the embodied energy of this product is minimised and if resource depletion is reduced as much as possible by using recycled items – amount of points given will depend on the extent of the steps taken in this area. A similar methodology is used to reward the minimisation of the embodied energy of steel, one point is given for projects where 60% of the steel used (by mass) is reused or has a recycled content of 50% or higher. A further point can be obtained where this is the case for 90% of the steel used within the project. The wording for this point was altered in the update to version three for offices, stating that these points apply where steel is reused as well as recycled. There are also points available for the reducing the amount of PVC used within the project and for the use of sustainable timber. A key new point added in this section in the update to version three for offices, is Mat 9 – design for disassembly, this point rewards projects that design parts of their building to be taken apart at end of life – either 50% and above of the structural framing, roofing and facade cladding systems should be designed for deconstruction, or 95% of the total facade should be designed for disassembly. This point looks to minimise the impact of the building at the end of life – enabling higher material recovery for reuse (GBCA, 2010).

As can be seen from the above discussion, Green Star seems to have much more scope to reward the consideration and minimisation of the embodied energy of the project, and it also starts to consider the impact of the building at the end of its life. Green Star can be seen to not only reward design for deconstruction, but to potentially encourage projects to include it within their design that would not have otherwise have done so. With increasing importance given to the environmental rating of a building, all ways to obtain points will be considered, which will include the potential for design for deconstruction within projects.

2.6.5 Comparison of Environmental Assessment Methods

It can be argued that there is some scope for rewarding material reuse within BREEAM, the Code for Sustainable Homes, LEED and Green Star. Each of the assessment methods address this issue in different ways; it could be argued that LEED and Green Star both more actively encourage this practice of reuse by having credits that are specifically devoted to rewarding it, which might mean that projects would consider using reused materials specifically to earn these credits. Whereas BREEAM and the Code for Sustainable Homes reward material reuse as part of an assessment of the environmental impact of all the materials used, which means the points could be earned without reusing materials. Green Star is the only assessment method which rewards design for deconstruction, and can be seen to be the most progressive assessment method when it comes to the consideration of the embodied energy of a project. Saleh (2009) suggests the addition of a credit to LEED to reward design for deconstruction, with a maximum of three points available. He outlines a possible assessment scheme, and suggests that at a minimum, design teams should prepare a deconstruction plan and design a baseline ten percent of the building for deconstruction. An alternative way in which design for deconstruction could be encouraged within all the assessment methods would be to include a prerequisite clause that states that the building's end of life must be considered and planned for at the design stage, in order to minimise waste materials and maximise material reuse. This is an important consideration, particularly as buildings seem to have shorter and shorter life spans, demolition or deconstruction can often occur in the designer's life span. In additional to this, buildings are repositories of valuable materials, even more so as natural resources gradually become more scarce and more expensive, so it makes sense to design to be able to recover these materials easily and with minimal damage to them.

2.6.6 Proposed Green Demolition Certificate

An alternative way to encourage consideration of the removal of a building at its end of life is through the use of a Green Demolition Certificate. Guy (2003) outlines a proposal for such a certificate, for use by government agencies or building owners to reward green demolition. The stated goals of this certificate are to recover materials for reuse or recycling, thus removing demolition material from the waste stream that goes to landfill. It also has community driven goals: to 'contribute to the environmental and economic health of the community', to 'regard necessary building removals as a community development opportunity' and to 'retain historic building character in a community' (Guy, 2003, p.1). It is a credit based system and in a similar way to LEED assessments there are a series of prerequisites that must be fulfilled. In addition to this, at least twenty-five credits must be earned, out of the fifty-two available. There are a number of ways in which to earn credits: consideration of the site during/after building removal, waste reduction, material recovery, materials management plan, and consideration of worker health and hazardous materials, being some of the main areas in which points can be earned. The specific way in which these credits can be achieved are outlined in the paper by Guy (2003), it is easy to understand, and would be relatively simple to implement. It could potentially be a very effective way to encourage deconstruction and material reuse in existing buildings, as well as helping demolition contractors develop a more sustainable way of thinking.

2.6.7 Alternative ways to promote deconstruction

Another way to promote the idea of design for deconstruction is within government legislation. Most legislation just doesn't mention deconstruction, however some actually comes close to discouraging it – in New South Wales, Australia, if one wants to use second hand materials within a new build, every item must be listed as part of the building application – this has to be done in advance of the build and can potentially be a lengthy process. One could imagine this might discourage architects, engineers or clients actually specifying reused materials, even if they were considering doing so (Crowther, 2003).

Within the UK, according to Fletcher (2001) in interviews with demolition contractors, the general consensus seems to be that increased legislation would encourage a reduction in construction and demolition waste and an increase in recycling.

2.7 Case Study – reinforced concrete car park structure in seismic zone

Gjerde et al.(2003) describe this case study as part of CIB publication 287. It considers a predominately pre-cast, reinforced concrete structure that forms a car park in Auckland, New Zealand. This car park was designed with the specific intention that it could be deconstructed and moved to an alternative site at a later date, freeing up the site for further commercial development once the economic situation is right for the developer. What is particularly unusual about this project is that the structure was designed to withstand seismic forces. Generally in seismic zones, structures are designed to be monolithic which fundamentally makes them very difficult to deconstruct. However, this structure was carefully designed to allow the majority of it to be deconstructed and reused, there is an eighty-five percent predicted recovery rate for the structure. According to Gjerde et al. (2003) the structural engineers used a number of techniques to allow deconstruction, including making the majority of the structure pre-cast. The columns were bolted into the foundations (the foundations were not designed to be moved, but possibly reused on the same site for a different structure), which allows for the removal of the columns at a later date. Corbels were cast with the columns, the reinforced concrete beams were then joined in a manner that means that they can be cut apart when deconstruction occurs. The floor is constructed from pre-cast, reinforced concrete, double tee units joined together with friction grip bolts, which will allow them to be deconstructed and reused. This is the case for the majority of the floor units, however where they connect to the shear walls (which are found in each corner of the structure), a concrete topping was required to transfer the loads to the walls. This means that these sections of the floor units would not be able to be deconstructed. The four shear walls that occur in each corner of the structure are provided to resist the seismic forces that the structure might have to endure. According to Gjerde et al. (2003) the structural engineer on the project felt that the deconstruction at the end of use for the structure would be no more expensive than demolition, and that the slightly higher initial costs to build a deconstructable building would be recovered when the elements were reused on a different site, thus saving the costs of having to start from scratch. Given the likelihood that the structure would be reconfigured on a new site with different requirements, the elements were standardised as much as possible. This project is a good example of how deconstruction can be designed into a structure, thus enabling reuse of the components and preventing large amounts of materials going to landfill. The technology and construction techniques used in this project could be used on other pre-cast concrete projects, however a major barrier to this is the uneven floor surface that is present when the flooring units are bolted together as in this project. This is not considered to be a problem within a car park but would be in many commercial and domestic projects. According to Gjerde et al. (2003), one possible solution is a raised floor system that contains services and also gives an even floor surface.

2.8 An outline of the major barriers to deconstruction

There are a number of barriers to deconstruction and material reuse, these are summarised in table 2, and discussed in more detail in the following sections.

2.8.1 Existing perception towards reused materials

Peoples' perception towards materials that have already been used can be quite negative, taking a view that second-hand materials might be substandard. Gorgolewski (2006, p.490) feels that the reasons for not using more recycled/reused materials are 'often exacerbated by prejudice and lack of clear information and clear guidance'. It is also often felt that it is not safe to reuse structural materials, which maybe the case for certain materials, but not all, as has been discussed within section 2.3. The perception of timber can be the exception to this rule, salvaged timber is often considered very valuable, although it is rarely reused structurally. Old timber is often considered to be more durable than newer, younger timber; old timber is also often considered to have more character than new timber so is in high demand for architectural applications (Storey & Pedersen, 2003). People's attitudes towards reclaimed bricks can also be favourable. They are popular reused products, and generally demand high prices due to the warm, worn appearance of them, which is very difficult to recreate with modern mass produced bricks (Webster & Costello, 2005).

One way the perception towards reused materials might be changed is to educate people as to the potential benefits of reusing materials – that they are often cheaper, whilst still being of high quality (Storey, 2002). It is also important to emphasise that it is safe to reuse certain structural elements. For example, most steel components could be reused, as defects (deflections or distortions) will be visible. According to Gorgolewski (1999, p.26), 'Steel frame buildings are particularly suited to being dismantled, and therefore allow the components and sometimes whole buildings to have a further useful life'. He goes on further to say that 'for structural steel sections, the expected performance of reclaimed components can be predicted more easily' (Gorgolewski, 1999, p.26) when compared to many other materials. Whilst it is easier to predict the behaviour of a reused steel section, this is not to say that other materials cannot be reused structurally, they may just require testing first. Timber, concrete and brick can be reused structurally as has been discussed earlier within this report.

2.8.2 Economic considerations

Designing for deconstruction is likely to have a higher initial cost, both in terms of design time and therefore cost and in construction price. In many cases clients will find it hard to justify this higher initial cost, particularly if they cannot see how they will benefit from a building that is designed to be deconstructable. More ecologically minded clients may see that the future benefits of minimising waste and maximising the use of resources within the building (as opposed to using more of the earth's virgin resources) are worth the potential extra cost. However, for clients to take this view they need to be aware of the issues and benefits involved. Lui, et al. (2003) state the importance of promoting deconstruction awareness to potential clients, architects, engineers and other designers; explaining that this will lead to the 'more widespread implementation and practical use of deconstruction' (Lui et al. 2003, p.187). More widespread use of deconstruction will also encourage further developments and enhanced use of technology within the field, which will further promote its use.

At the end of the building's life it is generally seen that demolition is the most cost effective way to remove a building, due to the speed at which this can be done. However, deconstruction can be a viable removal technique that is not necessarily more expensive. Whilst it is normally a more time consuming process, and will therefore incur higher labour costs, the salvaged materials can be sold which generally offsets the higher labour costs; reusing and recycling materials rather than taking them to landfill will also result in savings by minimising landfill costs, which can be very high in some areas (to specifically discourage land-filling materials). The Overture project in Madison, USA achieved savings of around $29,000 by deconstructing the buildings within the project and reusing or recycling the salvaged materials. When compared with predicted landfill costs, had the buildings been demolished and the majority of the debris taken to landfill, the potential cost of the project was $357,000, whereas the actual projects costs (including additional consultation fees for deconstructing) totalled at $328,000 (Newnhouse, et al. 2003).

2.8.3 Is deconstruction more dangerous than demolition for construction workers?

Consideration should be made of the construction and deconstruction processes, from the point of view of worker safety, at an early design stage. This way some potential hazards can be designed out of the building, or at least minimised. Many of the safety issues that affect the deconstruction process will be the same as those that affect the construction process, as deconstruction is essentially the reverse of the construction process. As with all construction/demolition projects, a risk assessment should be undertaken before work commences and activities specific to deconstruction should be considered. Deconstruction can be more hands on than demolition, which can mean that there is potentially more risk for the workers. However, as long as this is given due consideration and precautions are taken where necessary, deconstruction should not result in more accidents than demolition. An important fact that should be considered before deconstruction is the soundness of the structure, as this will be dismantled piece by piece, the safest way to do this should be evaluated, taking into account any propping that may be required. If risk assessments for the construction process are recorded and saved with records of the building, these can highlight key potential issues for the deconstruction process. In summary, the deconstruction process should not be more dangerous for construction workers than demolition of the same building and the risks encountered will be similar to those involved in the construction process (Hinze, 2002).

2.8.4 Lack of incentives to deconstruct

One of the major barriers to deconstruction/designing for deconstruction is that there are very few incentives in terms of legislation. Many practices which are considered to be sustainable design have legislation supporting them – either for example requiring the design team to consider the insulating properties of the building and for these to meet a certain standard, or there are schemes, like BREEAM which reward sustainable design considerations. However, there is no specific legislation in Great Britain that requires the design team to consider designing for deconstruction (Addis & Schouten, 2004), and as discussed earlier there is no explicit wording within BREEAM to reward designing for deconstruction. Addressing these two issues could potentially make a huge difference to the implementation of design for deconstruction within the UK, as it would give clients an incentive to consider it within their scheme.

2.8.5 Re-certification of materials for structural reuse

Re-certification of structural materials is currently a fairly significant barrier to deconstruction and the subsequent reuse of structural components. It potentially affects different materials in different ways. In some countries, like New Zealand, timber can be reused structurally if a structural engineer states that it is fit for reuse, which means that it must be seen to last for at least fifty years in the context of its new use (Storey, 2002). In the USA, theoretically, salvaged timber can be re-graded using the existing grading rules, although these do not take into account problems specific to reused timber, like nail holes. There is also the problem that many grading companies will not re-grade salvaged timber to be used for structural purposes, as there are concerns that they will be held liable for any future problems with it. This issue should be improved in the future as a certification system for salvaged timber is currently being developed by the USDA/F’s – forest products laboratory. Once this is implemented is should become much easier to reuse timber for structural purposes (Chini & Bruening, 2003, pp.23-24). Whilst further work does seem to have been done in this area, specific certification from the forest products laboratory does not seem to have been issued. However, there is now an FSC (Forest Stewardship Council) standard (2007) for sourcing reclaimed material for use in FSC product groups or FSC certified products, which may be making the reuse of timber easier.

A possible development that may help the identification of structural steel members is compulsory CE marking for steel elements. CE marking demonstrates to ‘purchasing clients, the authorities and others that the product complies with the appropriate harmonised European Standard’ (BCSA, 2008 p.11). The CE mark can be placed in one of three places: the product, the packaging, or in the manuals or supporting literature. Ideally, the CE mark and basic material properties will be placed on the product as this would make it easier to identify elements within buildings that are about to be deconstructed, the CE mark could then link into more detailed information about the product contained within construction drawings, enabling the maximum amount of information about the element to be stored, which should make it easier to reuse the element. It would also be possible to use electronic tagging of the elements to store the design information for retrieval at the deconstruction state. Saleh (2009) suggests building information modelling (BIM) as a digital way of storing design information, drawings, and deconstruction plans for projects so that information can be easily accessed in the future when deconstruction will take place. If there is clear information about the material properties and what forces the element was designed to withstand, then it should be much easier to re-certify and reuse the element.

Within the British design codes of practice there are allowances made for the reuse of structural materials, however test data is often required, which means it will take more time and money to specify reused products. The design codes can be seen to imply that the use of new materials is preferable and normal practice, which may discourage people from reusing materials (Addis, & Schouten, 2004). In addition to this, if people recognise that it is difficult to reuse materials, this may prevent them from designing for deconstruction on the basis that it would serve little purpose if the materials cannot be reused at the end of the building's life, and the additional cost would be incurred for nothing.

2.8.6 Insurance/legal constraints

According to Addis and Schouten (2004) many insurance policies discourage the use of reclaimed materials by increasing the price of the policy. Educating insurance companies as to the actual risks of using reclaimed materials and the advantages of using these materials might encourage the companies to reduce their premiums and thus help to promote reuse. There are also potentially some legal constraints to using reclaimed materials – standard contracts often specify the use of new materials, and where reclaimed materials are requested to be used instead, the specifier will have to justify the use of the alternative material, and in many cases will have to provide a manufacturers guarantee (Addis, & Schouten, 2004).

2.8.7 Lack of supply/demand chains

Who has possession of the reclaimed materials after the deconstruction of a building? It is presumed, in many cases, that the recovered materials will be claimed by the contractor (selling these materials may well be included within the tender for the job). If the contractor takes possession, then it would be their responsibility to carry out an inventory of materials as the deconstruction of the building occurs, so that they know what materials have been salvaged. The contractor would also be responsible for selling these materials on, storing them for sale at a later date, or as a last resort recycling them if they cannot be sold. This is potentially a whole other dimension of work for the contractor, and as such many contractors might not want to get involved. A further problem for this is that within the UK, and indeed many countries where deconstruction is being considered as an alternative to demolition, there is a lack of a supply and demand chain for reused materials (Guy & Shell, 2002). Development of such a system or the growth of second-hand material shops as discussed by Odom (2003) would enable deconstruction to become a more appealing option for contractors. It would become much easier to sell the materials on, and therefore provide an additional source of profit for the contractor. According to Gorgolewski (2006, p.491) 'mechanisms are required to stimulate the market for recovered resources.' Some work has been done on the idea of developing business models for reused materials (Guy & Ohlsen, 2003; Penn et al. 2003; Lui, et al., 2003), however, the majority of this has occurred within the USA, so systems specific to the UK may need to be developed. Lui, et al. (2003) suggest an internet database to record reused items that are available or required, so people could search for the materials necessary for their construction project, this scheme was piloted in Australia, but a similar idea might work within the UK.

Barriers to design for deconstruction and material reuse	A&S	D,L,D	G&C	G&S	JH	M&S	S&P	DM
Perceived risk in specifying reused materials	🟩				🟩	🟩	🟩	
Lack of legislation requiring consideration of DfD or reused materials	🟩			🟩				
Perception of second-hand materials, generally people prefer new	🟩						🟩	
Additional design costs	🟩							
Insurance constraints - can be unfavourable to use reclaimed materials	🟩							
Design codes of practice generally encourage specification of new materials	🟩							
Financial constraints - DfD likely to more expensive	🟩		🟩		🟩		🟩	
Composite construction	🟩		🟩		🟩		🟩	
Designing for robustness - can reduce ease of DfD	🟩							
Performance guarantees for reused materials	🟩						🟩	
Lack of reused materials market		🟩		🟩	🟩		🟩	
Ensure materials are salvaged in a safe manner		🟩		🟩	🟩			
Time constraints - deconstruction can take longer		🟩		🟩	🟩		🟩	
For existing structures, the type of jointing used, & inaccessible joints			🟩	🟩	🟩		🟩	
For concrete structures, reinforcement corrosion will not be visible - tests needed					🟩			
Visible aesthetic degradation of reused materials					🟩			
Contamination of materials (eg. From fire protection)					🟩			🟩
Site/storage for recovered materials				🟩			🟩	
For existing structures, lack of information about materials & techniques used							🟩	🟩
Loss of craft skills to create exposed connections that are aesthetically pleasing too			🟩					
Perception that DfD systems will compromise value, aesthetics, & safety			🟩					
For steel, coatings could contain banned chemicals								🟩
Coatings on steel can contaminate the shot used to remove the coating								🟩
Additional fabriaction may be required on steel sections								🟩

Table 2.2: Summary of the barriers that design for deconstruction and material reuse face

References:
A&S: Addis & Schouten, 2004.
D,L,D: Dolan, Lampo, & Dearborn. 1999.
G&C: Guy & Ciarimboli, unknown date.
JH: Hurley et al. 2002.
M&S: Morgan & Stevenson, (SEDA Guide), 2005.
S&P: Storey & Pederson, 2003.
DM: Moore, 2010.

2.9 Overcoming barriers to design for deconstruction

The barriers are not insurmountable. Education and the raising of awareness plays a major role in encouraging individuals to design differently. But there must be a reason for a change in approach; if the benefits were outlined and demonstrated then there is a tangible reason to adopt this strategy. If people could quantify a benefit to their project, it gives a reason to incorporate a new approach. Then once a new tactic becomes tried and tested and is seen to be successful more people will follow.

In this vein, the widest range of people should be exposed to the idea of design for deconstruction, from designers to legislators and from contractors to the general public. One approach would be to demonstrate the potential of the approach via a series of case studies; this would be likely to appeal to design professionals. Another would be to find a way to allow designers to quantify the benefits for specific projects and thus convince themselves and their client that the idea has merit. Incentives encouraging design in this way are an alternative method; this might be through quicker planning approval, credit in environmental assessment methods or even improved public perception of a company because it demonstrates sustainability. The opposite tactic is for legislation to require that end of life is more fully considered and planned for; this would significantly increase the number of buildings designed for deconstruction. The more buildings designed in this way, the larger pool of future resources there will be and the more successful the strategy. These approaches are explored and discussed further throughout this thesis; environmental assessment methods in Chapter 3, quantified benefits in Chapter 5, and Chapter 7 for case studies.

2.10 Identification of building types that may be particularly suitable for DfD

It is useful to identify those building types that may be most suited to design for deconstruction so that ideas explored throughout the thesis can be tested with and against these. Then further conclusions can be drawn as to their suitability. In general terms those buildings which have short life spans, frequent changes in use or requirements or have a high embodied energy ratio in comparison to operational energy are considered to be ideal for this strategy. They may also be low rise structures so that composite construction can be easily avoided. Building types that might fit this description are schools, supermarkets and warehouses.

Schools often have short life spans, and changing requirements, due to varying demographics and the need to have the best facilities for schools. Pons (2010) discusses the advantages of using steel technologies that employ reversible joints within school buildings, stating that 'these prefabricated school buildings can be extended or reduced when the amount of necessary places for students fluctuates; they can be transported to another site or change their function' (Pons, 2010, p.489). Designing this level of flexibility into school buildings is important, as these buildings can then become valuable resources to the community and their potential exploited for many years. They will also possess an inherent sustainability in that when steel components are no longer required within the school (due to downsizing), they can be reused in other buildings or stored to be reused in the same school when an extension is required.

Supermarkets are generally low rise buildings, with large spans and little attached to the structure. The larger spans give more future uses to the structure, and the design type often lends itself to design for deconstruction. Furthermore, the structure will make up a large percentage of the embodied carbon and so reducing the embodied carbon of the structure will be the most effective way to reduce it for the whole building. In addition to this, where large supermarkets chains are involved they could then have their own stock pile of materials. When a supermarket in one place needs rebuilding or significant refurbishment, then elements from an old supermarket elsewhere could be reused, minimising cost and creating a material loop within the company. This display of sustainability could also be beneficial to the company's reputation, with corporations vying for recognition in this area, for example Marks & Spencer aim to be the most sustainable retailer in the world by 2015 (Nichols, 2012).

Warehouses are also thought to be an ideal building type for design for deconstruction. Whilst they may have long design lives this is not always the case and they are very good example of a building whose embodied energy makes up a large proportion of the total energy within the total life cycle energy of the building. According to Lane (2010) the embodied energy of a distribution warehouse makes up around 60% of the lifetime carbon footprint. For this reason, when trying to minimise the energy use and carbon emissions associated with these buildings it makes sense to target the embodied energy rather than the operational energy. An effective way to reduce the embodied carbon of steel structure would be to either specify reused materials or design for deconstruction so that the materials can be reused in the future.

These building types will be revisited and the merits of designing them for deconstruction further debated in Chapter 8.

2.11 Conclusions

To ensure a sustainable future, attitudes to resource use and energy consumption have to change. Through strategies like design for deconstruction, material reuse can be maximised, thus limiting those raw materials that must be extracted from the earth, and reducing the amount of energy required for reprocessing where materials are reused rather than recycled. Two different approaches have been identified to encourage new approaches like design for deconstruction, inclusion within environmental assessment methods and the quantification of benefits incurred.

Environmental assessment methods are becoming increasingly common and can provide the standard for sustainable buildings to aspire to. They can be used to guide building design to much more sustainable standards, providing buildings that not only have a minimal impact on the planet, but start to give something back. Including new strategies within these can raise awareness and encourage more buildings to incorporate tactics such as design for deconstruction. It is important that these assessment methods are continually updated and altered to fit with evolving standards, both from a technological viewpoint and a more idealistic one. These assessments can set standards that then trickle down to the whole building market, potentially having a massive impact. Refer to Chapter 3 for a more in depth discussion and exploration of LEED credits.

The other approach identified is quantification of the benefits of design for deconstruction. If an advantage cannot only be revealed in an abstract sense but calculated in some form, then it becomes more tangible and it is more likely that people will design in a way to incur this benefit. This could have an even higher impact if potential gains are quantified for designers' own schemes. Chapters 4 through to 7 investigate methods to do this and estimate the advantages of design for deconstruction for different projects.

From this literature review two materials in particular have been identified as particularly suitable for design for deconstruction: steel and timber. In a booklet produced to explain sustainable steel construction the BCSA and Corus (Unknown date, p.6) state that steel frames 'can easily be dismantled and reused. Bolted connections allow components to be removed in prime condition and easily reused either individually or en masse as entire structures'. Not only is this an ideal approach in terms of sustainability – minimising construction waste, minimising resource use and minimising energy use (by reusing the steel component, rather than melting down the steel and recycling it), it is also economically sound. 'The most economic solution for a steel-framed building is either to refurbish it or for its components to be demounted and rebuilt elsewhere' (BCSA & Corus, unknown date, p.11). The same approach can be made for timber structures, using bolted joints so that at end of life the components can be reused. Whilst this may not make such a significant reduction on embodied carbon as it would for a steel structure, it does avoid sending timber waste to landfill, where it would release greenhouse emissions as it decomposes (WRAP, 2011).

Creating a sustainable future is a significant challenge and the built environment forms a large part of this. Boundaries will need to be pushed and many obstacles will need to be overcome, but by continuing research to expand these horizons and educating design professionals on the progress made, this future can be achieved. The remainder of this thesis aims to explore and quantify the opportunities that design for deconstruction presents, aspiring to make a small contribution to the future sustainability of the planet.

3 LEED Analysis

3.1 Introduction

Environmental assessments have been identified as a way to incentivise different methods of sustainable design. In order to understand the assessments more thoroughly an analysis was undertaken of LEED to discover which credits were easiest and hardest to earn. LEED was chosen over alternatives for example BREEAM and Green Star as it contained detailed information on credit uptake whereas the others do not. Of particular interest are the material reuse credits within LEED as understanding the uptake of these may aid discussions on the availability of reused materials. The projects were all assessed by LEED version 2. There has since been one major upgrade to version 3, and the update to version 4 is currently under consultation. This demonstrates the fast pace of this area of work and the importance of having a good understanding of the credits.

3.2 Background

In the current political climate, sustainable assessment methods are becoming more and more necessary. In California, an executive order from the Governor in 2004 decreed that all new (or renovated) state owned and financed buildings must have a LEED rating of silver or higher (Schwarzenegger, 2004). Whilst building standards vary across the United States, using sustainable assessment methods as part of the design process is starting to become common practice within the construction industry. With some buildings accused of merely having sustainable add-ons to gain credit and not being innately sustainable and suggestions of credit chasing to obtain certain building ratings (Zimmerman & Kibert, 2007), this idea of a credit becomes paramount. How easy is it to gain a credit in a LEED assessment? Which credits are easiest to obtain, both in terms of design effort and economic feasibility?

LEED (Leadership in Energy and Environmental Design) was developed by the US Green Building Council and is used throughout the United States, and increasingly on an international scale, with some countries developing their own versions of this assessment method – for example, LEED Canada (CaGBC, 2010). It gives four levels of certification: certified, silver, gold and platinum and, according to the US Green Building Council, 'LEED certification provides independent, third-party verification that a building project meets the highest green building and performance measures' (USGBC, 2010).

LEED versions 2.0, 2.1 and 2.2, sort credits into six main categories:

- Sustainable Sites (with 14 possible points),
- Water Efficiency (with 5 possible points),
- Energy and Atmosphere (with 17 possible points),
- Materials and Resources (13 possible points),
- Indoor Environmental Quality (15 possible points),
- Innovation and Design Process (5 possible points).

The points from each category are then added together, for a maximum score of 69. Platinum projects must have a score between 52 and 69; gold between 39 and 59; silver between 33 and 38 and finally certified projects between 26 and 32. There are also a several prerequisites which must be fulfilled before certification can be achieved.

LEED undergoes periodic updates as required. The pilot version, LEED 1.0 was launched in 1998, then after undergoing major changes, LEED version 2.0 was released in 2000, with slight alterations being made to this resulting in version 2.1 in 2002 and version 2.2 in 2005 (USGBC, 2009, p.6). It was updated to LEED version 3 in 2009. This version was significantly altered, with forty-one new credits, four of which make up a new category – regional priority – to address local issues to projects. There are also further prerequisites for all building projects to promote a basic level of sustainable design. Additional details of the upgrade will be discussed later within this paper.

3.3 Method

In order to assess which credits are easiest to obtain within LEED, twenty-three platinum case studies were initially considered; all these buildings were assessed using LEED for New Construction, version 2.0, 2.1, or 2.2. These different versions essentially assess the same credits, however the wording in the later versions has been altered to clarify the point of certain credits. The case studies cover several different buildings types, and are located across America. The US Green Building Council website contains detailed case study information on a large amount of LEED certified buildings. It was from this website that data on the 23 case studies was extracted. Details on where projects earned credits were put into a spreadsheet for calculation and initial analysis. This laid out which projects obtained which credits, from this the percentage of projects obtaining a specific credit could be worked out.

Certain building types were investigated to ascertain if they were more likely to earn specific points. Another study explored the impact of location on which credits were obtained. However, only looking at twenty-three case studies did not provide enough data when these were split into further groups. So it was decided to add further case studies to the data set, these were again obtained from the US Green Building Council's website. There was less information on these buildings – in terms of design strategies employed and specific building use. Nonetheless, information on where projects gained credits was available for a further 38 platinum rated buildings. The building use could easily be discovered by searching for the building project and finding the website for it. In total 61 building projects were studied. They were divided into five building types: educational buildings, office buildings, combined office and public buildings (for example libraries, assembly areas, and interpretive centres), public buildings and residential buildings. There were five buildings that could not be easily put into one of these categories: a hotel (this could potentially be considered public or residential), a laboratory, an airplane hangar and two medical centres (these could be considered public buildings, but due to significantly different operational requirements they were excluded from this group and therefore the analysis).

To analyse the buildings by location, they were sorted into different states. Some states only had one case study building within them from which little could be concluded. However quite a few states had multiple case studies so averages could be taken and the results analysed. Analysing the buildings in terms of location could have been done in several different ways, by the climate in which they reside, or into rural, urban or suburban areas. However, it was thought that organising by climate would potentially be more subjective as climate types would need to be defined, and many areas have extremely varying climates which would potentially make it difficult to categorise buildings. Assessing the case studies dependant on rural or urban location is possible, but deciding at what point an area was suburban or urban could be subjective. It was therefore decided that sorting buildings by state was the most objective way to categorise by location. In addition, building regulations can be decided on a state wide basis and this could factor into where credits were obtained.

Only platinum case studies were considered as this is the level of environmental specification that ideally all buildings will aim towards. In addition to this, given that platinum is the level which requires the most points, concentrating on these case studies will be the most straightforward way of discovering which points are easiest to obtain.

3.4 Results and Analysis

3.4.1 Analysis of Overall Categories

As discussed above, initially only 23 case studies were studied and analysed grouping all the case studies together. First, each individual case study was considered, the number of credits earned in each category was divided by the total number of credits available in that category, and from this a percentage was calculated of the number of credits achieved in each category. For example, in the sustainable sites category, 14 credits are available, if a project obtained 10 of these credits then the percentage of credits obtained is: (10/14)*100 = 71%. Once this was calculated on an individual project basis, all the projects were looked at together and an average was taken of the percentage of credits achieved in each category. It was found that the percentage of credits gained was lowest in the materials and resources, with on average, only 56% of credits being obtained. Whereas, 98% of credits were achieved in the Innovation and design category; overall, 79% of credits were acquired, about 75% of credits must be obtained for the project to gain platinum status.

When the extra case studies were added the same process was followed. The average percentages obtained were very similar for the 38 case studies as they were for the initial 23 case studies, as was expected. An overall average percentage for each category for all 61 case studies was also worked out. These percentages can be seen in Figure 3.1.

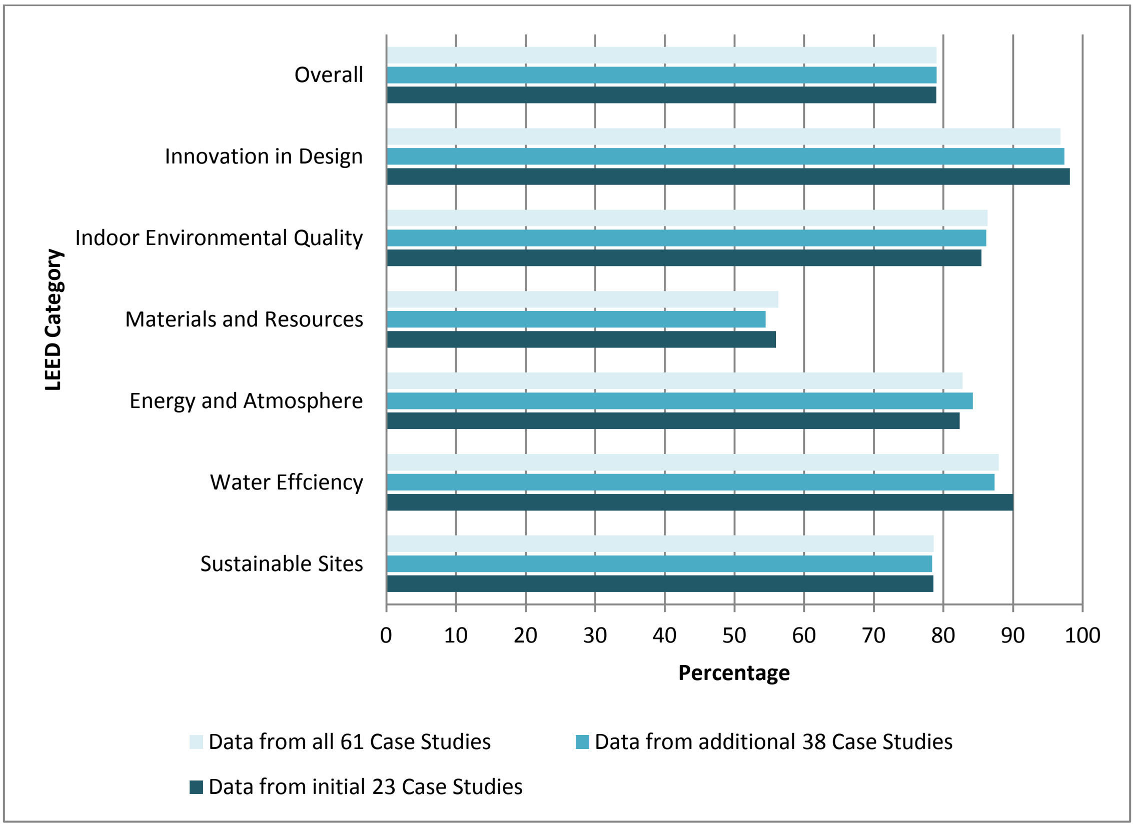


Figure 3.1: Percentage of Credits obtained in each LEED Category

3.4.2 Individual credit analysis:

In order to fully investigate why certain categories were obtaining higher or lower percentages of credits, it was necessary to look at individual credits to ascertain which credits are particularly hard to achieve or easy to achieve.

Figure 3.2 is a typical example of the results obtained when looking at specific credits within the individual categories. It shows the average percentage of projects that obtained the individual credits within the materials and resources category. As can be seen credits associated with building and material reuse are obtained by few projects. Greater reuse of materials within new build projects would result in lower embodied energy associated to the essential components of the building, which is a way to reduce carbon emissions.

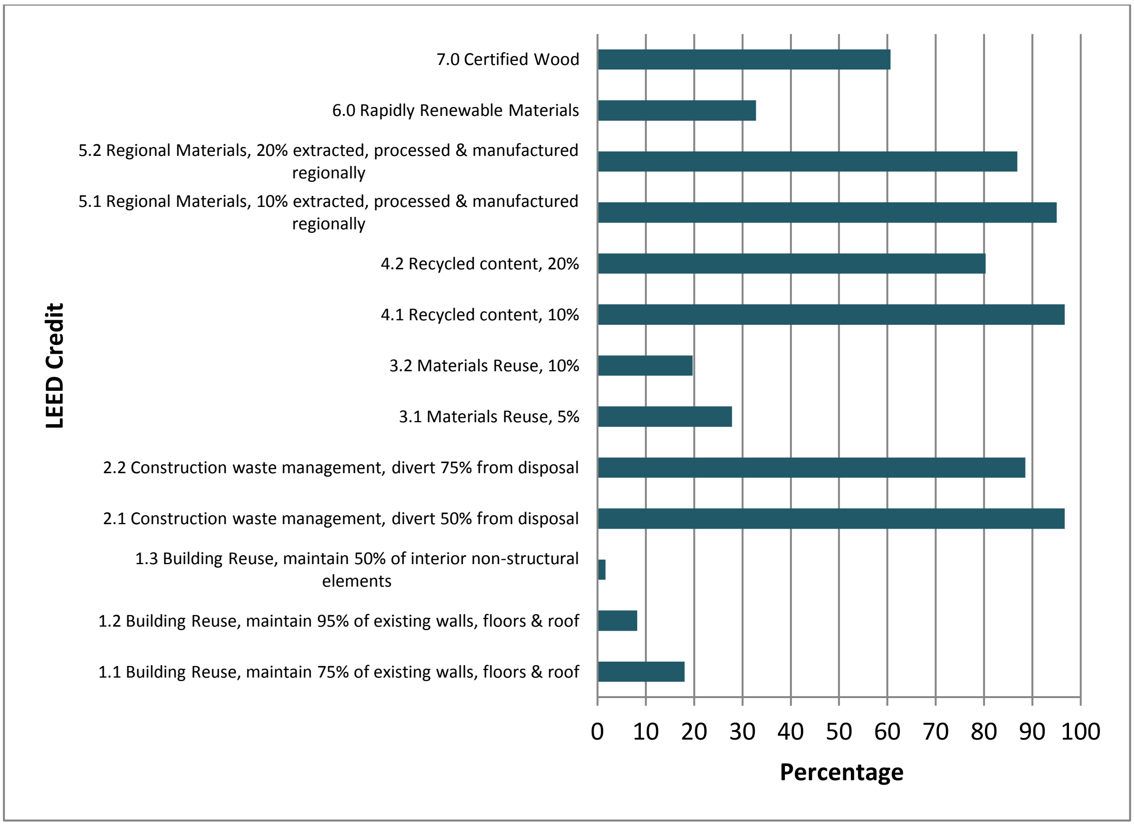


Figure 3.2: Percentage of projects obtaining specific credits within the Materials and Resources category

3.4.3 Credits that seem easiest to obtain

Initially, when just 23 case studies were analysed, there were four credits where 100% of projects gained full points:

- Materials and Resources: 4.1 Recycled content, 10%;
- *Water Efficiency: 1.1 water efficient landscaping, reduce by 50%;*
- *Water Efficiency: 3.1 water use reduction, 20% reduction;*
- Indoor Environmental Quality: 7.1 thermal comfort, design.

However, after the additional 38 case studies were added, and all 61 studies considered, only the two water efficiency credits were obtained by all projects (highlighted in italics). Materials and resources 4.1 Recycled content, 10% was achieved by 97% of projects, and indoor environmental quality 7.1 Thermal comfort, design was obtained by 93% of projects. Where all projects are obtaining a specific credit, it could be argued that the issues these credits address should become prerequisites within LEED, given that LEED is said to target the top 25% of buildings within America, high standards within LEED should be expected. Further prerequisites would raise the environmental performance of the LEED accredited buildings, no matter what level of certification the buildings are achieving.

An excellent example of this potential development can be seen in the upgrade to LEED version 3. This addresses the issue that all platinum case studies were obtaining *credit 3.1: water use reduction, 20% reduction*; so in LEED version 3, a 20% water reduction becomes a prerequisite for every project. Additional scope is included to reduce water use within projects: more credits are allocated to reward water use reduction. The project will gain two points for a 30% water reduction, three points for a 35% reduction and four points for a 40% reduction (USGBC, 2009, p. 26); whereas before in LEED versions 2.0, 2.1 and 2.2, one point was gained for 20% reduction and then a further point for a 30% reduction (USGBC, 2005). This demonstrates the importance of routinely updating environmental assessment methods. As certain practices become easier to achieve, they become standard practice, and then credits added to reward steps that take environmental performance of buildings even higher. In this way, higher and higher standards will be achieved, thus minimising the environmental impact of buildings.

However, not all the credits where the case studies gained full points have been adapted in LEED version 3. The other credit that addressed water efficiency: *WE.1.1 water efficient landscaping, reduce by 50%* has been retained, and in fact, two points are gained for fulfilling this credit in version 3, where only one was given in version 2. However, in version 3 the total amount of points that can be gained increases to 110 from 69 in version 2 (USGBC 2005 & 2009). So it may be that more points are given to water efficient landscaping to scale water efficiency issues up within the total LEED assessment.

Credit 4.1, recycling content, 10% is retained in exactly the same capacity in version 3 (USGBC, 2009). This could have been made a prerequisite within Materials and Resources in the updated version given that 97% of platinum case studies looked at gained this credit, and 89% of them gained *credit 4.2, recycled content, 20%*. Updating LEED is this way, would enforce the attitude that recycled materials should be used as much as possible. Credit 4.2 could be retained as before, and an additional credit added for recycled content at 25% or 30% to encourage building projects to go that extra step in using recycled materials.

Credit 7.1, thermal comfort, design, is the last credit that all the initial platinum case studies obtained, however, only 93% of projects gained this credit when all 61 case studies were considered. This credit is kept exactly the same within LEED version 3, and essentially requires projects to design HVAC systems in accordance with an ASHRAE (American Society of Heating, Refrigerating, and Air-conditioning Engineers) standard, the aim is 'to provide a comfortable thermal environmental that promotes occupant productivity and well-being' (USGBC, 2009, p.75). When this is the stated aim it could certainly be argued that all buildings should be trying to achieve this and that there is a reasonably strong argument for this to become a prerequisite within Indoor Environmental Quality. However, it may be that the USGBC feel that there needs to be some credits within LEED that can be easily attained in order to encourage design teams to subject their buildings to environmental assessment of this kind; this is however speculation on the author's part.

3.4.4 Credits obtained by 90+ % of projects

It was thought that where 90% and higher of the projects were obtaining a credit; it could be argued that these credits were quite easily obtainable. Energy and Atmosphere credits: 1. *optimise energy performance* and 2. *on-site renewable energy* were not assessed within this as there are multiple point options for each them and whilst most projects would obtain the first points, few projects obtained all of them. Sixteen credits (out of the fifty-one considered) were achieved by 90+ % of the initial 23 case studies looked at. When the additional case studies were considered, only fourteen credits were obtained by 90+ % of the 61 case studies, there was an overlap of ten credits when the two options were compared. The ten overlap credits are shown in red in the list below, credits that were only achieved by 90+ % of projects in the first 23 case studies are shown in black; and credits that were obtained by 90+ % of projects when all 61 case studies were considered but not when the initial 23 case studies were considered are shown in grey.

The credits that 90+ % of projects achieve:

Sustainable Sites (SS):
- 1.0 Construction activity pollution
- 4.2 Alternative transport – bike storage and changing rooms
- 4.4 Alternative transport – parking capacity
- 5.2 Site Development, maximise open space
- 6.2 Storm-water design – quality control
- 7.1 Heat Island effect, roof;

Water Efficiency (WE):
- 3.2 Water use reduction, 30% reduction;

Energy and Atmosphere (EA):
- 3. Enhanced commissioning
- 4. Enhanced refrigerant management;

Materials and Resources (MR):
- 2.1 Construction waste management, divert 50% from disposal
- 4.1 Recycled content, 10% (post-consumer + ½ pre-consumer (when only the initial 23 case studies were considered, 100% of projects achieved this credit)
- 5.1 Regional Materials, 10% extracted, processed and manufactured regionally;

Indoor Environmental Quality (IEQ):
- 1.0 Outdoor air delivery monitoring
- 3.1 Construction IAQ management plan, during construction
- 4.1 Low-emitting materials, adhesives and sealants
- 4.2 Low-emitting materials, paints and coatings
- 4.3 Low-emitting materials, carpet systems
- 5. Indoor chemical pollutant source control
- 7.1 Thermal control, design (when only the initial 23 case studies were considered, 100% of projects achieved this credit)
- 8.2 Daylight and views, views of 90% of spaces.

Whilst complying with many of these credits could be seen to be good design practice – regardless of the environmental assessment, the inclusion of them within the assessment does mean that design teams are specifically required to consider them. In addition, given that they are the points most easily won, most projects seeking LEED accreditation will incorporate them. Hopefully, in time, many of these credits will become standard design practice in not only LEED assessed projects but in all construction work, thus making all building design more considerate of potential environmental impacts.

Some legislation is starting to indicate that designers must consider some of these issues for all buildings. The new Green Building Standards Code in California (which became effective in January 2011) aims to standardise a minimum performance for residential and non-residential buildings: '20% reduction in potable water use' must be achieved (CALGreen Code, 2010, p. 21) by all projects. Construction waste practice is also being addressed and projects must 'recycle and/or salvage for reuse a minimum of 50% of the non-hazardous construction and demolition debris' (CALGreen Code, 2010, p.25). The specification of low-emitting materials is also encouraged in order to improve air quality; and an energy use reduction of 15% is being encouraged for all projects, although this is not mandatory, the California Energy Commission feels that this is a standard that all green buildings should be looking to achieve (CALGreen Code, 2010, p.35). It is hoped that other states will follow California's lead, and develop Green Building Standards of their own, moving construction towards a more sustainable future.

3.4.5 Credits obtained by less than 50% of projects

There are eight credits that are considered to be difficult to obtain (under current design practices) as fewer than 50% of the 61 case studies gained these credits. Five of the credits are considered to be closely linked with site choice, so these will generally only be obtained if the site is specifically chosen to fulfil one of these credits or by luck happens to. Two of these credits are found within sustainable sites: 2. *Development density and community connectivity*, and 3. *Brownfield Development*. The first of these is dependent on the location of the project and site choice. To obtain this credit the project must be on a previously developed site and be within a community of a certain density or within half of a mile of a residential community of a certain density and at least ten basic services, which must be accessible by foot (USGBC, 2005, p.10). The second of these credits, Brownfield development, is also dependant on site choice. According to a Davis Langdon study (2009), looking at LEED costs and credits within New York City, both of these credits (SS.2 and SS.3) were achieved by a much higher percentage of construction projects in New York City when compared with statistics for the whole of the USA; with 92% of projects in the case study obtaining SS.2 and 54% attaining SS.3. This implies that winning these credits is more favourable in a dense urban environment.

The other three credits that are largely dependent on site choice (in conjunction with design decisions) are within Materials and Resources: 1.1 *Building Reuse - maintain 75% existing walls, floors and roof*, 1.2 *Building Reuse – maintain 95% existing walls, floors and roof*, and 1.3 *Building reuse – maintain 50% of interior non-structural elements*. All these credits are reliant on there being an existing building on the site and that this building is in a suitable state to be reused.

The other three credits which are thought to be more challenging to acquire are associated with materials: 3.1 *Materials reuse, 5%*, 3.2 *Materials reuse*, *10%* and 6.0 *Rapidly renewable materials*. The difficulties in attaining the first two credits may be partially due to a lack of legislation and design guidance to support the reuse of materials, particularly structural materials, material reuse can also be discouraged by some insurance policies (Addis & Schouten, 2004). Even if the difficulties outlined above can be overcome, there is a lack of a supply chain for reused materials. If specific sizes of materials are required these can be challenging to find. One way to overcome this is to source reused materials at an early design stage so the building design can be adapted to incorporate the materials (Guy & Shell, 2002).

As discussed in within the literature review within Chapter 2, design for deconstruction would be an effective way to increase the future supply chain of reused materials. Where design for deconstruction is utilised within a project it may be that the project would be eligible for an innovation point, as designing in this way will reduce the waste produced at the end of a buildings life, maximise material recovery and where these materials are reused will reduce the embodied energy of future buildings. Innovation points are given where projects 'achieve significant, measurable environmental performance using a strategy not addressed in the LEED 2009 for New Construction and Major Renovations Rating System' (USGBC, 2009, p.83).

The last material's credit that few buildings achieve is: 6.0 *rapidly renewable materials* – these must account for 2.5% of the total value of the building products used/specified, these materials are generally from plants that are harvested in ten year cycles (or shorter), examples given include bamboo, wool, cotton insulation and cork. These are not materials that are particularly commonly used and it will depend on the project as to whether they are suitable.

There is a credit within Indoor Environmental Quality: 6.2 *Controllability of system, thermal comfort* that only 48% of projects obtained when the first 23 case studies were considered, however once all 61 studies were taken into account 61% of projects achieved this credit, it is therefore not considered particularly hard to obtain.

3.5 Analysis by location

As discussed earlier in the chapter, projects were sorted by the State in which they were built. The majority of states just had one building project in, therefore average data could not be taken for these and they were not included in the comparison or analysis. There were however ten states that had three or more projects and so average data was calculated. Figure 3.3 shows the location of the case study projects. California has far more platinum case studies located within it when compared to any other state. This may be due to more legislation with regards to sustainable buildings within this state, as discussed earlier.

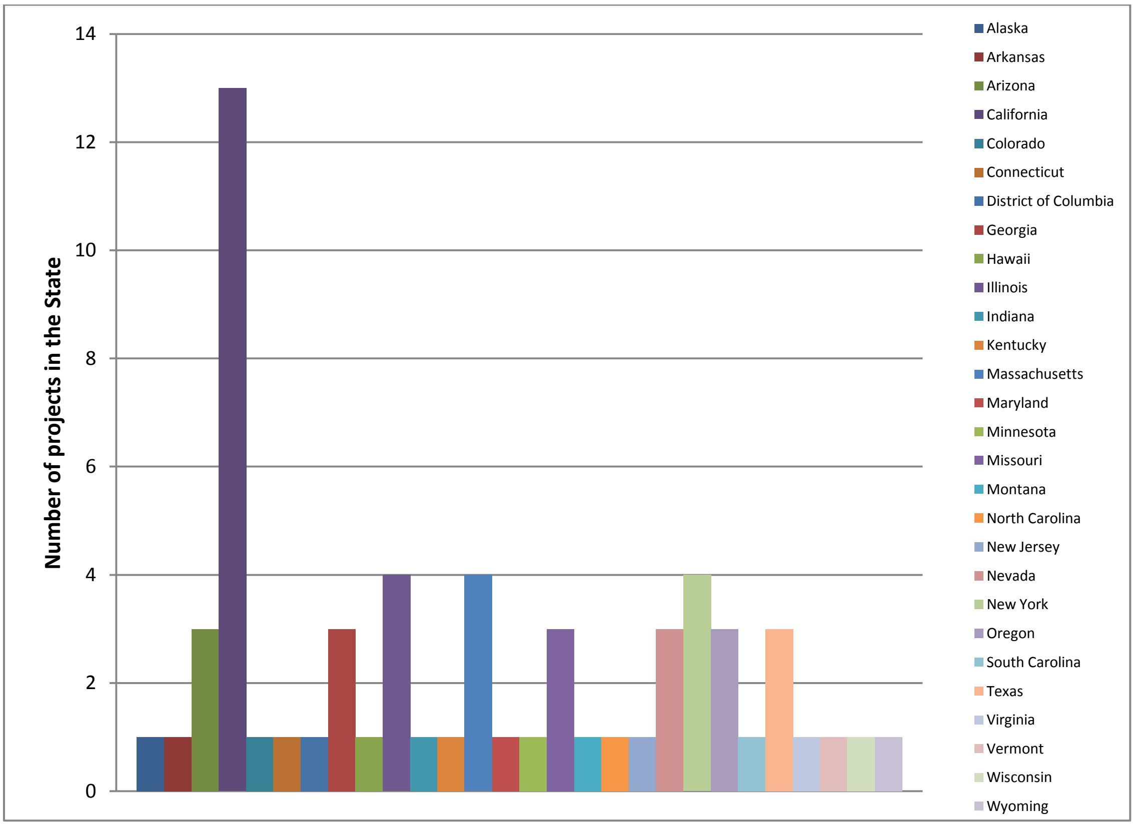


Figure 3.3: Location of Case Study Projects

As before, average percentages were taken of the credits obtained within each LEED category and this was calculated for projects within each state. In Figure 3.4 it can be seen that projects in all states tend to obtain significantly less credits in the materials and resources category when compared to the other groups.

Projects within some states seem to perform better in some categories than others. Those within Arizona, on average, score higher in the energy and atmosphere group of credits when compared to all projects; 94% of credits are obtained compared to 83% nationally. All three projects gained full points for optimising energy performance of the building. However, with only three sets of data it could be that it is purely the nature of these projects to have high energy performance rather than a trend within this state, particularly as energy legislation within Arizona is implemented on a county basis rather than across the state, except in the case of state owned buildings (BCAP, 2010a). The projects within California also on average obtain a higher amount of credits in the energy and atmosphere category, with 90% of credits obtained on average, compared to 83% nationwide. This is however likely to be due to state-wide legislation as earlier discussed. Projects within Missouri also obtain slightly more credits on average in the energy and atmosphere category, however, like Arizona there are no state-wide energy codes implemented except for state owned buildings (BCAP, 2010b). So it is more likely that these projects targeted high energy standards, rather than being encouraged to by the state.

Projects within New York obtained significantly lower than average points within the energy and atmosphere category, with projects only obtaining 66% of the credits available, compared to 83% of credits achieved when all projects are looked at. There is data from four projects in New York, it may be that the nature of these projects meant that they did not aim for high energy standards, none of the projects in question gained full credits for optimising energy performance, and one project in particular obtained low scores across the category, therefore bringing the average down. New York has a mandatory state-wide building code for both residential and commercial buildings (BCAP, 2010c), so differing codes across the state will not be factors in the varying energy performances of the case studies in this state. It is difficult to establish a trend with the data analysed in this state, as one of the buildings has a low energy performance, one higher than average, and the other two projects have slightly lower than average energy performances.

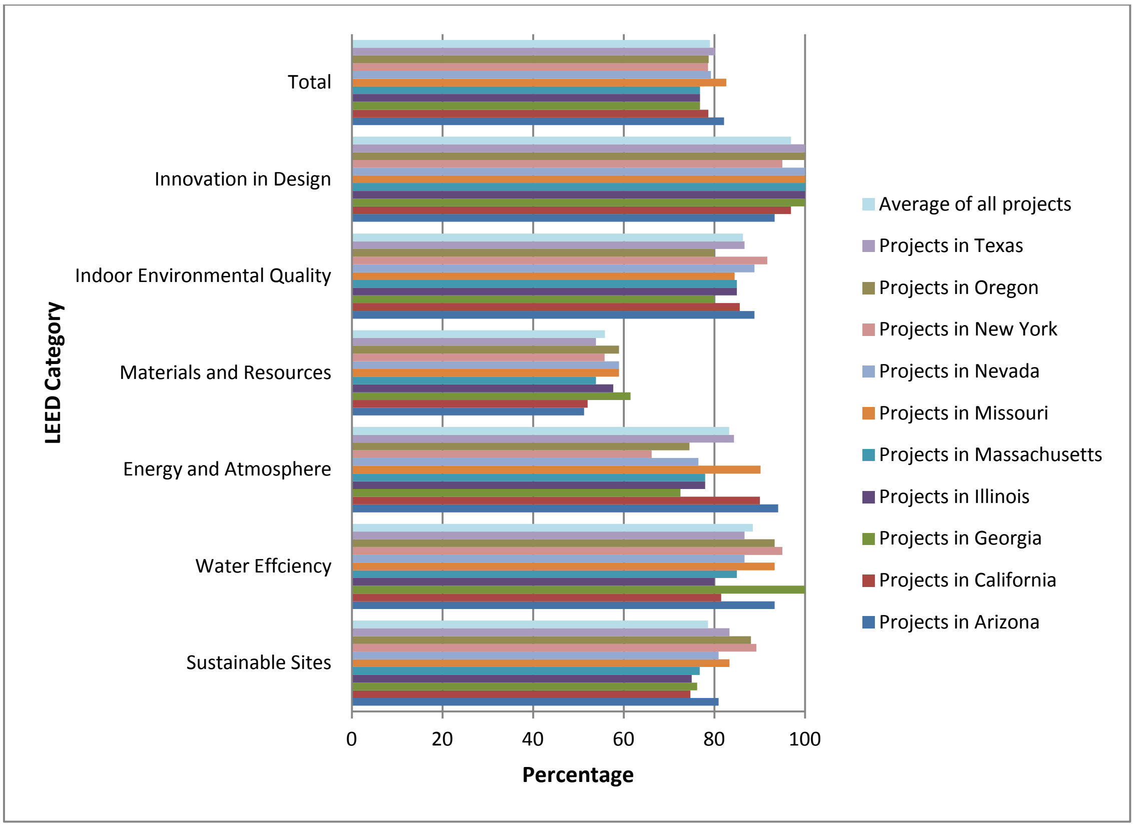


Figure 3.4: Percentage of credits achieved in each LEED Category, sorted according to project's location

There is a range of distribution, across the states, in the credits obtained in each of the categories, as shown in Figure 3.4. However some of these categories, for example, sustainable sites and innovation in design, are less likely to be dictated by state legislation than the energy and atmosphere group of credits. The variation is more likely to be due to individual project differences, locations of the projects in terms of urban/rural and varying climates.

Given the low amount of credits obtained on average in the materials and resources category, further investigation was required comparing the projects in different states. In particular, the credits associated with material reuse and the recycled content of materials were analysed, shown in Figure 3.5.

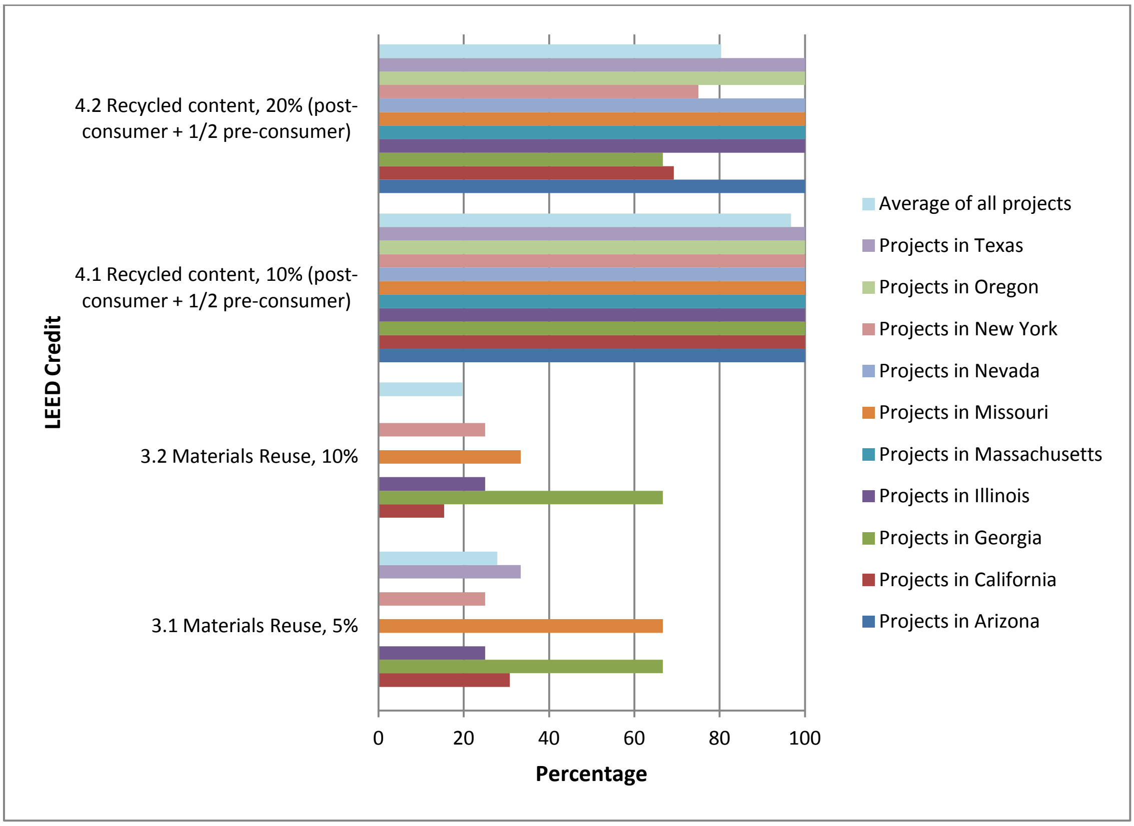


Figure 3.5: Percentage of projects obtaining reuse and recycling credits within LEED, sorted by location

The majority of projects obtain credit 4.1, *10% recycled content*, the potential expansion of this credit (and its partner credit 4.2) has been discussed earlier. The major issue that can be seen is the wide variation in the percentage of projects obtaining materials reuse credits. In some states, no projects obtain these credits, whilst in Georgia two out of the three case studies obtain both credits. It may be that within Georgia there is a better reused material market, or that these projects particularly targeted these credits. There are steps that could be taken to improve the reuse of materials and thus help projects obtain these credits: legislation could be developed supporting the reuse of materials and the supply chain for reused materials could also be increased.

3.6 Analysis by building type

The projects were split into five groups of building types: educational buildings, office buildings, combined office and public buildings, public buildings and residential buildings (public buildings include libraries, assembly areas, and interpretive centres). Some buildings could not be easily fitted into any of these categories and so were excluded from this analysis. Within each building type, averages were taken of the percentage of credits achieved in each category, shown in Figure 3.6.

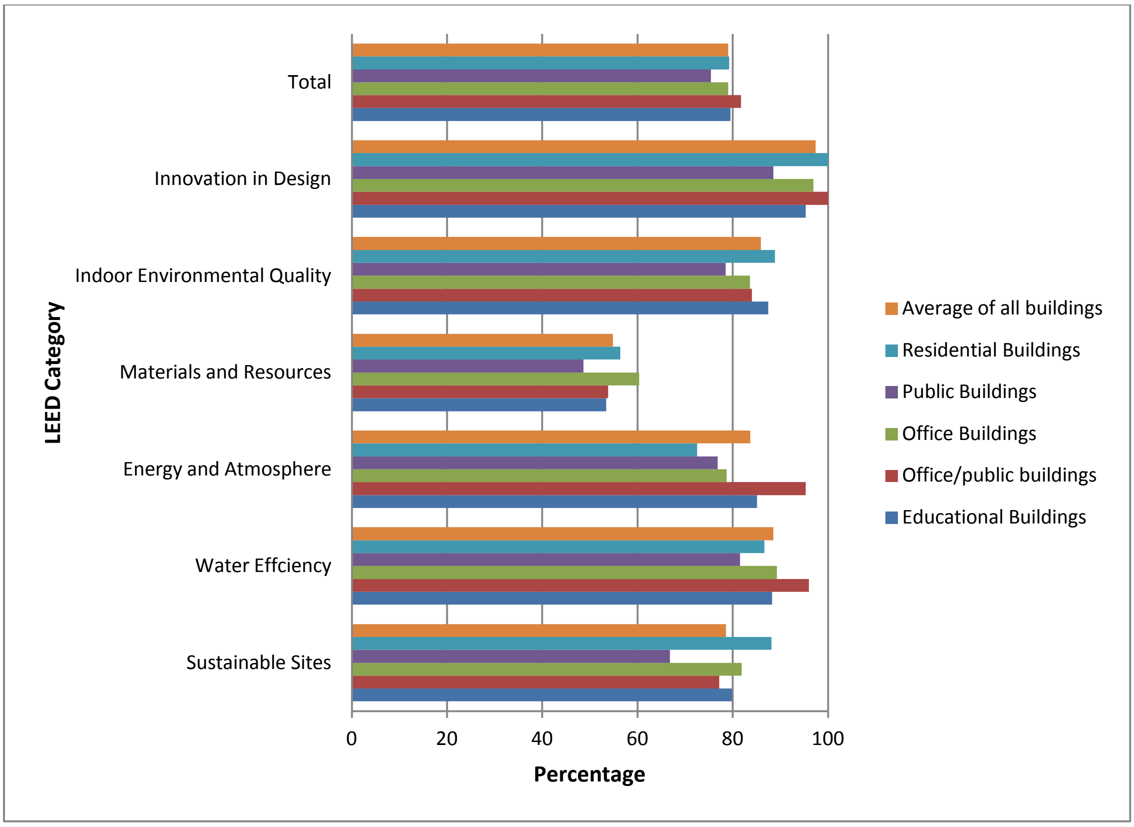


Figure 3.6: Percentage of credits achieved in each LEED category, sorted according to building type

Office/public combined use buildings achieve more credits overall and in the water efficiency and energy and atmosphere categories when compared with the average for all buildings. Whereas purely public buildings, on average, across all categories achieve less credits than the majority of other building types. It may be that multi-purpose buildings (like office/public buildings) have higher targets or more scope within their budgets that allows them to attain more credits.

The reuse and recycled materials credits were analysed in more detail to investigate if different building types were more likely to achieve these credits, shown in Figure 3.7. From this, office buildings seem more likely to achieve this credit. This may be because more of the office buildings are renovation projects, which means that they may have better access to existing materials. From the graph it would appear that residential buildings are also more likely to achieve the credits for reused materials. However there is significantly less data for the residential buildings than other building types, only three of the case studies were classified as residential, so this trend might not continue if more case studies were analysed.

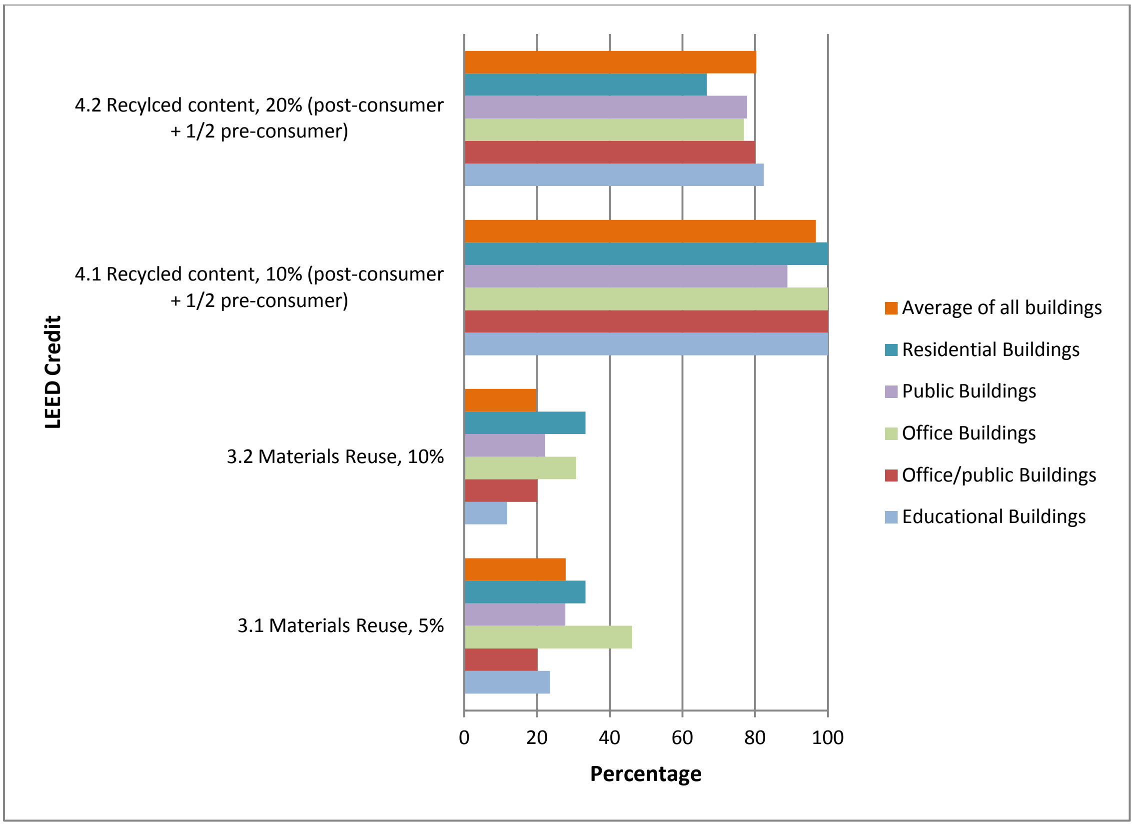


Figure 3.7: Percentage of projects gaining reuse and recycling credits, sorted by building type

3.7 Update to Version 3

In the update to version 3, the number of points available increased from 69 to 110 and an additional regional category was also added, this new category has four points to be earned within it. There is also a point to be earned for appointing a LEED accredited professional, which in version 2.0, 2.1 & 2.2 was one of the credits within the innovation category, it is now a separate entity (USGBC, 2009). This increase in points also changed the effective weighting of the different categories. The update to version 3 takes into account comments from LEED users, USGBC members and the general public (Owens, 2008). This version of LEED should therefore be more of a reflection of what the design and building community feel to be important in terms of environmental assessment.

Category	LEED Version 2.0, 2.1, & 2.2	LEED Version 3	Increase or decrease
Sustainable Sites	20.3%	23.6%	Increase
Water Efficiency	7.2%	9.1%	Increase
Energy & Atmosphere	24.6%	31.8%	Increase
Materials & Resources	18.8%	12.7%	Decrease
Indoor Environmental Quality	21.7%	13.6%	Decrease
Innovation	7.2%	4.5%	Decrease
Regional	N/A	3.6%	

Table 3.1: Percentage of credits available in each category, comparing the relative weightings of versions 2.0, 2.1, & 2.2 to version 3

As can be seen in the above Table 3.1, three of the categories increase in their relative weights and three decrease. The most substantial changes occur in the Energy and Atmosphere category in which the effective weighting increases by 7.2% and in the Indoor Environmental

Quality category in which the effective weighting decreases by 8.1%. The Materials and Resources category also has a significant decrease in the effective weighting, by 6.1%.

It is likely that the weighting of the energy and atmosphere category has increased as this issue is considered incredibly important across the globe, and will be seen to be a way to help reduce future climate change; according to Owens (2008) the update does alter weightings according to what their relative importance is considered to be. The weighting of the Indoor Environmental Quality category may have decreased due to some comments that LEED seems to place particular emphasis on the health and comfort of occupants when compared to other environmental assessment methods (Julien, 2008). However it also may be that sufficiently high levels of indoor environmental quality are achieved with LEED versions 2.0, 2.1 and 2.2 and that this did not need to be altered, particularly given that the same credits are retained in this category in version 3. The decrease in the relative weighting of the materials and resources category may be partially due the relatively low amount of credits obtained by projects in this category, and by making this category less important in terms of the whole assessment, it becomes less essential to investigate why these credits are not being achieved. In addition to this, emphasis is not currently placed on the embodied energy of buildings but on the operational energy, so the materials group of credits carries significantly less weight than the credits associated with operational energy.

The addition of the new regional category relevance is an important step for LEED. It makes LEED more transferable to different climates and allows for more flexibility with regards to local issues. These credits do not form new criteria but give bonus points to projects that achieve specified existing credits that have been highlighted to be important in certain areas. For each zip code in a state, six existing credits are listed that if achieved will enable the project to gain a bonus point. Four bonus points can be earned in total so projects can target which of the credits to achieve (USGBC, Unknown date). At the moment these credits can only be applied to projects within the US, although the USGBC is considering the best method to provide similar incentives to international projects. As an alternative to this some countries have already developed their own version of LEED or are in the process of doing so, Canada was the first country to do this, with India soon following behind, Brazil and Italy are both also looking to develop their own versions of this assessment method (Parker, 2009). Nonetheless, the way in which LEED assesses some credits may not be favourable when transferred to other countries, often credits are linked to the US dollar, to which exchange rates will need to be applied to if this method of assessment is applied in other countries, and this can potentially negatively impact the results of the assessment (Parker, 2009). This may yet change, in 2009 in the was an agreement between BREEAM, LEED and Green Star to develop a common way to measure carbon emissions from buildings, in order to provided consistency in the assessments (Kennett, 2009). This change may become evident in LEED version 4.

3.8 Conclusion

From the analysis carried out it can be seen that some credits are more commonly achieved, inferring that they are easier to obtain. These, as discussed, can potentially be formed into prerequisites to further raise environmental standards of LEED accredited buildings, and hopefully become standard design practice for all construction projects. The data analysed starts to suggest that location and building type can influence which credits can be most easily achieved, or that particular credits will be targeted by specific projects. However, further work should be done in this area, with more extensive data, before more solid conclusions can be made. There are some credits that are rarely achieved and hence must be more difficult to attain. The reasons for this have been explored and potential ways to overcome the barriers involved have been suggested. Nonetheless, some areas, for example, the reuse of materials need to be investigated further in order for more projects to actively target these types of credits. Embodied energy issues are likely to become increasingly important as operational energy is minimised. This is likely to be the next area in the construction industry to address in terms of minimising carbon emissions, so credits associated with these issues will become progressively more significant.

4 Development of a Life Cycle Assessment Methodology

4.1 Introduction

The purpose of the PhD is to conduct an appraisal of design for deconstruction. A careful review of the literature suggested that the most effective way to do this would be to quantify the environmental benefits of designing in this way. It is important that the work takes a whole life cycle approach (Blengini & Carlo, 2010a; Hernandez & Kenny, 2010), incorporating embodied carbon, which can make a significant contribution to the whole life carbon. Studies (Sturgis & Roberts, 2010) show that in warehouses, which generally have a low operational energy, the embodied carbon may make up as much as 60% of the whole life carbon of the building. The embodied carbon makes less of a contribution in office buildings, but nonetheless can make up as much as 45% of the total life cycle carbon. This approach was also emphasised in the report by the Innovation and Growth Team (a steering group of experts from across the construction industry) (2010), which suggested that it is important to consider embodied carbon as well as operational, recommending that a standardised method of measuring embodied carbon is developed and agreed upon which can then be used as a design tool. The IGT also recommend that a whole-life carbon assessment system should be developed and rigorously tested, this should then be added by the treasury to the Green Book (HM Treasury guidance for Central Government) so that a 'realistic price for carbon' is factored into feasibility studies (Innovation and Growth Team, 2010, p. 26). However, Wallhagen et al. (2011, p. 1871) state that 'there is still some way to go before life cycle thinking is actually put into practice in building design because of a lack of tools that are suitable to use in the design stage'. Other work (Kaethner & Yang, 2011) emphasises the importance of structural engineers understanding the environmental impact of their designs but suggests that the data available is incomplete. Work has been completed to add environmental impact data in the form of embodied energy and carbon to a structural frame analysis software – Oasys GSA. However, this would be best used at later design stages when more information is available so this type of complex modelling can be done. It will likely not be appropriate for use at a conceptual design stage when key decisions are made. This suggests that it may be necessary to develop a tool to assess whole life carbon at an early design stage. However, before a new tool is developed, a number of different sustainable building analysis tools have been studied in order to ascertain if any of these could be used for the study and to explore the options that are currently available. An analysis and critical review of these is presented in section 4.2.

4.2 Overview of Existing Sustainable Building Analysis Tools

There a number of different types of tools available to assist with the design and exploration of sustainable buildings. These tools take different approaches, some focus on specific areas like waste reduction, operational carbon or embodied carbon; others take a more complete life cycle analysis approach.

4.2.1 Waste Minimisation Tools:

4.2.1.1 DoWT-B: Designing out Waste Tool – for Buildings, available from 2010

This is a freely available tool from WRAP's website. The majority of the tool is used online, although some of the output and analysis can be downloaded as a series of spreadsheets. The tool aims to minimise construction waste through better building design. Designers input basic details about their construction project, floor area, number of storeys, construction type, and the amount of glazing and further details are added about the substructure, superstructure, finishes and services, using a series of tick-box options. From this information the tool generates estimates for the waste output of the construction project, assuming baseline design practice; this data is compared to waste estimates for good design practice. The tool then identifies areas of improvement, and puts in place a framework to allow the designer to consider alternative ways of minimising waste, demonstrating how different strategies will impact on the waste output. A series of design principles are used as baseline steps to mitigate waste, these principles are design for: reuse and recovery; off-site construction; material optimisation; waste efficient procurement; deconstruction and flexibility (WRAP, 2010).

The tool encourages different ways of thinking about minimising waste, and promotes sustainable design from this perspective. It allows for comparison of different projects, enabling designers to investigate what impact using different construction types has on the waste output. It also provides an estimate of the embodied energy of the project. However, it is not very clear as to how the embodied energy is calculated and what dataset is used to do this; improved transparency in this area would be helpful.

4.2.1.2 SMARTWaste, available from 2008

SMARTWaste is a waste minimisation tool for construction projects that can be freely sourced from the Building Research Establishment (BRE). It is an interactive web-based tool that helps the designer formulate a waste management plan. Project details are input into the tool (similar to those required for DoWT-B), and a benchmarking calculator is used to help estimate the waste likely to be generated on-site. However, the waste estimates appear to be very approximate (e.g. when a case study was formulated and investigated, the waste output did not change when the frame type was altered from concrete to steel). The tool allows the user to put together a waste management plan and then track the waste output throughout the construction works. The user decides whether the waste is going to be reused, recycled, recovered or disposed of and then gives potential cost implications of the waste disposal. It would be helpful if the tool looked at the environmental implications of the waste disposal method as well as the cost. It does however link into BREEAM/Code for Sustainable Homes and explains where points can be earned that are relevant to waste minimisation and management. The program shows the actual waste outputs graphically as well as numerically (Building Research Establishment (BRE), 2010).

This tool has similar aims to DoWT-B, in that they both aim to minimise the waste output from construction projects, and both appear to be successful in doing so. However, on reflection, it is believed that DoWT-B encourages overall sustainable design more than SMARTWaste through the consideration of the different design principles, and that it is therefore, potentially a more useful tool.

4.2.1.3 True Cost of Waste Calculator, available from 2008

This freely available, web-based tool, calculates the carbon and monetary cost of materials that have been wasted on construction sites and therefore aims to reduce waste by raising awareness of the potential impacts. This tool is also from the Building Research Establishment (BRE) and the website gives a very transparent outline of how the tool works. Default rates for waste have been taken from BRE's Green Guide to Specification but alternatives can be used in order to explore the impacts of this. The embodied carbon data is taken from SimaPro, with Ecoinvent used as the dataset, this includes cradle to gate data and disposal related data. The cost data was taken from Laxton's Price Book 2008.

Initially the user has to create a project, inputting basic information about location, project dates, sizes, building and construction type; this information is then saved. The tool requires the user to enter the amount and type of materials that will be used on the construction site.

The material types are split into categories: bricks, tiles and ceramics, inert, insulation, metals, gypsum, binders, plastics, timber, floor coverings (soft), asphalt and tar; some of these categories are broken down further into specific materials. Default waste rates are then applied, the percentage is shown, and the user can also add their own waste rate percentage. This information is saved and linked to the results page which shows the impact of the waste in numerical terms as well as displaying it graphically. Both the carbon impact and the cost implications are shown (Building Research Establishment (BRE), 2008).

This is a very useful tool that allows users to quantify the impact of waste and by so doing gain an understanding about where the biggest potential is to save both carbon and money. Whilst both DoWT-B and SMARTWaste would be effective in reducing waste they do this from a different perspective by encouraging the user to think of various disposal options. This calculator is more useful to identify specific problem areas with the highest impact. Quantifying the impacts more effectively highlights problem areas and encourages users to minimise the impact of waste.

4.2.2 Embodied Energy and Carbon Calculators for Buildings & Structures

4.2.2.1 Faithful + Gould Construction Carbon Calculator, available from 2008 for operational energy, embodied energy added in 2012

This carbon calculator from Faithful + Gould was originally a downloadable spreadsheet that focused on estimating the operational carbon of a building. It has recently been up-dated to a web-based tool and expanded to also incorporate embodied carbon. Initially, the user selects the type of building (hotel, retail, school, warehouse or flat) then inputs the area, and specifies whether the building is naturally ventilated or air conditioned and has a narrow or deep plan. Based on this initial information the application estimates how many tonnes of CO_2e the building is likely to produce in a year. It also suggests a figure that it may be possible to reduce the emissions to, but it does not give any indication of how this might be done. There is a click option to see the embodied carbon emissions and estimates are then shown for what the embodied carbon of the building is likely to be and what it could be reduced to (Faithful + Gould, 2012). No indication is given on how this estimate is made, although it is presumably based on the floor area input.

In many ways this application seems a step back from the original spreadsheet which was available to download. The original spreadsheet was focused on operational carbon and required more input information which suggests the results may have been more accurate. It was also far more transparent in its workings as it listed assumptions that had been made, and where factors had been applied showed what these were. (Although it was possible to change these factors which would perhaps be a disadvantage.) The original spreadsheet didn't however consider embodied carbon; the addition of this to the web tool demonstrates an increasing interest in this area.

It is concluded that while the Construction Carbon Calculator is useful for a quick estimate of both operational and embodied carbon the results may not be particularly accurate and it would be useful to have more information about how the values can be reduced. It is however recognised that this is a marketing tactic so that designers will contact Faithful + Gould to help reduce the carbon footprint of their project. Increased transparency of how the tool works and what datasets it uses would be useful.

4.2.2.2 Carbon Footprinting Tool for Bridges, available from 2011

This carbon footprinting tool is a free, downloadable spreadsheet that has been developed by TATA Steel, BCSA, and Atkins. It calculates the CO_2e emissions from the materials used, the transport of materials and plant to site, the construction and maintenance of the bridge as well as the emissions associated to the traffic delay caused by the construction and maintenance of the bridge. Initially, users are required to input basic information about the bridge, bridge type: whether it is a road, rail or foot/cycle path; if it is a road then the type of road should be specified: motorway, rural A road, urban A road, rural minor road or urban minor road; the type of obstacle that bridge crosses should be selected: road, rail or watercourse; if the obstacle is a road then the road type should once again be selected. It is also necessary to input the estimated construction duration and the bridge length and width. Once the initial details have been input more specific information regarding the materials used should be recorded. The volume of reinforced concrete or structural steel used can be specified, and the specification is broken down into foundations, sub-structure and superstructure. The spreadsheet then estimates the contribution of maintenance and from possible traffic delays. The results are shown both numerically and in the form of a pie chart; this enables the contributions of the different components (foundations, substructure and superstructure) to be easily seen, the ratios of impacts of the site's setup/close down, design/construction, maintenance and traffic delay can also be seen. There is a helpful page in the spreadsheet which outlines the assumptions that have been made, giving good transparency, here it is stated that the Inventory of Carbon and Energy (ICE) from Bath University is used as the main dataset (Bridges Carbon Calculator, 2012).

This is a very useful tool that can be used quickly and effectively to assess the potential impact of a bridge design. It is transparent in its workings and easy to use and understand. It would however useful if there was a wider range of material options and more input options for the concrete mix so that users could explore the impact of using cement replacements.

4.2.2.3 Butterfly – currently underdevelopment

This is a tool that is currently under development which builds on a life cycle costing application from BLP insurance who are working in partnership with Willmott Dixon, UCL Energy Institute and the University of Cambridge's Centre for Sustainable Development. The tool is designed to assess material choices against their performance for both new build and retrofit residential properties. It will be CAD compatible, allowing projects to be uploaded to the tool where it will then 'generate the energy calculations and measure the design attributes against industry standards and energy reduction targets' (BLP Insurance, 2011). It is hoped that it will allow life cycle and environmental impact exploration of designs at an early stage; it will also predict life cycle costing of designs. The output will be given in terms of life cycle costs, operational energy and carbon, embodied energy and carbon and an assessment of the level attained for the Code for Sustainable Homes. It uses Bath University's Inventory of Carbon and Energy for a dataset, as well as BLP's durability, costs and component attributes data. Example results are provided as part of a presentation which can be found on BLP's website. It is suggested that a fully working version of Butterfly will be released by the end of 2012 (BLP Insurance, 2011).

This tool could potentially be very useful to explore the impacts of designs, however it seems to be suggested that CAD drawings will be required to use the tool; at a very early conceptual design stage these are unlikely to have been completed. It would be useful if Butterfly allowed basic material input to account for this. The transparency and accessibility of the results cannot be assessed at this time as it is not yet possible to use the tool. This could be a useful tool to aid designers' decisions from a whole life cycle approach for residential projects.

4.2.2.4 Construction Carbon Calculator – from the Environment Agency, available from November 2011

This is a freely available spreadsheet that can be downloaded from the Environment Agency's website. It allows users to input basic information about their project, and then more detailed material information – the quantity of each material in tonnes used within the project as well as the mode of transport to site and the distance travelled should be input. There is also the useful option of inputting additional material information for any materials that aren't already included within the tool. The amount of energy required for plant, equipment and site accommodation can be entered, personnel travel can be estimated. The tool is very transparent and there is a page which shows the source data that is used and the references for this. The main source of the material data is the Inventory of Carbon and Energy from Bath University. Once all the information has been recorded a report is generated, which is a page within the spreadsheet, this shows the total carbon footprint of the project as well as a breakdown showing the contribution of different areas to the total CO_2e. This breakdown would be useful to highlight key areas of impact which could then be targeted for reduction. There is a user guide within the spreadsheet which outlines the aims of the calculator, explains the different pages within the spreadsheet and offers some carbon reduction tips (Environment Agency, 2012).

This is a very effective cradle to site study of the carbon footprint of a building project. The contribution of construction and personnel can also be modelled, although this may be more approximate as designers are less likely to have this information readily available, particularly with regards to plant requirements. The tool is easy to use and offers good transparency on its workings, the input data that it requires is quite detailed and will require a fair amount of compilation before entering into the tool, this suggests that it may be too onerous a task to be completed at an early design stage.

4.2.3 General Life Cycle Assessment Tools

4.2.3.1 SimaPro 7, available from 2006

SimaPro life cycle assessment software enables users to analyse the environmental performance of products and processes. The main database is ecoinvent, although other data sets can be selected e.g. the US LCI database, the ELCD (LCI data from EU-level business associations), US input output, EU and Danish input output, Dutch input output, and LCA food dataset (PRe Consultants, 2010). This gives a wide scope of data to enable a complete analysis of whole process routes. It is possible to map out the processes that lead to the production of a material or product and SimaPro shows the network clearly, demonstrating which processes have the most impact. The user can also create and model new processes that are not already within SimaPro and these can be copied between different projects. There are a number of impact assessment methods integrated within Simapro, these have automatic normalisation factors and sort the impacts into different categories, e.g. acidification, to enable easier and more efficient analysis. The user can compare different products, exploring which areas have minimal environmental impact, helping to identify the most sustainable product choice. It is also possible to model and analyse complex waste treatments and end of life scenarios (PRe Consultants, 2010).

SimaPro is very useful for analysing specific processes and products, particularly when exploring more complex end of life scenarios. However, in order to do this it is necessary to have sufficient background knowledge of LCA, which many people will not have. In addition to this, the results are presented in a way that is difficult to understand quickly, the graphics cannot be comprehended at a glance and so the result loses impact when trying to convey information to a less specialised audience. This means that it is likely that an extra step will be required to simplify information for delivery. It is for these reasons that SimaPro is unlikely to be used to model entire buildings, particularly at an early design stage as sufficient information would not be available to model it. It would also require a specialist to model and then interpret the results, unless designers had the time to learn and utilise these additional skills.

4.2.3.2 Envest 2, available from 2003

This is an environmental impact assessment and whole life cost tool that designers can purchase to assess environmental and cost aspects of their projects. It is a web-based tool, from the Building Research Establishment (BRE), available in two versions: Envest 2 estimator and Envest 2 calculator. The first uses environmental and financial data to assess the whole life performance of a design, the latter places emphasis on whole life costs. The environmental impacts are grouped into twelve different impacts, ranging from climate change to waste disposal. The tool can be used to make direct comparisons between different designs and it is suggested it could be used to present 'the environmental and financial credentials of different designs to clients' (Building Research Establishment (BRE), 2012).

As this tool has to be purchased it has not been possible to trial it. From the website it does not seem to be transparent in terms of the datasets and calculation methods used, this could however be available within the purchased tool. This tool does not appear to consider the whole life cycle of a building, but focuses on material specification and includes a prediction on the operational impacts.

4.2.3.3 Umberto 5, available from 2007

Umberto is a piece of software that can be purchased to conduct life cycle assessments. It enables the user to model and assess products and processes. Material and energy flows can be modelled, as well as carbon footprints. It has various ways of visually representing flows and results, using Sankey diagrams[1] in addition to graphical analysis. Comparisons can be made between different products, sensitivity analysis can be performed and it is also possible to conduct carbon footprint calculations according to PAS 2050 – a methodology used in the UK to calculate the carbon footprint of goods and services. Ecoinvent is used as one of the datasets, data is also available from other sources (specific names are not mentioned on the website), and it is possible to model and store new processes. There is also the potential to explore the cost implications of different materials and processes (Umberto, 2012). Umberto seems to be a comprehensive LCA tool that would be useful to model materials and processes, the addition of the cost analysis would also be useful. It is hard to ascertain how comprehensible the graphical output is from the tool. This can often be a problem with LCA tools of this type, the graphs can be hard to understand for non-specialists, which means there is potentially another step to simplify information before it can be conveyed to a wider audience. Modelling a whole building design within Umberto would be a very complex and time consuming process so it is unlikely that designers would do this.

4.2.3.4 GaBi 4, available from 2008

This is a life cycle assessment tool that can be purchased and used to improve the sustainability of products and processes. It is available in a number of different versions, and contains a number of different LCA databases that the user can choose from; these include the GaBi Databases, ecoinvent and the US LCI dataset. One or all of these can be used within models, potentially making studies more complete. It is suggested on the website that to conduct a building life cycle assessment GaBi Build-it should be used (GaBi, 2012). It is thought, however, that this would be a too detailed and time consuming process for most designers to go through. The example output also appears to be complex and not easily understandable, which would make it less effective for use outside of the specialised LCA community. It is believed that this is more suitable for mapping and exploring specific products and processes to better understand which areas could be targeted to reduce the environmental impact of them.

---

[1] Sankey Diagrams are scaled illustrations that display the flow within a process or system (Cyberphysics, 2008).

4.2.4 Environmental impact building analysis tools that use a life cycle analysis methodology

4.2.4.1 LISA – LCA in Sustainable Architecture, available from 2003

This program is an easy to use, simplified life cycle analysis tool, designed to assist in sustainable design. It presents a series of case studies, predominately based in Australia, that consider the whole life cycle of projects, from construction, throughout their useful life, finally considering basic demolition/end of life of the project. The program is downloadable from the LISA website in conjunction with the case studies. To use the tool, a case study must be selected and the user can then investigate the environmental impacts of different design decisions. The tool presents broken-down environmental impacts in both a numerical and a graphical format (the graphical format is more useful); the user can alter certain design decisions and investigate how these decisions affect the resulting environmental impact. An example of one of these variables is the specification of no recycled steel or all recycled steel for various component parts. The alterations made are then compared to the original example within the graphical output, enabling the user to see the difference in environmental impact. The details of the case study are broken down into a number of different categories, and these categories can be compared graphically to see which contributes most or least to the environmental impact of the project. The categories can also be displayed individually within the graphical output, to investigate the impact of the different aspects of each category. What the different categories are seems to depend on the case study chosen (LISA, 2003).

The program is very easy to use and transparent as to how environmental impacts are calculated. It clearly shows the environmental benefits of various design decisions, therefore helping designers to make these types of decisions in their own projects. However, it would be useful if this tool would enable designers to input their own projects in order to investigate their specific environmental impacts.

4.2.4.2 BEES v3 – Building for Environmental and Economic Sustainability, available from 2003

This is a freely available tool that aims to help designers with the selection of building materials/components, assessing the environmental performance of them in conjunction with the economics of the choice. This tool was developed by NIST (National Institute of Standards and Technology) in the USA and has been developed and updated over a number of years, version 4.0 is the current release. The tool has data for about two hundred and thirty different building products. It assesses a number of different environmental impact factors which contribute to an environmental performance score. The program also has economic performance scores for all products (made up from first costs and future costs). The user can define the weighting of the environmental performance versus the economic performance to contribute to one overall score. It is important to note that the lower the BEES environmental score of a product, the better the product is in terms of environmental performance (BEES 4.0, 2007).

Currently, when considering the selection of structural elements there seems to be an emphasis placed on concrete products – there is a wide variety of different concrete mixes that can be selected to investigate the environmental and economic benefits of the product, however there seem to be no other options for different materials. The program seems easy to use and would be helpful when selecting building products. The user can define what graphical output is displayed, exploring different environmental aspects with different graphs if so desired. A larger variety of building products available for selection would be helpful, so that the user could compare the impacts of steel, concrete and timber beams for example.

4.2.4.3 Athena Impact Estimator for Buildings, available from 2005

This tool is designed to carry out an assessment of whole buildings, based on LCA methodology. Only an incomplete trial version can be downloaded for free, the full tool must be purchased. The program is aimed at projects in North America, and takes into account the environmental impacts of material manufacturing, including resource extraction and recycled content; related transportation; on-site construction; regional variation in energy use; transportation and other factors; building type and assumed lifespan; maintenance and replacement effects, and demolition and disposal. The user has to input initial building data and then uses pre-set dialogue boxes to describe the different assemblies – requiring for example the width, span and live load of a floor assembly. The estimator then shows the cradle to grave implications for these decisions, with a number of different environmental impact outputs. Reports can be generated to show the different impacts; this can also be shown graphically. The software also allows for a comparison of different options and production of a bill of materials based on the assemblies selected. In terms of embodied energy and carbon, the estimator seems largely concerned with the structure and envelope, and not the potential impact of 'fit-out' items. The repair and maintenance effects do however seem to be considered. End-of-life effects are considered but the analysis seems limited and is obviously not the focus of the tool (Athena Institute, 2010), (Athena Institute, 2008).

4.2.5 IMPACT, underdevelopment

Another new tool, IMPACT, is being developed to specifically look at the embodied energy of buildings. A number of companies are collaborating to develop a plug-in to existing CAD systems to show the embodied energy of the materials within the design. This this program was scheduled to be available from 2011 for some CAD systems and from 2012 from the other remaining selected CAD systems (Lane, 2010) but at the time of writing (July 2012) there was no further information regarding this tool.

4.2.6 Conclusions about existing tools

There are a number of different tools available to assess a range of sustainability criteria; some dealing in specifics, for example, waste created in the construction process and assessing the embodied and operational energy/carbon of projects, others taking a broader approach assessing a range of criteria and collating this into an overall environmental impact rating. Many of these tools have been designed specifically to explore impacts in buildings, whilst others are targeted more generally at products and services and are thus complex to apply to whole building projects. It is the latter which allow for the modelling of different end of life scenarios. However, the complexity in doing this combined with the intricacy of modelling a whole building within these programs means that investigations would be extremely time intensive and require extensive additional life cycle assessment knowledge. Designers would be unlikely to carry out these investigations themselves; therefore studies would only be conducted if specialists were employed. The other tools do not allow for the modelling of specific end of life scenarios and many do not consider these at all. None of the tools allow for consideration of design for deconstruction or account for the advantages of a future benefit that has been designed into the building.

It has been identified that an important part of 'appraising design for deconstruction' is to quantify the environmental benefits of design for deconstruction. No existing tools will currently do this. Therefore, a methodology to conduct this study will be developed, as discussed in the following section. Then investigations will be carried out to quantify the environmental benefits of design for deconstruction. As part of this work a tool will be developed, based on this methodology, to allow designers to explore the specific benefits to their projects.

4.3 Life Cycle Assessment Methodology

4.3.1 Introduction

As has been discussed extensively within the literature review, there are number of reasons to design for deconstruction: it facilitates reuse of materials, enabling savings in embodied energy and carbon in future buildings, reduces the waste sent to landfill and lessens the exploitation of natural resources. The purpose of this work is to 'appraise design for deconstruction', demonstrating to designers and clients the explicit benefits of designing in this way, by quantifying benefits for specific projects, moving discussions away from the abstract to calculated advantages. There is nonetheless a difficulty in convincing clients to potentially pay slightly extra for their project to be designed for deconstruction when the benefit is not incurred until some point in the future, when the project is deconstructed, and then the value of the salvaged materials can be claimed. One argument is that the client could be seen to be investing in carbon, as products with a high embodied carbon are likely to have a higher value in the future due to carbon tariffs and policies to reduce emissions. By investigating the whole life carbon of a project, the future carbon saving created by facilitating reuse can be calculated. However, there are no current whole life cycle assessment methodologies specifically for buildings that enable a cradle to cradle study with full consideration of end of life options. The following sections in this chapter will explore different methodologies and life cycle assessment strategies that could be developed and applied to this work, setting the framework for further investigations.

4.3.2 Life cycle assessment framework

4.3.2.1 LCA goals and scope

There are multiple goals of this PhD study: to investigate, quantify and then compare the environmental impacts and benefits of different end of life treatments on both a component level and a whole building scale. In addition to this, end of life impacts and benefits will be compared to the impacts that occur at the different life cycle stages. This requires a whole life cycle analysis of a building to be carried out – from cradle to cradle - meaning that the initial extraction of materials right through to the end of life scenario will be included in the study. In addition to this, ideally any re-fabrication that will be required to prepare the material for its next life should also be included in the investigation. The study will therefore include a number of different stages: material specification (including material extraction, processing, manufacture and transport to site), construction, operational phase of the building, maintenance and repair, demolition/deconstruction and end of life scenarios for individual material components.

The LCA study will be carried out with two end of life scenarios, each specific to the different material components and dependant on if design for deconstruction has been incorporated as well as other key design decisions. The end of life options are reuse of material, recycling or landfill of material. An assumption is made that recycling, where it is standard practice, will be carried out but no credit is given for this as most datasets incorporate the benefits of a recyclable material within the environmental impact figures. The methodology outlining how the benefits of reuse will be calculated is discussed in section 4.3.5.

4.3.2.2 LCA Functional Unit

The output of the impacts of the whole life cycle of the building as well as the different end of life options will be investigated in terms of energy intensity (kWh/m^2/yr), carbon intensity (kgCO$_2$e/m^2/yr), and where applicable landfill avoidance (tonnes). Ideally, water usage (kg) would also have been investigated, but at the time of writing insufficient data could be found and collected for use. The energy and carbon intensity metrics are those that have been proposed as global protocol for measuring energy use and greenhouse gas emissions by a collection of experts, whose recommendations are supported by the United Nations Environment Program (United Nations Environment Program, 2010). Whilst it is suggested that metrics should be on a per year basis, it may be that when comparing the environmental impact of the different life cycle stages that it is more effective to consider them over the whole life span of the building. Both options will be explored within the study.

Selection of the life span of a building is contentious as these can vary so greatly. Haapio and Viitaniemi (2008) conducted a study to explore the effect of varying life spans on the environmental impact of domestic buildings. However, for this study, it has been decided that an initial default value of 50 years will be taken; this is what is specified, as a life span, in BS EN 1990-2002 for building structures and other common structures (British Standards Institution, 2010, p. 28). A number of LCA studies use a 50 year life span: Malmqvist et al. (2011) used it within their study and in a spreadsheet to conduct simplified LCAs, Wallhagen et al. (2011) used it in a study of an office building in Sweden and Van Ooteghem and Xu (2012) used it in their LCA study of a single-storey retail building in Canada. However, whilst 50 years will be used as a default within the tool it will also be possible for the user to change this value if they feel that the design life of the building will be significantly different.

The individual products or components will be assessed over a hundred year period as the PAS 2050 method states that this is the time period that the impact of Greenhouse Gas emissions should be assessed over, following the manufacture of the product (PAS 2050, 2008, p. 27). This suggests that for those buildings that use the default value for the life span that the components can be used twice within the assessed period. It should be noted that for durable materials, such as steel, use could be possible beyond 100 years and therefore estimates made on the number of potential reuses may be conservative.

4.3.3 LCA System Boundaries

The system boundaries are as shown in Figure 4.1. The box labelled existing data is where life cycle information (LCI) data will be used from existing data sets. The main dataset that will be used is the Inventory of Carbon and Energy (Hammond & Jones, Inventory of Energy & Carbon version 2.0, 2011) but for more information on LCI data sets see Section 4.3.8: Life Cycle Inventory. Cut-off points with regards to material extraction, processing and manufacture will have been drawn as part of the formulation of this dataset. As in many studies, the emissions associated with the production of capital goods will not be included in the study. (Capital goods are items like machinery, equipment and the buildings within which the products being studied are produced.) According to an 'Introduction to LCA' (Goedkoop, De Schryver, Oele, Durksz, & De Roest, 2010) from SimaPro, if all the processes involved in the life cycle are included in the study but the capital goods are excluded, then the work is a second order study. In addition to this, the transportation of workers to site, and the running of the site office are considered to be outside the boundaries of the investigation as they do not contribute directly to the life cycle carbon of the building, and can be argued to be part of an individual's carbon footprint and a company's carbon footprint.

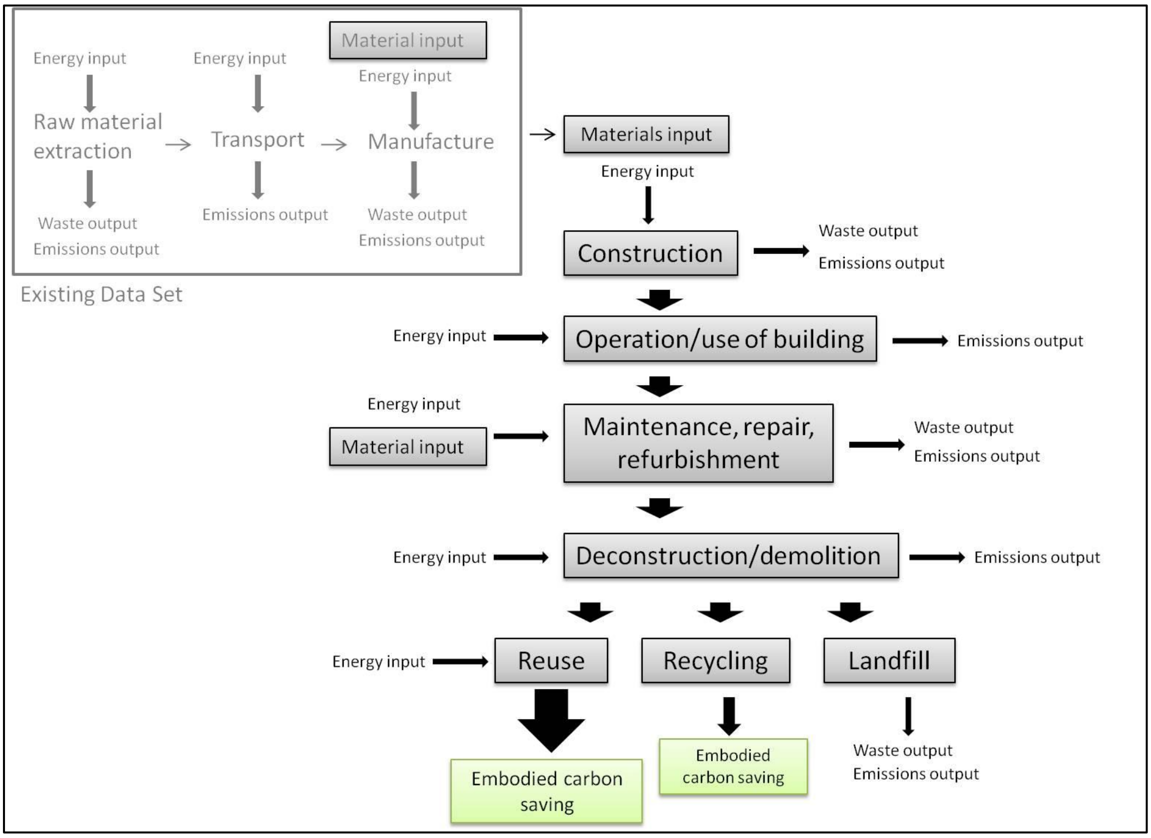


Figure 4.1: System boundaries of the life cycle of a building

4.3.4 Discussion of Life Cycle Analysis Methods

There are a number of different types of analysis that could be used to conduct an LCA study, namely process based, input-output based or hybrid based (generally with an emphasis on either process or input-output).

4.3.4.1 Processed based analysis

Processed based analysis is the most commonly used method, it is based on the main production processes within the study, investigating the resource and energy input into the process flows and the resulting emissions and waste from it. A diagrammatic approach is often taken, tracing the flow of the product back to the beginning of the process, essentially forming a network of interlinked processes. Theoretically a process should be traced back to the initial starting point, however it can be difficult to define where this point is and if many interlinked processes are involved this can complicate the matter further. Therefore it becomes necessary to draw a defined cut-off point, which means that there can be some system incompleteness within the study. A matrix approach can also be taken in process analysis, a number of matrices are set up and the 'LCI is calculated by inverting the technology matrix and multiplying it by an environmental matrix' (Suh, et al., 2004, p. 658). This approach is used in various pieces of software and within some public LCI databases (Suh, et al., 2004). This method will also suffer from some incompleteness as it is dependent on the boundary condition that has been set. A matrix approach will not however be taken within this study.

4.3.4.2 Input-output analysis

This is a top down technique based on economic data. The input-output tables are generally produced at a national level on a regular basis and show how different sectors are connected through the input and output between them. Life cycle analysis studies using this approach can be considered to be more complete, they will generally pick up aspects that may have been missed out when a process flow is drawn, as they encompass economy wide impacts. The economic sectors can be quite general in nature so if specific sub-sectors are being modelled the results may become more approximate. There is also a risk that the data will be out of date which can cause significant differences in those sectors that develop quickly. In addition to this, those sectors/countries that have a large amount of imports can have higher levels of uncertainty in their data. The environmental data from different sectors can also be incomplete or limited which can introduce further sources of error (Suh, et al., 2004).

4.3.4.3 Hybrid analysis

Hybrid analysis combines the two approaches to obtain more complete results with less risk of error. The boundary between where the different types will be used is often dependant on the availability of data, but in general terms, the downstream requirements (construction, use and end-of-life) will often be assessed using process analysis and the material extraction and manufacture will be assessed using input-output analysis. Suh et al. (2004) found that when the same study was carried out using the process method and a hybrid LCA the results from the hybrid LCA were 18% higher than those from the process based analysis. This is likely to be because the hybrid analysis is more complete so includes more of the impacts that were cut off in the process analysis.

4.3.4.4 Suitability of different methods to building life cycle analysis

It is important to consider which of these LCA methods are most suitable for life cycle analysis of buildings and specifically for use as part of the tool. A number of studies (Suh, et al., 2004; Mattila, Pakarinen, & Sokka, 2010; Dixit, Fernandez-Solis, Lavy, & Culp, 2010), demonstrate the benefits of hybrid analysis, with Dixit et al. (2010) stating that 'input-output based hybrid analysis is considered complete and nearly perfect in the life cycle analysis of buildings'. However, whilst there are benefits of hybrid analysis, 'process analysis is the most frequently used method' (Emmanual, 2004, p. 1254).

Within the work, existing life cycle information (LCI) for materials and components will be utilised, so the choice of method for the material data will have already been defined. It is therefore likely that cut off points will have been drawn as part of the boundary conditions, this will likely introduce some incompleteness to the study, which is unavoidable. However, as the LCI data to be used is commonly sourced data, for example the Inventory of Carbon and Energy (Hammond & Jones, 2011), any cut offs within the data that occur are well accepted as this data has been used as the main data source or as part of a set of data within many other studies (Khasreen & Banfill, 2010; Knight & Addis, 2011; Bramley, Ciotti, Parnaby, & White, 2010; Kaethner & Yang, Environmental impacts of structural materials - finding a rational approach to default values for software, 2011; Lee, Traka, & Hensen, 2011; Monahan & Powell, 2011). Process analysis will be used as a basis for the remainder of the study as data is most available in this form and due to the material data the study will already have an inherent incompleteness which could not be combated through a hybrid approach.

4.3.5 Discussion of environmental impact for products with multiple uses

One major issue with regards to reusing materials is how the environmental impact of the material is shared between life cycles. Consider, the longer a product's life span the less environmental impact the product has per year. Therefore, by reusing components that have a longer life span than the assembled building the environmental impact attributed to the first building could potentially be reduced. There has been little work done in this area, particularly where buildings are concerned. Of specific interest to this work is how best to account for designed-in future benefits.

Some studies (Ramesh, Prakashm, & Shukkla, 2010) ignore the energy savings that can be gained by recycling or reusing materials from a demolished building, 'primarily due to the fact that there is no common agreement over attributing this saved energy to the demolished building' (Ramesh, Prakashm, & Shukkla, 2010, p. 1594). Whilst other studies do acknowledge that the embodied CO_2 of buildings can be reduced by reusing materials and 'preparing for demounting and future reuse' (Wallhagen, Glaumann, & Malmquist, 2011, p. 1869) but do not discuss if or how this should be dealt with, implying that it hasn't been addressed in the study. Early work in this area (Brocklesby, 1998, p. 86) assumed that all recycled and reused materials no longer had an embodied energy once they had been removed from the initial building. More recent work in the area suggests a number of different approaches, these are discussed in the following sections, and have been summarised in Table 4.1.

	British Standard	**BRE**	**PAS 2050**	**SimaPro**
What it is:	Code for life cycle analysis procedure	Methodology for assessing environmental impact of material selections	Methodology for the carbon footprinting of goods and services	Life cycle assessment software
How reuse is dealt with:	Identifies three allocation methods for reused materials	Benefits of reuse are tied to economic assessment	Benefits of reuse shared equally across all life cycles	Reused materials treated as discounts in the life cycle analysis
Pros/cons:	Provides a useful framework but difficult to implement practically	Prediction of future economic values is extremely problematic over 20-50 year cycles	Easy to understand and implement	Prohibitively detailed for use at conceptual design stage

Table 4.1: Summary of reuse methodologies

4.3.5.1 British Standards Approach

BS EN ISO 14040:2006 (British Standards Institution, 2006a) and BS EN ISO 14044:2006 (British Standards Institution, 2006b) both deal with life cycle analysis procedures. BS EN ISO 14044:2006 (British Standards Institution, 2006b) deals with the issues of reuse and recycling in the context of allocation, suggesting that the same allocation methods applied to co-products should be used for reuse and recycling scenarios. The ISO states that 'reuse and recycling may imply that the inputs and outputs associated with unit processes from extraction and processing of raw materials and final disposal of products are to be shared by more than one product system' (British Standards Institution, 2006b, p. 15), meaning that it is important to carefully consider the system boundaries with regard to reuse and recycling and to identify whether the material is part of a closed-loop or an open-loop system as different allocation procedures may apply. A closed loop procedure not only applies to closed loop product systems but also to those open loop systems where no inherent changes occur to the material properties. In these cases, as the reuse or recycling of the material displaces the use of virgin material, the need for allocation is avoided. For those materials that do not incur an inherent change to their material properties and are recycled into a different product system, an open loop allocation procedure should be applied. For this, where feasible, allocation should be based on physical properties i.e. mass; where this is not possible, economic value, or as a last option, it should be based on the potential number of subsequent uses of the recycled material (British Standards Institution, 2006b).

4.3.5.2 Building Research Establishment Approach

The Building Research Establishment (BRE) has done some work in this area as part of their 'Methodology for the Environmental Profile of Construction Products' (Building Research Establishment (BRE), 2007). This suggests that allocation to recycled or reused products should be based on economic value, as in the ISO discussed above, but the methodology gives a more comprehensive overview of how this might be approached than the ISO does. When utilising this methodology it is important to define where the base point is and what the base material is. Allocation to recycling is only taken up to the point that is useful for the material to be recycled, for example the base point for a steel section to be recycled is the manufacture of the steel slab, which is referred to as the base material. If the section was to be reused then the base point would be after the section manufacture, and the steel section would be the base material. Allocation is based on the ratio of the economic value of the base material to the value of the material to be recycled or reused. This is best explained within the BRE document through the use of an example: the recycling of aluminium. The value of a one tonne ingot is approximately £1250, from the initial tonne, 0.988 tonnes will be the product yield, the scrap from this is estimated to be 90% of this, (0.9 tonnes) with a value of £750/tonne. Therefore the environmental impact allocated forward to future recycling is (Building Research Establishment (BRE), 2007):

$[(0.988*(90/100))*750]/(1*1250) = 53\%$ (Eq 1)

Whilst the BRE methodology explains the allocation method much more fully than the ISO, it does seem to disregard that the ISO states that where possible allocation should be based on physical properties, e.g. mass. There are also potential difficulties with allocation based on economics as it can be difficult to predict rising material prices, the value of carbon that is embodied within some materials and how best to incorporate inflation. Another uncertainty is which scrap price to use, should it be based on an average value at the primary manufacture of the material or based on a predicted price in the future (that accounts for inflation) or on an actual price in the future if the calculation is done then?

4.3.5.3 PAS 2050 Approach

'PAS 2050 – How to assess the carbon footprint of goods and services' (2008) also deals with how to treat the environmental impact of reused and recycled products. This also draws on information from the ISOs that have already been discussed. PAS 2050 states with respect to recycled materials that may be considered to store carbon, 'a product using recycled material receives a carbon storage benefit (as long as you can demonstrate that the recycled material was created for the purpose of being used in the product)' (PAS 2050, 2008, p. 28). The latter part of this is problematic, as recycled materials will often not have been created to be specifically recycled at their end of life but rather this is the most sustainable method of disposal for many. Whilst some products may have been designed so that the individual components can be separated to facilitate recycling, this does not technically fulfil the bracketed section of the quote above. PAS 2050 (2008, p. 30) also deals with how to assess the carbon footprint of recycled products in a more general way. First it is necessary to define whether the recycled material is in a closed or open loop system. If the product is in a closed loop system (for example polyethylene terephthalate (PET) soft drinks bottles can only be made from old PET bottles not other PET material), then the ratio of recycled to virgin material should either be calculated or industry averages should be used. For open loop systems it is suggested that an approach that follows BS EN ISO 14044 should be followed, which essentially means that recycling rates across the whole material system should be considered. However, this does not specifically deal with how to credit those materials that can recycled in the future. The energy that would be saved by displacing the specification of virgin materials could be calculated and this could therefore be seen as a credit to the material. The approach for those products that are to be reused is in many ways simpler. The expected number of times that the product will be reused should be estimated, the total life cycle carbon, excluding the use phase, should be then be divided by this number. The resulting figure should then be added to a single use phase of the product and this gives the life cycle emissions for one life of the product (PAS 2050, 2008, p. 34).

4.3.5.4 SimaPro Approach

The LCA tool SimaPro (PRe Consultants, 2010) also has a method of dealing with future reuse and recycling. When graphically showing the environmental impacts of the product that is being analysed, positive and negative sections are shown. The positive sections show the environmental impact that is caused by the majority of the life cycle of the product whilst the negative section demonstrates the advantage that results from recycling or reusing the product. The advantage is seen as the avoided impact from specifying virgin materials. Recycled or reused materials have a lower environmental impact than virgin materials and it is this difference in impact that is given as the saving if reused or recycled materials are specified. Another LCA tool, LISA (LCA in Sustainable Architecture) (LISA, 2003), also takes this approach.

4.3.5.5 Methodology to be used within subsequent work

Concerning the reuse of products the methodology promoted in PAS 2050 is: ‘total product life cycle GHG emissions, excluding the use phase, are divided by the expected number of times the product is reused, including emissions associated with any remanufacturing required to make it usable again’ (PAS 2050, 2008). This approach will be adopted for buildings within subsequent work. It is acknowledged that application of this approach does require a prediction of the number of potential lives of the product but this can be done in a conservative manner and then adjusted at a later date if necessary. Within subsequent work, the default option is two potential lives, assuming these span fifty years each, within the hundred year span of the investigation. Within the tool, there will be designer override options for cases where different life spans are considered more appropriate.

4.3.6 Graphical output options for methodology

There are a number of different ways that this future benefit of design for deconstruction could be shown, these are now discussed.

Using the Inventory of Carbon and Energy dataset, for world steel (Hammond & Jones, Inventory of Energy & Carbon version 2.0, 2011), the embodied carbon of a 6m section sized 457 x 191 x 98 UKB is 1197kg CO_2e. If one investigated this using the metric ($kgCO_2e/m^2/yr$) recommended within the Common Carbon metrics document (United Nations Environment Program, 2010) then the life span of the component becomes crucial. Figure 4.2 explores how the embodied carbon per year of the component changes with an increasing life span of the component. Increasing the life span of a component can either be done by designing the whole building for adaptability so that the building can be easily altered thus allowing it to provide the required spaces and services to the users. Alternatively, or perhaps as well (as the two concepts work well in unison) the building can be designed for deconstruction, to allow the future reuse of the individual components. By reusing a component, rather than recycling it, the life span of the component is extended.

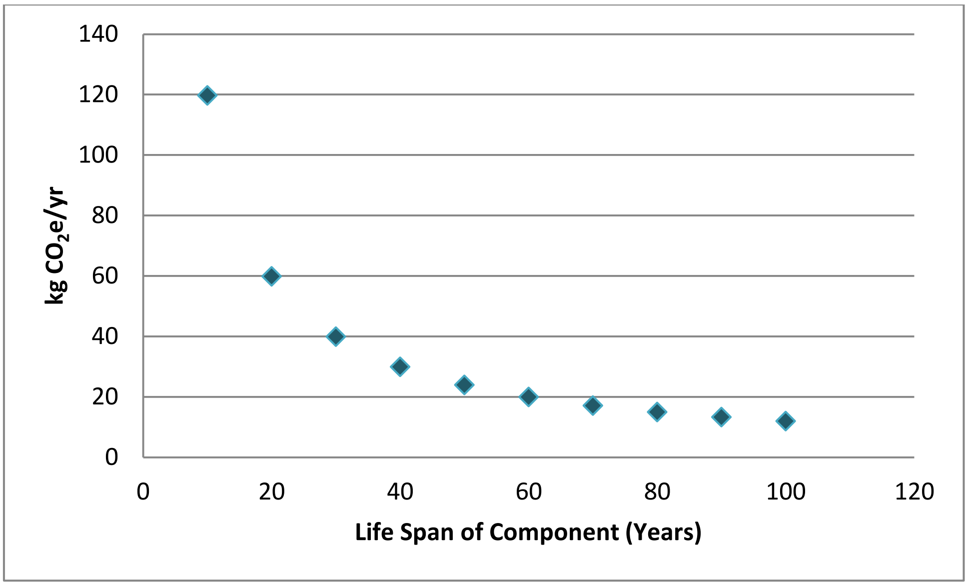


Figure 4.2: The embodied carbon of a steel beam spread out over its life span

However, in terms of graphical output for the tool, this does not accurately demonstrate the benefits of design for deconstruction, as it only shows the benefits of increasing the life span of a component, which can also be achieved by increasing the life span of the whole building. One way in which to show the benefits of design for deconstruction and the reuse it enables is demonstrated in Figure 4.3. This effectively uses the PAS 2050 methodology, splitting up the embodied carbon between the number of predicted lives of the component.

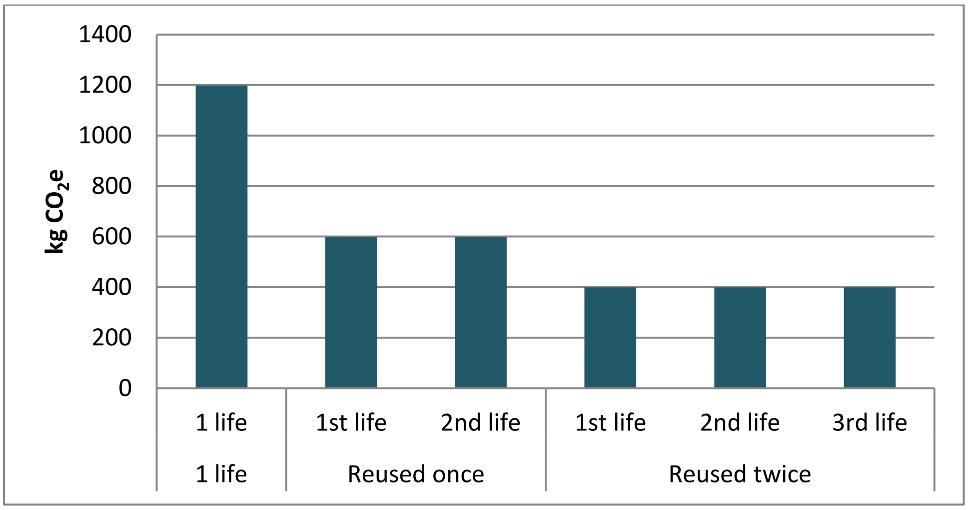


Figure 4.3: Embodied carbon of a steel beam, showing how the impact can be spread out between different lives

This type of graphic easily shows the benefit of reusing materials in terms of reducing their embodied energy (assuming the PAS 2050 methodology). This is shown on an individual component level and is effective at this level, however, it would be less effective on a whole building scale as not all components could be reused and so it would start to become too complicated a graphic. It would perhaps be more effective on a whole building level to investigate the whole life cycle and give an effective reuse credit (that quantifies the carbon emissions that are avoided in the future by designing for deconstruction and then reusing where possible). This approach is shown in Figure 4.4, for information on how the different life cycle stages were calculated see section 4.3.7.

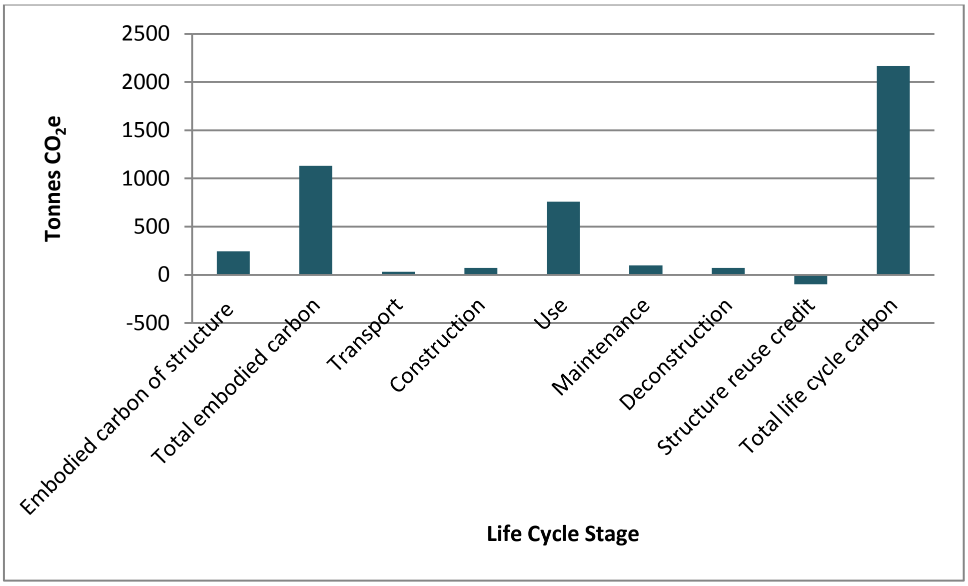


Figure 4.4: Graph showing CO_2e emissions produced at each life cycle stage of a building

A fourth alternative is to compare a project where the structure has been designed for deconstruction with the same project where design for deconstruction has not been incorporated. This clearly shows the benefit as it is comparing the two options directly, see Figure 4.5. This is the clearest way to demonstrate the benefits of designing for deconstruction; it is this approach that will be adopted in further work.

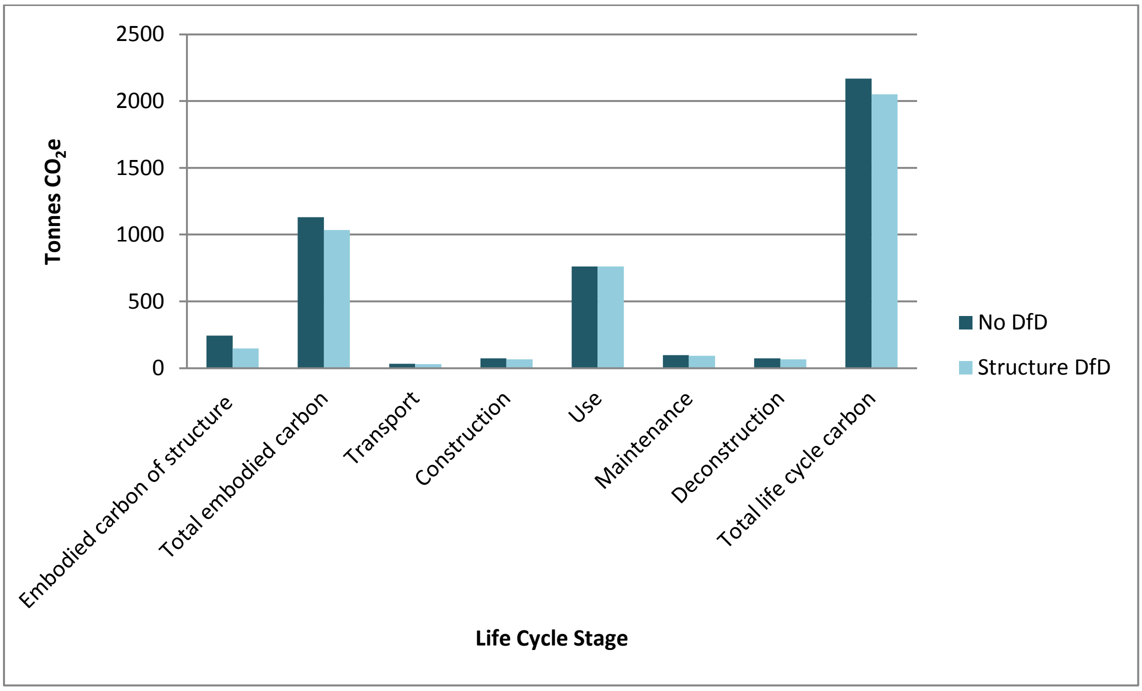


Figure 4.5: Graph showing CO_2e emissions produced in each life cycle stage of a building, comparing a building where the structure has been designed for deconstruction with a building where it has not

4.3.7 Life Cycle Stages

The study will be split up into the different life cycle stages a building goes through, these can be seen within Figure 4.6. The following sections outline potential data for each of these stages and where necessary suggest average figures that could be used for simplified, whole life cycle analysis studies of building projects.

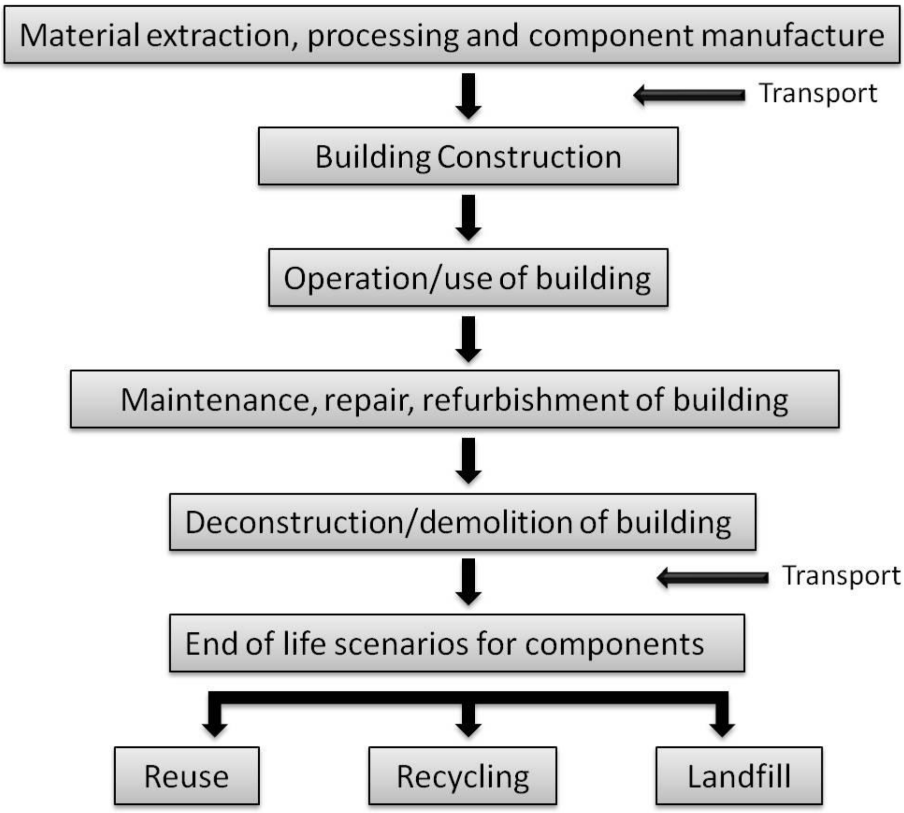


Figure 4.6: Life cycle stages of a building

4.3.7.1 Material extraction, processing and component manufacture

The data for initial material extraction, processing and component manufacture will be sourced from existing datasets, this will be discussed in more detail in Section 4.3.8, Life Cycle Inventory. As existing data is used for materials and components the boundaries for this data will have been defined by others; this data is considered to be a product of a cradle to gate study. There has been increasing amounts of work done to assess the embodied energy and carbon of materials and buildings (Buchanan & Honey, 1994; Cole & Kernan, 1996; Yohanis & Norton, 2002; Huberman & Pearlmutter, 2008; Haapio & Viitaniemi, Environmental effect of structural solutions and building materials to a building, 2008; Utama & Gheewala, 2009; Blengini & Carlo, 2010a; Blengini & Carlo, 2010b), (Ortiz-Rodriguez, Castells, & Sonnemann, 2010; Lee, Traka, & Hensen, 2011) and this work shows the potential range of figures and potential ambiguities in the data, demonstrating the importance of a completely transparent study to clarify how results have been arrived at. Early work in the area generally compared different structural systems – concrete, steel and timber, however the results were not always consistent. Conclusions were that wood structures had the lowest embodied carbon values but there is some contention between the values for concrete and steel structures. Cole and Kernan (1996) found that for a specific sized office building that a steel structure (1.48GJ/m^2) had a higher embodied energy than a concrete structure (1.17GJ/m^2), this study was based on Canadian data. Whereas, Buchanan and Honey (1994) conducted an investigation in New Zealand and the embodied energy figures were significantly higher (4.4GJ/m^2 for the steel structure and 3.4GJ/m^2 for the concrete structure).

Brocklesby conducted a study exploring the embodied energy of a number of case studies, mainly investigating concrete and steel. He examined the impact the frame has on the total embodied energy, with results varying from 12% of the total for a timber structure up to 34% for a steel frame. These are compared with Buchanan and Honey's results which are much higher with 41% of the total for the timber frame, 61% for the concrete frame and 67% for the steel frame (Brocklesby, 1998, p. 103). If the main range of results are taken, the average frame makes up 27% of the total embodied energy in a building. This study highlights the variation that can occur within these types of studies. There are potentially a number of reasons for this; there could be discrepancies in what is being included as structure, for example how much of the roof is included? This is not always made clear. There could also be large variations in the initial embodied data of materials that have been used in the studies. Within further investigations a sensitivity study will be carried out to explore the impact on the final result if different datasets are used, see section 5.5 for more details.

More recent work tends to discuss embodied carbon ($kgCO_2e/m^2$) instead or as well as embodied energy. This is likely for two reasons, firstly because legislation tends to focus on carbon emissions and so it is important to know how much carbon is produced as a result of the production of materials for buildings. Secondly, with increasing renewable energy resources being used, even if energy is being used it may have low or no carbon emissions associated with it. Finally, for a fair comparison of the environmental impact of materials the embodied carbon is a better unit than the embodied energy, as the embodied carbon will also include greenhouse gases that are emitted during the actually production process of the material and not solely consider the energy used for the process.

Recent work, named Target Zero, has been carried out in this area by a collaboration of companies. This explored among other things the embodied carbon of a number of different building types. There was a focus on steel structures but concrete and timber were also assessed (Target Zero, 2012). Table 4.2 shows a summary of the information that resulted from this work, with the addition of a calculation for what percentage of the total embodied carbon that the frame makes up, the percentages range from 14% to 55% of the total. This demonstrates the importance of minimising the embodied carbon of the structure as it has such a significant impact on the total embodied carbon of a building, particularly for some building types. The average percentage of the embodied carbon that the structure makes up of the total frame is 36.3%. At the time of writing there has been little other work assessing the embodied carbon of this range of building types to enable a comparison. It is worth noting that the target zero carbon emission figures for each material are considered to be total lifecycle CO_2e emissions, this means that certain assumptions are made about end of life decisions: 99% of steel sections and 92% of steel reinforcement are closed loop recycled; 77% of concrete is recycled in an open loop and 80% of timber is sent to landfill (TATA Steel, BCSA, 2012).

Building Type	**Embodied Carbon per square meter ($kgCO_2e/m^2$)**								
	Steel Option			**Concrete Option**			**Timber Option**		
	Whole Building	Structure	% of total	Whole Building	Structure	% of total	Whole Building	Structure	% of total
School	301	118	39	344	156	45	-	-	-
Office	452	219	48	506	266	53	-	-	-
Mixed-use	395	218	55	467	259	55	-	-	-
Warehouse	234	32	14	-	-	-	266	59	22
Supermarket	376	58	15	-	-	-	384	66	17

Table 4.2: Embodied carbon of different building types, adapted from Target Zero (TATA Steel, BCSA, 2012, p. 15)

4.3.7.2 Transportation

It is important that material transportation is taken into account within life cycle analysis studies of buildings, because this can have a large impact and also it can help to illustrate the benefits of sourcing materials locally. Inclusion of this within the tool would potentially help designers quickly assess whether it is worth specifying a more sustainable material that is sourced from significantly further away than a material that initially appears to have a higher embodied carbon but is sourced locally. The environmental impact of transportation may make a considerable contribution depending on the weight and amount of material required, as well as the transportation type. In addition to this, whilst for some materials transport has little proportional environmental impact, for others it can have a significant impact which could potentially influence design decisions. For example, Brocklesby states that 'a concrete frame will impose a higher transportation cost which can be as much as twice that for a similar steel frame' (Brocklesby, 1998, p. 250).

The distance materials have to travel to site can also vary dramatically depending on the country in which construction is taking place. Venkatarama Reddy & Jagadish (2003) suggest that in India, materials like cement and steel can often be transported 500km or more, although they go on to say that when the energy associated with this transport is compared to the embodied energy of these materials that the impact is comparably small. However, presumably if the transportation of all construction materials in the UK for example was added up this figure would be significant so it is important to minimise these distances. It is perhaps the more unusual materials where transport will have a great proportional impact. The study suggests that marble can be transported over 1500km in India (Venkatarama Reddy & Jagadish, 2003), likely because it cannot be sourced locally.

The method of transportation can also have a significant impact on the energy and carbon associated with it. There have been significant amounts of work done in this area to estimate average emissions from different transport types. Detailed data published in a Guardian blog (Choppin, 2009) compares emissions from different transport types, exploring the effect different percentage occupancy has on per person emissions. The UK Building Blackbook gives average CO_2 emissions for different transport types (see Table 4.3) to account for the transport of labour to and from the site. The basis of the data shown is unclear e.g. for large transport types like trains, buses and aeroplanes average emissions per person appear to have been calculated, whereas for the smaller vehicles the total emissions for the vehicles are tabulated, so if people were sharing transport the emissions per person would be reduced. Table 4.3 is therefore for information only to give a feel for the emissions associated with different transport types. As has already been discussed in section 4.3.3, the transport of workers to and from site is considered outside the bounds of the investigation.

Transport Type	CO_2 Emissions, kg/km
Train	0.0400
Underground	0.0560
Bus	0.0930
Aeroplane: short haul	0.1800
Aeroplane: long haul	0.1120
Water	0.0755
Hatchback: petrol	0.1750
Hatchback: diesel	0.1350
Saloon: petrol	0.2050
Saloon: diesel	0.1580
People carrier: petrol	0.2420
People carrier: diesel	0.1960
SUV: petrol	0.2910
SUV: diesel	0.2380
Smaller van	0.1430
Transit van	0.2090
Motorbike	0.1000
Bicycle	0.000

Table 4.3: CO_2 emissions associated with different transport types, adapted from UK Building Blackbook (Franklin + Andrews Ltd, 2010, p. xvii)

The transport of materials to the site is however within the boundaries of the investigation and, has already been discussed, this can in some cases have a significant impact. The UK Building Blackbook provides estimates, which can be seen in Table 4.4, to allow the calculation of the carbon emissions associated with transportation.

Transport Type	CO_2 Emissions (kg/t/km)
Road	0.32
Rail	0.04
Water	0.01

Table 4.4: General emissions figures for the transport of materials, adapted from UK Building Blackbook (Franklin + Andrews Ltd, 2010, p. xvii)

Additional work has been carried out by Brocklesby (1998, pp. 34-40) who conducted an extensive investigation into energy use and the associated emissions of different vehicle types and different fuel types. Another study by Huberman and Pearlmutter (2008) worked out that the average amount of energy required to transport materials is 1.57MJ/tonnes/km if the materials were transported by truck. From this it would then be possible to work out the emissions associated with this energy use using emission factors like those that can be found in the Common Carbon Metric Protocol (United Nations Environment Program, 2010, pp. 46-48), this has emission factors for different fuel types for different greenhouse gases. Generalised figures, like those in Table 4.4, could be used to calculate the emissions associated with transport if decisions had been made about where to source materials from. It would simply be a case of multiplying the distances travelled by the mass of the materials being transported. There is some contention over whether to include the emissions associated with the return distance of the transport. If the transport is returning to its origin empty then the associated emissions should be included within the study, if it picks up other goods then the emissions should not be included. However, using the data in this way involves detailed modelling and knowledge about the project, which will only be available at late design stages or for existing projects; it is very unlikely that this could be modelled at a conceptual design stage.

However, more generalised estimations on a per m^2 basis or that estimate the percentage that transport contributes to the whole life cycle carbon could be used at a conceptual design stage to give an approximate indication of the impact of transportation. Work has been done in Sweden to quantify the energy used in transporting materials for domestic projects, calculating this per m^2 of floor area. This study takes an input-output approach and estimates the energy use associated with transport to be 1.2GJ/m^2. When compared with other LCA studies, which take a process analysis approach, this is significantly higher than an average energy use of 0.1GJ/m^2 (Nassen, Holmberg, Wadeskog, & Nyman, 2007). Work focusing on the carbon emissions of housing in France, by Peuportier (2001) suggests that transport could contribute to 1.5% of the life cycle carbon emissions if all materials are transported 100km by truck, rising to 2.4% of the total if significantly bigger distances were covered – 5000km by ship and 500km by truck. Although both of these studies give figures that would allow the estimation of the impact of transport at a conceptual design stage, they are both based on construction at a residential scale and if the results were extrapolated to other building types this might not give a fair representation of the impact of construction.

The approximate figures discussed in the paragraph above could be used to estimate the impact of transportation in studies within this thesis. A value of 1.5% of the life cycle carbon emissions could be used, assuming transport by truck over 100km distances. However, due to the imprecise nature of these estimates, particularly when applied to other building types, they will not be included within the tool. It is felt that where specific numbers or percentages are supplied people are inclined to take these as given and may not appreciate the level of estimation that is involved. It is also thought that it might take focus from the original research aim of ‘appraising design for deconstruction’, and that the concentration should be on the savings that can result for this design strategy, on which transportation will have no impact. Development of more precise estimations of the impact of transport, is suggested as part of further work, see Recommendation 6 for more details.

4.3.7.3 Building Construction

It is often thought that the construction phase has a minimal impact in terms of whole life carbon emissions of buildings, nonetheless it does still make a contribution. In some studies (Duffy, 2009; Suzuki & Oka, 1998; Ortiz-Rodriguez, Castells, & Sonnemann, 2010) when construction is discussed as a phase this includes the embodied energy/carbon of the materials. However, here the construction phase refers solely to the energy used to physically put the building together and does not include the embodied energy/carbon of the materials.

There have been various different studies that explore the impacts and requirements of the construction process. Brocklesby carried out an exploration of the energy required in construction, investigating construction energy and associated carbon emissions required for construction, including the different fuel types. He suggests that generally the energy used on site will be electricity or from diesel (1998). Buchanan and Honey (1994) give some generalised energy coefficients for certain aspects of construction in New Zealand. Kofoworola and Gheewala (2009) investigated the life cycle energy use of an office building in Thailand and estimated that construction made up 0.6% of the total life cycle energy.

Scheuer et al. (2003) investigated other precedent studies to work out estimates for how much energy is used in construction and took a value of 5% of the total embodied energy of the building to account for construction energy. Huberman and Pearlmutter (2008) adopted a construction figure of 8% of the initial embodied energy based on approaches from other studies. Nassen et al. (2007) used input-output analysis to estimate that construction activity uses 0.5GJ/m^2 of a dwelling, compared with an average from other LCA studies of 0.2GJ/m^2. These studies are mainly process based which can result in cut-offs and so lower estimations of environmental impact.

From a review of the literature, an averaged value of 6.5% of the initial embodied energy will be used to estimate the contribution of construction to the life cycle energy. As discussed within section 4.3.7.2, this estimation will not be included within the tool as there is a concern that people may take the information too literally and not appreciate that it is an estimated guide to potential impacts. Further work may develop a more precise guide which could later be used.

4.3.7.4 Operation/use of the building

This is the area that legislation focuses on reducing (Lausten, 2008); in most buildings it is responsible for the largest percentage of emissions over the whole life cycle (Target Zero, 2012). However, this thesis focuses on future buildings which will likely have lower in-use emissions than current buildings. There is a difficulty in predicting operational energy use as it depends firstly on the standards on which construction was based, and secondly on the quantity of unregulated emissions. Building regulations focus on those emissions that can be reduced by the construction team: fixed lighting, heating, cooling, ventilation, hot water and building services. Unregulated emissions are those from electronics and appliances (TVs, computers etc) in buildings that are used by the occupiers (Shapps, 2011); it is difficult to predict the emissions that will occur from these.

One strategy to estimate the operational emissions of future commercial buildings would be to use the Display Energy Certificate (DEC) rating that the building hopes to achieve. DECs are required for public buildings that have a usable floor area greater than 1000m^2 and provide an energy rating for a building based on the actual energy used. The ratings vary from A (very efficient) to G (the least efficient) (Communities and Local Government, 2008a). The CO_2 emissions that the building emits per year are shown on the certificate, so these could be a good way of estimating the average amount of CO_2 a building emits in a year, based on a predicted rating. The advantage of using DECs is that they will include the unregulated emissions that building regulations don't target. The A to G rating bands are shown in Table 4.5. The operational rating can be calculated using the equation below.

OR = (Building CO_2 emissions/Building area) x (100/Typical CO_2 emissions per unit area) (Eqn. 2)

Operational Rating	A to G label
0 to 25	A
26 to 50	B
51 to 75	C
76 to 100	D
101 to 125	E
126 to 150	F
More than 150	G

Table 4.5: DEC operational rating bands (Communities and Local Government, 2008b, p. 22)

From this information, by reworking the equation, it is possible to work out the average CO_2 emissions per year for each rating. The typical CO_2 emissions per unit area are calculated for different building types so that there are comparable performance benchmarks, twenty-nine main categories of buildings are used (Communities and Local Government, 2008b). Example CO_2 emissions for each rating can be seen in Table 4.6, an illustrative typical benchmark (75.1kgCO_2/m^2) is taken for an office. An outline of energy benchmarks and examples of illustrative typical benchmarks for different building types can be found in TM46: Energy Benchmarks (CIBSE, 2008). The example emissions are calculated based on a building with an area of 1000m^2. For each operational rating a low value, an average value and a high value is shown. It is thought that new build construction should have a least a B rating due to the improved performance measures and energy efficiency of the building fabric. As a guide of the potential impact of the operational energy/carbon an average B rating will be used in further investigations.

Operational Rating	Kg CO_2
Low A (0)	0
Average A (12.5)	9387.5
High A (25)	18775
Low B (26)	19526
Average B (38)	28538
High B (50)	37550
Low C (51)	38301
Average C (63)	47313
High C (75)	56325
Low D (76)	57076
Average D (88)	66088
High D (100)	75100
Low E (101)	75851
Average E (113)	84863
High E (125)	93875
Low F (126)	94626
Average F (138)	103638
High F (150)	112650

Table 4.6: Example CO_2 emissions for different operational ratings

These estimates would be mainly applicable to UK buildings. A study by Scheuer et al. (2003) which investigated a University building in the USA, estimated the energy required in use and compared this to data from the Department of Energy. Extensive information is available as part of the Commercial Buildings Energy Consumption Survey (CBECS) (US Department of Energy, 2012) on the energy use of different building types, this is broken down into the fuel types used as well. This information could be used to estimate energy use in buildings within the USA, although the energy use should be lower in future buildings; accounting for how much lower is potentially challenging. In conclusion, there are mechanisms to estimate the energy use and associated carbon emissions that are attributed to the use phase. These can therefore be included within whole life carbon explorations.

4.3.7.5 Maintenance, repair and refurbishment of the building

Input-output analysis seems to be a commonly used method when calculating the maintenance/repair of a building, as in Duffy and Suzuki & Oka (2009; 1998), whilst these two studies take slightly different approaches they are both based on economic data.

Duffy (2009), in a study investigating the housing sector in the greater Dublin area, uses values of total expenditure on housing repair, maintenance and improvements, in combination with the energy intensity for the construction sector and the total number of housing units – working out an average annual maintenance energy use – this could then be multiplied by the variable life span to calculate the total energy used on maintenance. In this study, when the maintenance is considered within the whole life cycle it accounts for 6% of the CO_2 emissions.

In a similar study, based on office buildings in Japan, Suzuki and Oka (1998) estimated how often different components within the building would need to be replaced or repaired and then work out the energy and carbon associated with this. The study concludes that over a life span of forty years, the CO_2 emissions associated to maintenance/renovation are 128kgCO_2/m^2. In this study, when the contribution of this is considered in terms of the whole life cycle of the building it accounts for 3% of the whole life carbon. However, in a study of the UK construction industry it is suggested that refurbishment together with demolition only makes up 0.4% of the total carbon emissions that the construction industry can influence (BIS - Department for Business Innovation & Skills, 2010). The scope of this study includes emissions directly and indirectly related to demolition, waste removal and the process of refurbishment, so it may not be including the embodied carbon of materials used in the refurbishments, which the other studies include.

Work by Cole and Kernan (1996) demonstrates the potentially significant impact of reoccurring embodied energy to the whole life embodied energy, life spans of components and the whole building are key to this. Other studies have also investigated the impact of maintenance and refurbishment by estimating the life spans of components and then calculating how many times these will need to be replaced within the life span of the building. Mithraratne and Vale (2004) give estimates for the life span of a number of major components within a house and Scheuer et al. (2003) estimate the life spans of components used within a University building in the USA. For a more precise study these types of estimates could be used to calculate the maintenance requirements for specific building projects.

The advantages and disadvantages of refurbishing buildings versus demolishing or deconstructing them and then rebuilding was explored by Dong et al. (2005) who investigate this from a life cycle perspective, examining the different environmental impacts of each option. It would be interesting to see how the results of the study would differ if the original buildings had been designed for deconstruction, this is outlined as an area for further work.

As the quantitative area of the study will focus on the structure this should not require replacement within the predicted fifty year life span of the building, only maintenance requirements such as painting and fireproofing might be required. Therefore estimates of life spans would not be useful for this, for the purposes of this study an average percentage to estimate the impact of maintenance would be most useful. From the precedent studies discussed, an average value for the impact of maintenance would be 4.5% of the total life carbon.

4.3.7.6 Deconstruction/demolition of building

It is important to consider the energy used and the CO_2 emitted during the demolition or deconstruction of buildings. Due to the different methods which could be used these figures could vary considerably. Duffy (2009) calculates demolition using the input-output method, approximating that the associated emissions for demolishing a house are 8.3 kgCO_2/m^2, for an apartment building with a concrete or steel frame the emissions are higher, estimated at 15.1 kgCO_2/m^2. When considered within a whole life cycle, in this study, demolition makes up less than 0.5% of the emissions (Duffy, 2009). Kofoworola and Gheewala (2009) agree with this figure estimating that demolition would make up 0.4% of the total life cycle energy of an office building in Thailand. Another study (Scheuer, Keoleian, & Reppe, 2003) which specifically states that it is investigating demolition and not deconstruction calculates that it would take 350MJ/m^2 to demolish a University building in the USA, this work is based on a precedent study in Canada. It assumes that all energy is from a diesel fuel source, and so it would be possible to work out the carbon emissions associated to demolition as well. Cole and Kernan (1996) estimate that the energy required for demolition is roughly 1-3% of the initial embodied energy of the buildings. Brocklesby (1998) references various different energy demand figures for demolition, exploring the impact of different construction types, with the outcome being that concrete structures require the most energy, steel significantly less and timber structures requiring minimal energy use for demolition. He also shows a breakdown of the different areas in demolition and shows the associated impact of these (Brocklesby, The Environmental Impact of frame materials, an assessment of the embodied impacts for building frames in the UK construction industry, 1998, p. 206).

These studies consider standard demolition practice only. The energy and emissions associated with deconstruction may different; as deconstruction is essentially the reverse of the construction process the energy and emissions might be similar to those used and produced during construction. Khan (2011) explores the impacts and benefits of deconstruction, conducting an LCA study of three different case studies, showing that if the case studies are redesigned for deconstruction there is an environmental impact saving over the whole life cycle. This study does not however give the quantified carbon emissions associated with deconstruction. Therefore, for the purposes of further investigations, it will be assumed that the energy and emissions associated with deconstruction is the same as that of the construction process (as deconstruction is essentially this process in reverse), 6.5% of the embodied energy/carbon (see section 4.3.7.3). This is included as the environmental impact of the deconstruction stage in the whole life cycle environmental impact assessment of the building, as shown in Figure 4.4 and Figure 4.5.

4.3.7.7 End-of-life Treatment

In order to consider the end of life treatment of the components that make up a building it is necessary to make a prediction about what the standard procedure for reuse, recycling or disposal will be many years into the future. Blengini and Carlo (2010a) suggest that exploration of the end of life stage is perhaps one of the hardest areas of an LCA to carry out for precisely this reason. However, if a building has been specifically designed with future benefits in mind, and it is assumed that carbon intensive products and natural material resources will become increasingly valuable, then where components have been designed for reuse, it is thought that the majority of them would be reused.

Where components are designed to be reused, the environmental impact of these will be distributed as outlined in section 4.3.5.5. For some components it may be necessary for them to be re-fabricated or altered in some way before they can be reused. There may be some energy input and associated carbon emissions for this. CESMM3, a carbon and pricing book, (Franklin + Andrews Ltd, 2011) suggests that blast cleaning will have an impact of 0.71 $kgCO_2/m^2$ of steel and painting's impact would be 0.60 $kgCO_2/m^2$ of steel. These figures give a potential guide which could be used to estimate the impacts of preparing elements for reuse, as it is likely that they will be cleaned and re-painted before being used again. The environmental impact of preparing elements for reuse should be included in the whole life carbon estimate for the reuse life cycle, i.e. for an element that will be used twice it should be included in the impact of the second life of the element.

Where components are not reused it is assumed that standard practice for the material will be followed, whether it be recycling, incineration, landfill or an alternative route. Work by the BCSA and TATA (2012) has made assumptions about the end-of-life route for specific materials, this can be seen summarised in Table 4.7.

Material	**End of life assumption**
Fabricated steel sections	99% closed loop recycling, 1% landfill
Steel purlins	99% closed loop recycling 1% landfill
Organic coated steel	94% closed loop recycling 6% landfill
Steel Reinforcement	92% recycling 8% landfill
Concrete	77% open loop recycling 23% landfill
Glulam	16% recycling 4% incineration 80% landfill
Plywood	16% recycling 4% incineration 80% landfill
Plasterboard	20% recycling 80% landfill
Aggregate	50% recycling 50% landfill
Tarmac	70% recycling 23% landfill

Table 4.7: End of life assumptions made in an LCA study, adapted from Target zero report (TATA Steel, BCSA, 2012)

Table 4.7 identifies two different types of recycling, closed loop recycling and open loop recycling. Closed loop recycling is where once the material has been recycled it can then be used again for the same original purpose. Open loop recycling involves the material being used for a different purpose once it has been recycled; this is also referred to as down-cycling (Peuportier, 2001). A number of studies (Peuportier, 2001; Mercante, Bovea, Ibanez-Fores, & Arena, 2012; Saghafi & Hosseini Teshnizi, 2011; Lasvaux, Peuportier, & Chevalier, 2009) assess and explore the value of recycling materials. Peuportier (2001) discusses how to best credit the positive impact of recycling, and the importance of ensuring that it is not double counted, as it could be included within fabrication data and end of life data. It should however be noted that according to some studies (Mercante, Bovea, Ibanez-Fores, & Arena, 2012) recycling construction and demolition waste doesn't always have a positive impact, in some cases the processes of recycling the material can have a larger impact than the environmental impact that is avoided by recycling instead of sourcing virgin materials.

With regards to recycling, and this is particularly applicable to metals, there are two main methodologies which can be applied to initial data, these are the recycled content approach and the substitution method. The recycled content approach gives credit to those materials that have a recycled content within them, crediting recycling at the start of a project or a building's life. The substitution method rewards the potential for recycling, so it is an end of life methodology. This involves predicting how much of the material in the building could be recycled at end of life, this percentage of material is then treated as recycled and credited thus. The inventory of carbon and energy (ICE) which is used as the main dataset in this study supports the first method, the recycled content approach (Hammond & Jones, 2008). It is important to ensure that both approaches are not unintentionally applied, for example if data is used that credits recycled material within it and then the substitution method is applied, the benefit of recycling would be double counted. This study will adopt the recycled content approach. There are average recycled values for different construction material in the UK, these values for metals particularly, which already have high recycling rates, will likely stay constant for some time as there is not the scrap material available to increase the recycled content. The recycled content approach is therefore considered the most representative approach to take in order to explore the impact of a design.

Table 4.7 suggests that the majority of timber is sent to landfill. However, a report by WRAP (2011) says that the amount of timber being sent to landfill is being reduced. There are increasing demands for recovered timber in biomass facilities both on the continent and within the UK, meaning greater quantities of timber will be incinerated at end of life, replacing fossil fuel use, and reducing the amount of wood waste sent to landfill. In addition to this, Defra is planning to consult on the introduction of restricting the landfilling of wood waste (Defra, 2012). By designing for deconstruction the timber in buildings would be easily recoverable and where suitable it could be reused, recycled or incinerated in biomass facilities, and none need be sent to landfill. These other scenarios have less environmental impact than landfilling, where timber produces a mixture of carbon dioxide and methane as it decomposes (WRAP, 2011). This work demonstrates the changing nature of end of life scenarios. Designing for a specific end of life scenario – reuse, should increase the predictability of this and ensure minimal environmental impact at end of life.

Other potential disposal scenarios include: immobilisation with useful application, immobilisation, incineration with energy recovery, incineration, in rare cases landfill with energy recovery or simply landfill. Landfill avoidance, as a mass of material, could be included in further investigations. Rabl et al. (2008) conducted a study comparing the environmental impacts of sending solid waste to landfill or incineration; concluding that energy recovery from incineration plays a significant role in lowering the impacts, but it is not significant at landfill. However, there is limited work exploring the impacts of sending construction and demolition waste to these alternative scenarios and little quantification of the emissions that are produced by specific materials. Some work has been done by Ortiz et al. (2010) to explore the impacts of recycling, incineration and landfill of construction materials in Spain. It concludes that recycling is the most beneficial, then incineration, preferably with energy recovery, and that landfill should only be used as a last resort.

Due to the current lack of detailed data regarding the environmental impacts of construction and demolition materials in different disposal options, these will not be included in the study at this time. Once work in this area progresses and data is available outlining the impact of these other end of life scenarios it would be very useful to include them so that the full picture of the impact of different end of life scenarios can be calculated and shown.

For all the end of life scenarios there will be some transport involved in taking them away from site to the relevant new area. These distances could be assumed to be the same for all the options and a default value included within studies. Alternatively, as with Khoo and Tan's study (2010) because the transport associated environmental impacts will be the same for each option they could be excluded from the analysis of deciding which end of life scenario is most beneficial. For the end of life scenarios, transport will not be modelled and included in the study, at this time it is too difficult to try and estimate the potential distances, and it is not thought they would vary significantly between disposal types.

4.3.8 Life Cycle Inventory

The material life cycle inventory (LCI) data for use within the tool will predominately be sourced from the Inventory of Carbon and Energy (ICE) (Hammond & Jones, 2011), as has already been discussed in previous sections, this is a well used and accepted source of data, which includes a wide range of materials within it. However, in further investigations a sensitivity study will be carried out to explore the effect of using different datasets. The CESMM3 carbon and pricing book (Franklin + Andrews Ltd, 2011) and the UK Building Blackbook (Franklin + Andrews Ltd, 2010) will both be used as sources of data to compare to the ICE. As these are widely known pricing books it is assumed that the data within them will be used within industry and be accepted in this area, even if there is little reference to them in academic work. There are a number of other sources (Brocklesby, 1998; Venkatarama Reddy & Jagadish, 2003; Buchanan & Honey, 1994; Cole & Kernan, 1996; TATA Steel, BCSA, 2012) of limited data, generally about specific materials which could be used as an additional comparison or to fill in the blanks if specialist data is required that is not already available.

4.4 Conclusions

The aim of the work is to 'appraise design for deconstruction', to do this most effectively the environmental benefits of this approach need to be quantified. Ideally, this would be done on a specific project basis so that designers can appreciate the benefits to their project, thus encouraging them to include this design approach. A computer tool would be the most efficient and useful way to do this. A critical review of existing tools that are designed to compute the environmental impact of building projects was performed; no current tools could show or quantify the benefits of design for deconstruction; therefore it is necessary to develop a new tool that can do this.

A key component of the tool is how best to demonstrate the future benefit of reuse that has been designed into projects. The PAS 2050 (2008) approach has been adapted for use in buildings; this shares the environmental impact of a component over the number of predicted lives. Conservative estimates assume that buildings will have a fifty year life span. The study is conducted within a hundred year period and so components potentially have two lives within this. The length of life span, and therefore the number of lives of a component will be adaptable within the tool as it is acknowledged that some buildings will have shorter life spans.

An exploration of the whole life span of a building and the associated impacts will be carried out in later work. This is in order to obtain a full picture of the potential impacts, and to investigate the potential influence design for deconstruction has on reducing the energy and carbon over a whole life cycle, not solely within the embodied effects. The different areas of the life cycle have been mapped out and discussed. It will not be possible to complete detailed assessments to calculate the contribution of each area on an individual case study basis. This is because studies will be carried out at a conceptual stage of design and the information regarding the other life cycle areas will not be available at this time. Therefore estimates will be used to give an approximation of the potential impacts of the different areas. These estimates were derived and in some cases averaged from careful literature review of precedent studies, a summary of these can be seen in Table 4.8. The contribution of the embodied carbon can vary greatly depending on the building type and the materials used. Detailed calculations will be executed for the embodied energy and carbon of the structure. The contribution of the rest of the building to the embodied carbon will be estimated depending on the building type, see section 4.3.7.1 for more details. For end of life, the methodology for dealing with reuse has been outlined and the recycled content approach will be used with respect to recycling. The impacts of incineration and landfill cannot be accurately modelled at this time and so will not be included within further investigations.

Life Cycle Stage	Contribution/Calculation Method
Transport	1.5% of whole life cycle carbon
Construction	6.5% of initial embodied carbon
Use	Average B DEC rating to be used
Maintenance	4.5% of whole life cycle carbon
Deconstruction	6.5% of initial embodied carbon

Table 4.8: Summary of the contributions of the individual life cycle stages

These estimates will only be used in further investigations and not within the tool. This is because they only give an approximation of the impacts and should be used for discussion only and not as a design aid due to the level of approximation. This is particularly the case as this average data is taken from existing building projects where the use stage will generally have a higher impact than it will in future more energy-efficient buildings. Furthermore, the other life cycle stages will likely have a greater relative impact in the future. It is however very challenging to accurately predict this at an early design stage. In addition, it is felt that within the tool a focus on how design for deconstruction can lower the embodied energy/carbon of the structure will be a more effective way of demonstrating the benefits of Design for Deconstruction and will encourage greater uptake of this strategy. If more work is carried out to resolve the individual contribution of the different life cycle stages in new, energy efficient buildings then this could be incorporated into the tool at a later date, in order to provide an accurate representation of the impacts of a whole life cycle.

5 Feasibility Studies: a quantification of the environmental savings from design for deconstruction

5.1 Introduction

This chapter explores the benefits of design for deconstruction for a series of hypothetical structural bays. There is a focus on steel frame construction methods as this material was identified in the literature review as being particularly suitable for design for deconstruction. This chapter provides the first step in quantifying the benefits of design for deconstruction and is an exploration of the feasibility of this strategy. Potential carbon savings embodied in the structure are put into the context of whole life carbon to investigate what impacts the strategy has at this level. The methodology developed in Chapter 4 is used as a basis for this work.

5.2 Aims and Objectives

This work explores how design for deconstruction affects the embodied carbon of three different structural bay types and identifies, through a quantification of embodied carbon savings, which type derives the most benefit. Furthermore, the work investigates if design for deconstruction is a feasible strategy for all the bay types by assessing if the potential gain is sufficient to merit inclusion. The influence of design for deconstruction on predicted whole life cycle carbon impacts is also considered. In addition to these analyses, a sensitivity study is carried out to explore the effect of using different datasets by calculating the variation in results that occurs through the use of alternative datasets.

5.3 Impacts of Design for Deconstruction on the Embodied Carbon of Structural Bays

5.3.1 Method

The feasibility studies are based on the methodology developed in Chapter 4. The life span of the building is assumed to be fifty years. The study is set in a one hundred year time frame; elements suitable for reuse therefore have two life cycles and the environmental impact of reusable structure is divided between the two lives. By including design for deconstruction to facilitate future reuse a credit is effectively given to the element at first use, halving the environmental impact, this relies on the element being used again, as the design intent. The other half of the initial environmental impact is associated with the second use of the element. Any re-fabrication of the element for the second use should be included in the environmental impact assessment of that use.[2] The Inventory of Carbon and Energy (ICE) (Hammond & Jones, 2011) is used as the main dataset for the embodied carbon calculations.

The focus of this analysis is steel frame structures, therefore the columns and beams are all steel sections; the difference is in the floor type and connection detail. A composite floor that acts in unison with all the beams in the bay forms the first study. The second, details a composite floor where only the secondary beams act compositely. The final assessment is

---

[2] This approach is consistent and distributes the environmental impact over the predicted lives. However, it could be argued that the purpose of this methodology is to encourage designers to consider design for deconstruction now in order to secure a future supply of reusable materials. In the future when such a supply exists the emphasis will shift to encourage the specification of reused materials, at which time it may be considered acceptable to only account for the impacts associated with extracting, transporting and refinishing the elements. See also section 4.3.5.

made for a steel frame with pre-cast planks which act non-compositely, making up the floor design. All the bay types are based on a 6 x 6m bay size. Each was designed by the author so that the study could be conducted. The concrete within all designs is normal concrete, 25/30MPa, with no cement substitutes. Replacing the cement with substitutes such as fly ash or ground granulated blast furnace slag would reduce the embodied carbon of the designs but is considered outside the scope of this investigation. Connection detail was included as this would need to be specifically designed for deconstruction, contributing to a full embodied carbon assessment of each bay. For further details of assumptions made see Appendix A.

5.3.2 Composite Bay

The composite bay comprises two primary beams, three secondary beams, four columns and a shallow composite floor. All the beams are attached to the floor with shear studs which means that these cannot be reused as the shear studs cannot be removed without significant damage to the beams. However, the use of double angle cleat connections with bolting allows the columns to be separated from the rest of the structure within little damage (only bolt holes). These columns could then be reused after deconstruction in future projects. The embodied carbon calculation is shown in Table 5.1.

Element	**Type**	**Mass (kg)**	**EC (kg CO_2e/kg)**	**Quantity**	**EC Total (kg CO_2e)**	**DfD EC (kg CO_2e)**
Beam - P	254 x 102 x 28 UB	169.800	1.53	2	519.588	519.588
Beam - S	203 x 133 x 30 UB	180.000	1.53	3	826.200	826.200
Column	254 x 254 x 73 UC	365.400	1.53	4	2236.248	1118.124
Angle cleat	90 x 90 x 10	2.948	1.66	20	97.874	97.874
Bolts	M20, 60mm length	0.214	1.4	90	26.964	26.964
Concrete	130mm profile section	8380.800	0.113	1	947.030	947.030
Steel deck	1mm ComFlor	0.596	1.54	1	0.917	0.917
Steel Mesh	A193 mesh	108.720	1.4	1	152.208	152.208
Shear Studs	19 x 100mm	0.223	1.4	96	29.913	29.913
			Total		**4837**	**3719**
			Total per m^2		**134**	**103**

Table 5.1: Embodied carbon of composite bay

This shows that the embodied carbon of a composite bay could be reduced by 23% if the beam to column connections were chosen to facilitate deconstruction.

5.3.3 Partially composite Bay

This bay type is composed of four primary beams that make up the perimeter of the bay; these can all be designed for deconstruction and subsequently reused. There is a secondary, composite beam in the middle of the bay which will not be suitable for reuse. One column can be found in each corner, all of which could be reused. The shallow composite floor would not be suitable for reuse but the materials could be separated for recycling at end of life. The embodied carbon calculation for this bay is shown in Table 5.2.

Element	Type	Mass (kg)	EC (kg CO_2e/kg)	Quantity	EC Total (kg CO_2e)	DfD EC (kg CO_2e)
Beam - P	406 x 178 x 60 UB	360.600	1.53	4	2206.872	1103.436
Beam - S	254 x 102 x 22 UB	132.000	1.53	1	201.960	201.960
Column	254 x 254 x 73 UC	365.500	1.53	4	2236.860	1118.430
Angle Cleat	90 x 90 x 10, 290L	3.886	1.66	16	103.212	103.212
Angle Cleat	90 x 90 x 10, 150L	2.01	1.66	4	13.346	13.346
Bolt	M20, 60mm length	0.214	1.4	108	32.357	32.357
Floor -conc	130mm deep	8380.800	0.113	1	947.030	947.030
Steel Deck	1mm ComFlor 60	0.596	1.54	1	0.917	0.917
Steel Mesh	A193	108.720	1.4	1	152.208	152.208
Shear Studs	19 x 100mm	0.223	1.4	18	5.609	5.609
			Total		**5900**	**3679**
			Total per m^2		**164**	**102**

Table 5.2: Embodied Carbon of partially composite bay

A 37% decrease in the embodied carbon is demonstrated for this partially composite bay if it is designed for deconstruction.

5.3.4 Non composite bay

This bay is constructed from two primary beams, the other two perimeter beams are designed to take a tying force of 75KN only. There are four columns, one in each corner of the bay. Flooring is made up of precast hollowcore planks. The reinforcement within these consists of pre-tensioned strands; this becomes complicated when calculating the embodied carbon. The strands are made up from a series of wires. This potentially implies that the embodied carbon should be calculated using the factor for wire; option A in Table 5.3 shows this. However, this factor is stated to be uncertain within the ICE dataset (Hammond & Jones, Inventory of Carbon & Energy version 2.0, 2011), leading to questions about its suitability for use. When information within the dataset was further explored it was found that for calculations involving precast concrete it is suggested that the normal factor for reinforcement is used (Hammond & Jones, Inventory of Carbon & Energy version 2.0, 2011). The set of results referred to as option B use this factor. It was felt that further investigation was warranted; a metre length of strand was modelled in SimaPro (LCA software) to attempt to ascertain a more reliable figure. However, there was not sufficient information available to model all the processes, the energy input into stranding, and pre-stressing was not included, see Appendix A2 for full details. Option C within Table 5.3 uses the embodied carbon figure generated using SimaPro.

The DfD embodied carbon estimate was derived using the following assumptions:

- Beams and columns are all suitable for design for deconstruction and future reuse
- Precast planks are reusable
- No topping is used.

Element	Type	Mass (kg)	EC (kg CO$_2$e/kg)	Quantity	EC Total (kg CO$_2$e)	DfD EC (kg CO$_2$e)
Beam - P	406 x 178 x 54 UB	324.600	1.53	2	993.276	496.638
Beam - tying	254 x 102 x 22 UB	132.000	1.53	2	403.920	201.960
Column	203 x 203 x 60 UC	300.000	1.53	4	1836.000	918.000
Angle Cleat	90 x 90 x 10, 290L	3.886	1.66	8	51.606	51.606
Angle Cleat	90 x 90 x 10, 150L	2.01	1.66	8	26.693	26.693
Bolt	M20, 60mm	0.214	1.4	72	21.571	21.571
Concrete	150mm	8807.339	0.14	1	1233.028	616.514
Rebar A	45 x 12.5mm dia	260.098	3.02	1	785.496	392.748
Rebar B	45 x 12.5mm dia	260.098	1.4	1	364.137	182.069
Rebar C	45 x 12.5mm dia	260.098	2.22 per m	1	599.400	299.700
			Total, option A		**5352**	**2726**
			Total, option B		**4930**	**2515**
			Total, option C		**5165**	**2633**
			Total per m^2, option A		**149**	**76**
			Total per m^2, option B		**137**	**70**
			Total per m^2, option C		**143**	**73**

Table 5.3: Embodied carbon of non-composite bay

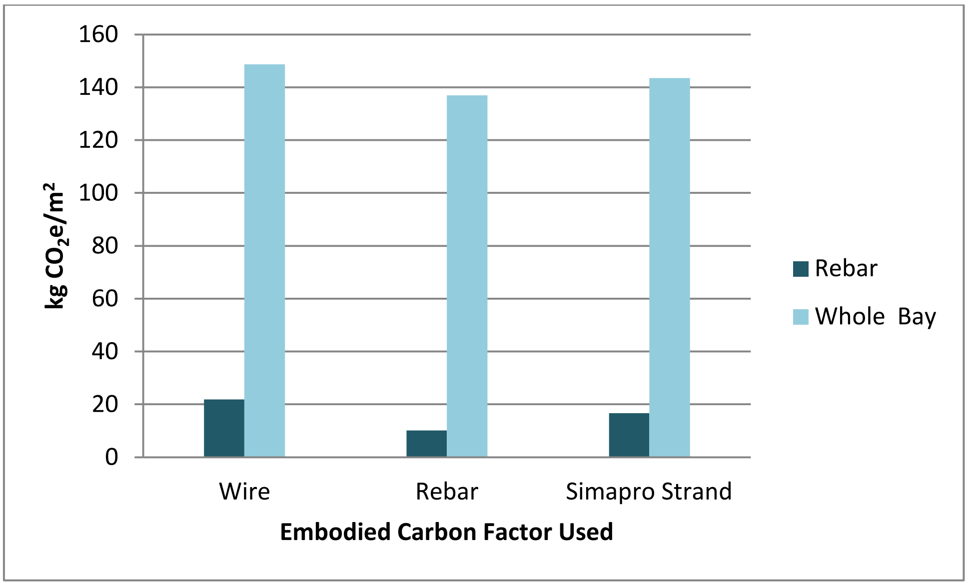


Figure 5.1: Effect of the reinforcement embodied carbon factor

Table 5.3 shows that there is large variation between the results for the different reinforcement embodied factors. Figure 5.1 displays this visually, results are highest when the factor for wire is used, lowest for the reinforcement factor and the SimaPro estimate is roughly in between the two. The difference is up to 12 kg CO$_2$/m^2, which is a significant variation. This shows the impact that the different reinforcement assessments can have on the total embodied carbon, even for small reinforcement quantities. A more extensive exploration and model of reinforcement strand within SimaPro forms Recommendation 9, so that more reliable results are available in the future. It is uncertain which of the factors used is most representative and therefore for the bay comparisons the middle value derived from SimaPro will be used.

Notwithstanding the uncertainty surrounding the factor to be used for the reinforcement, the benefits of design for deconstruction for the non-composite bay are clear i.e. the embodied carbon reduces by 49%.

5.3.5 Comparison of Bay Types

Table 5.4 shows the embodied carbon of each of the bay types, side by side, for easy comparison. For the standard design the composite bay has the lowest embodied carbon, this is to be expected as less materials are generally used in a composite design. However, once design for deconstruction is considered the non-composite bay embodies the least carbon. It is this bay design that shows the greatest benefit from design for deconstruction. This is due to the maximum amount of steel sections being designed for reuse. Whereas for the other two designs some or all of the beams are used compositely and so cannot be reused.

	Composite Bay	**Partially Composite Bay**	**Non-Composite Bay**
	Kg CO_2e/m^2	**Kg CO_2e/m^2**	**Kg CO_2e/m^2**
Standard Design	134	164	143
DfD Design	103	102	73

Table 5.4: Summary table showing the embodied carbon of each bay type

This comparison suggests that whilst initially a non-composite bay may have a higher embodied carbon than a composite bay, if the bays are designed for deconstruction and these designed-in benefits are accounted for, then the non-composite bay is the most sustainable choice in terms of embodied carbon and future reuse.

5.4 Impacts of Design for Deconstruction on whole life cycle carbon

It is important to estimate the impact that design for deconstruction has not only on the embodied carbon but in the scope of an entire life of a building. The non-composite bay example is used in this study, forming a hypothetical structure of 3 x 5 bays, on each level of a three storey building, culminating in a floor area of 1620m^2. Work conducted by Brocklesby (1998) suggests that on average the structural frame makes up 27% of the total embodied energy in a building; see section 4.3.7.1 in Chapter 4 for full details. The estimations for each life cycle stage are calculated using the percentages identified in Chapter 4, as summarised in Table 4.8. A fifty-year life span is assumed and ICE, UK data is used, except for the reinforcement strand where SimaPro data is used, as explained in section 5.3.4.

Three different designs are considered, a standard design (no DfD), the whole building designed for deconstruction (WB DfD) and the structure designed for deconstruction (S DfD). For each of the options it is only the embodied carbon that alters. All other life cycle stages are assumed to be consistent with the standard design. Table 5.5 shows a summary of the embodied carbon for each life cycle stage. The whole building estimate is derived from an assumption that the structure contributes 27% to the total. Table 5.5 shows that the whole building, where the designed for deconstruction results in the lowest embodied carbon, and the structure designed for deconstruction results in the second lowest value.

	No DfD	WB DfD	S DfD
Embodied carbon of structure	232	118	118
Total embodied carbon	1078	549	964
Transport	32	32	32
Construction	70	70	70
Use	760	760	760
Maintenance	95	95	95
Deconstruction	70	70	70
Total life cycle carbon	2104	1576	1990

Table 5.5: Embodied carbon, tonnes CO_2e, for all the life cycle stages

The impact of design for deconstruction over the life cycle stages is shown graphically in Figure 5.2. This shows the significant savings that can be made by designing either the structure or the whole building in this way. If the structure alone is designed for deconstruction then there is a 5.4% reduction in the whole life carbon, this rises to 25% if the whole building uses the strategy.

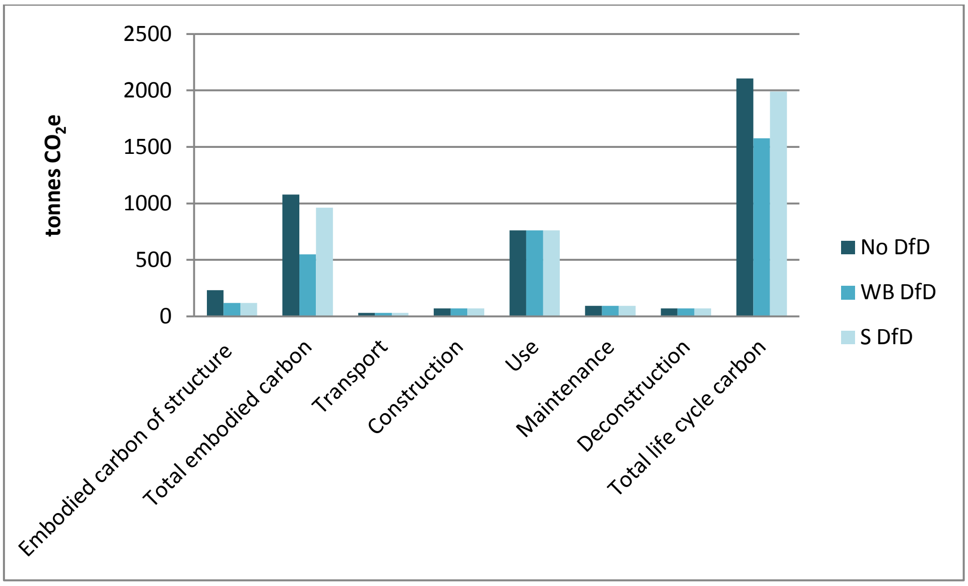


Figure 5.2: Life cycle embodied carbon for the three design options

5.5 Sensitivity Study of datasets

5.5.1 Method & initial discussion of Datasets

Each of the bays discussed in section 5.3 is analysed using four different sets of embodied carbon data. The results are compared and contrasted to explore the differences. The four datasets used are:

- UK Building Blackbook (UK BB) (Franklin + Andrews Ltd., 2010)
    - This is largely a pricing book which has now added embodied carbon estimates to it. There is a focus on those elements used within building design. Embodied carbon only includes carbon dioxide estimates not other greenhouse gases. The dataset will likely be used by quantity surveyors and potentially some design professionals.
- CESMM3 (Franklin + Andrews Ltd., 2011)
    - This, as above, is a pricing book which has recently had embodied carbon added to it; there is a more general scope within, covering civil and structural work. Likely users are also quantity surveyors and some design professionals and estimates include carbon dioxide only.

- ICE, World (Hammond & Jones, Inventory of Carbon & Energy version 2.0, 2011)
  - This collates data from a range of sources. The embodied carbon is assessed in carbon dioxide equivalents, including a range of greenhouse gas emissions. The world aspect of this relates to the steel products only, the recycling rates when assessed within the rest of the world are lower (35.5%) than EU rates, meaning that the embodied energy and carbon of these elements are higher. This dataset is included within the study to explore the impact if products are sourced from outside of Europe.
- ICE, UK (Hammond & Jones, Inventory of Carbon & Energy version 2.0, 2011)
  - This uses the same data as above, with the exception of steel data where a recycling rate of 59% is taken, as typical within Europe; this gives lower embodied values than above.

Within each of the tables in this section it should be noted that 'floor conc' refers to the concrete within the composite slab and 'floor rein' refers to all the steel elements within the composite floor i.e. the steel deck, mesh reinforcement, and the shear studs. In addition to this, within the CESMM3 calculation, the UK Building Black Book figure has been used for the steel decking as no comparable data could be found within CESMM3.

5.5.2 Composite Bay

This uses the same bay design as that in section 5.3.2. The embodied carbon of each of the elements and in total for the bay is calculated using each of the datasets; the results are shown in Table 5.6.

	Standard Design				**Dfd Design**			
	UK BB	**CESMM3**	**ICE, World**	**ICE, UK**	**UK BB**	**CESMM3**	**ICE, World**	**ICE, UK**
Element	**(kg CO_2)**	**(kg CO_2)**	**(kg CO_2e)**	**(kg CO_2e)**	**(kg CO_2)**	**(kg CO_2)**	**(kg CO_2e)**	**(kg CO_2e)**
Beams	1597	1853	1786	1346	1597	1853	1786	1346
Columns	2729	3080	2968	2237	1365	1540	1484	1118
Connections	150	148	166	125	150	148	166	125
Floor - conc	1091	1549	947	947	1091	1549	947	947
Floor - rein	279	319	243	183	279	319	243	183
Total	5846	6948	6110	4838	4481	5409	4626	3719
Total per m^2	**162**	**193**	**170**	**134**	**124**	**150**	**128**	**103**

Table 5.6: Composite Bay: range of embodied carbon values calculated using different datasets

There is a variation of 59 kg CO_2 within the standard design, and from the minimum to the maximum value there is a 44% increase in the embodied carbon per square metre. Similar results are seen within the DfD design with a 45% increase from the minimum. On average, there is a saving of 38 kg CO_2/m^2 if the composite bay is designed for deconstruction, which is potentially a very significant saving over an entire building.

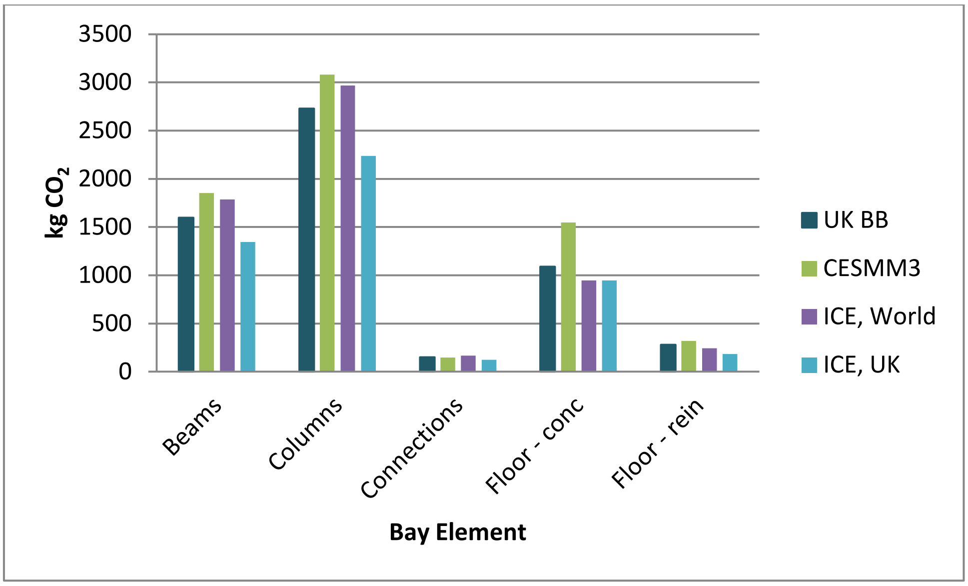


Figure 5.3: Composite Bay: the impact of different datasets on the embodied carbon of elements within the bay

The graph above shows how the embodied carbon of different elements varies depending on the dataset. CESMM3 gives the highest embodied carbon for all the elements except for the connections, and it produces a significantly higher embodied carbon for the concrete. The ICE, UK data yields the lowest results for all element types, whereas the world version is much closer to the CESMM3 results for steel elements. The UK Building Blackbook generally produces values in the middle of the range for this particular bay design.

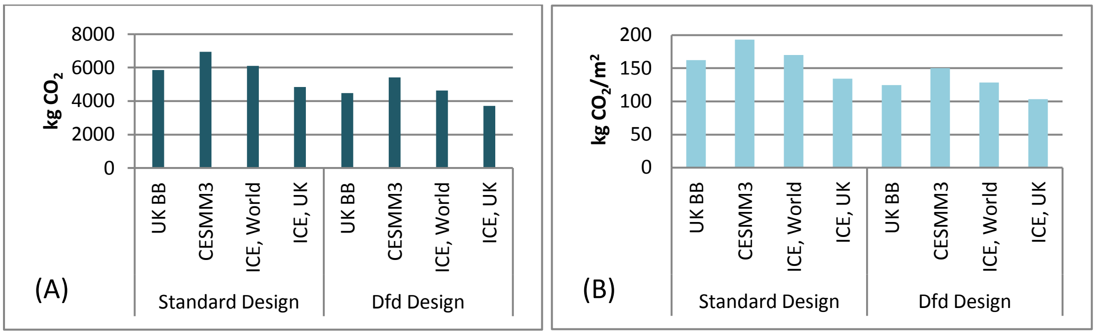


Figure 5.4: Composite Bay: the impact of different datasets on the total embodied carbon of the bay, (A) shows the total embodied carbon, (B) the embodied carbon per m^2

The impact of the datasets on the overall results is shown in Figure 5.4. As for the individual elements, CESMM3 gives the highest results, and ICE UK the lowest, for both the standard and the DfD design. The results shown display the large variation that occurs from the use of different datasets. It is important to be aware of the impact of this, particularly when comparing different studies, which may use different datasets.

5.5.3 Partially Composite Bay

This bay design is the same as that in 5.3.3. Table 5.7 shows the range of results for the different datasets. Different graphical breakdowns are displayed in Figure 5.5 and Figure 5.6.

Element	Standard Design UK BB (kg CO_2)	 CESMM3 (kg CO_2)	 ICE, World (kg CO_2e)	 ICE, UK (kg CO_2e)	Dfd Design UK BB (kg CO_2)	 CESMM3 (kg CO_2)	 ICE, World (kg CO_2e)	 ICE, UK (kg CO_2e)
Beams	2858	3317	3196	2409	1549	1797	1732	1305
Columns	2729	3080	2968	2237	1365	1540	1484	1118
Connections	179	172	198	149	179	172	198	149
Floor - conc	1091	1549	947	947	1091	1549	947	947
Floor - rein	241	286	211	159	241	286	211	159
Total	7099	8403	7520	5900	4425	5344	4572	3679
Total per m^2	**197**	**233**	**209**	**164**	**123**	**148**	**127**	**102**

Table 5.7: Partially Composite Bay: range of embodied carbon values calculated using different datasets

Within this set of results, for the standard design, there is a 70 kg CO_2/m^2 variation between the datasets, which equates to a 42% increase from the lowest set (ICE UK) to the highest set (CESMM3). A similar pattern emerges from the DfD design where a 45% increase is found. The average saving if the partially composite bay is designed for deconstruction is calculated to be 76 kg CO_2.

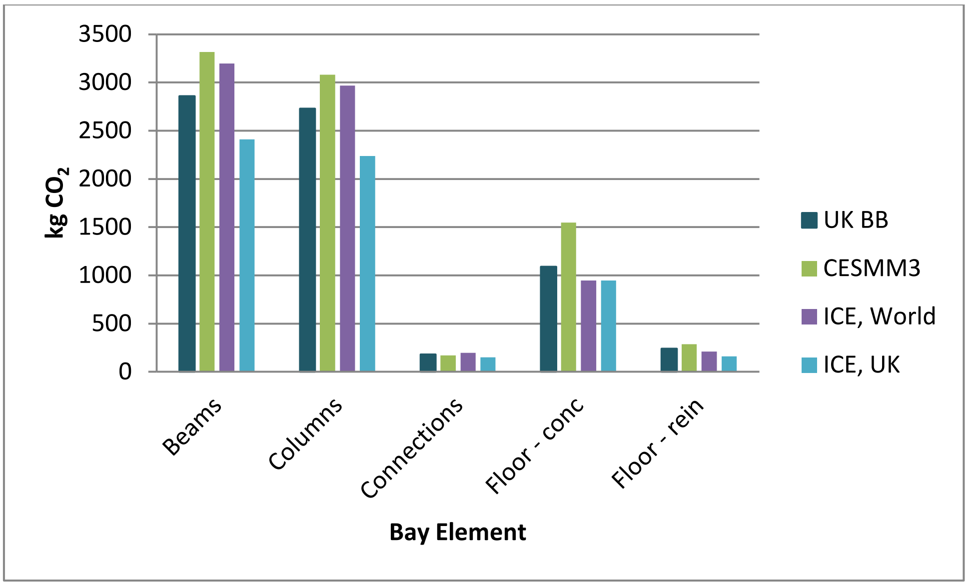


Figure 5.5: Partially Composite Bay: the impact of different datasets on the embodied carbon of elements within the bay

Figure 5.5 shows that, as in the composite bay example, CESMM3 gives the highest embodied carbon results for all the elements except the connections. ICE, UK gives the lowest results. It is also notable that the beams have a much higher contribution in this partially composite bay than in the composite bay. This is because the primary beams are larger sections as they are not acting compositely with the floor.

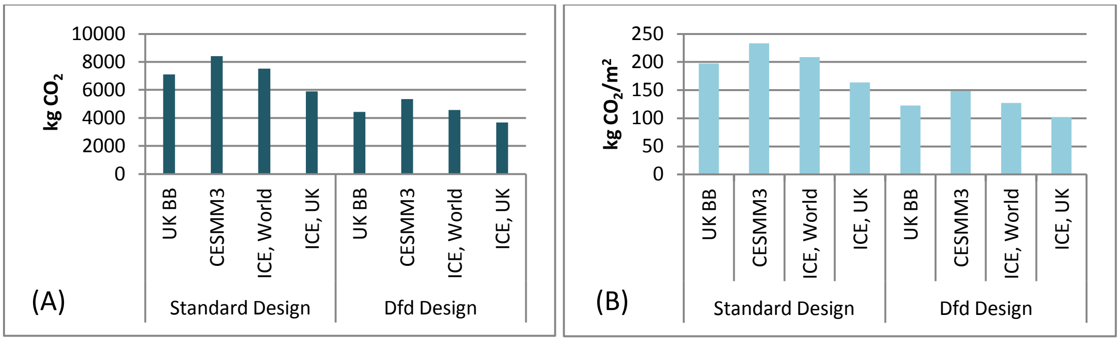


Figure 5.6: Partially Composite Bay: the impact of different datasets on the total embodied carbon of the bay, (A) shows the total embodied carbon, (B), the embodied carbon per m^2

The validity of these results was checked by modelling the DfD design within SimaPro. This estimated the embodied carbon to be 134 kg CO_2e/m^2, (see Appendix A3 for full details) which falls in the middle of the range of the other datasets; suggesting that the spreadsheet calculations have been carried out correctly as all estimates are within the same range.

The same pattern as in the composite bay emerges from Figure 5.6: CESMM3 gives the highest results, ICE UK the lowest.

5.5.4 Non Composite Bay

This is the same bay design as in section 5.3.4. For the ICE datasets the standard factor for reinforcement is used, as recommended within the dataset (Hammond & Jones, Inventory of Carbon & Energy version 2.0, 2011). The CESMM3 figure for precast concrete includes both the concrete and the reinforcement in a single estimate. The UK Building Blackbook does not include a comparable material for the reinforcement, therefore the concrete is estimated using Blackbook data and the reinforcement estimate is derived from the CESMM3 data and used within the Blackbook calculation. The results can be found in Table 5.8, Figure 5.7 and Figure 5.8.

	Standard Design				**Dfd Design**			
	UK BB	**CESMM3**	**ICE, World**	**ICE, UK**	**UK BB**	**CESMM3**	**ICE, World**	**ICE, UK**
Element	**(kg CO_2)**	**(kg CO_2)**	**(kg CO_2e)**	**(kg CO_2e)**	**(kg CO_2)**	**(kg CO_2)**	**(kg CO_2e)**	**(kg CO_2e)**
Beams	1658	1924	1854	1397	829	962	927	699
Columns	2240	2528	2436	1836	1120	1264	1218	918
Connections	120	115	133	100	120	115	133	100
Floor - conc	1146	1983	1233	1233	573	992	617	617
Floor - rein	355	(incl. above)	507	364	178	(incl. above)	254	182
Total	5520	6550	6163	4930	2820	3332	3148	2515
Total per m^2	**153**	**182**	**171**	**137**	**78**	**93**	**87**	**70**

Table 5.8: Non Composite Bay: range of embodied carbon values calculated using different datasets

For the non-composite bay there is a variation of 45 kg CO_2/m^2 for the standard design which equates to a 33% increase from the smallest value (ICE UK data) to the largest value (CESMM3). The results follow the same pattern as found in the other two bay types.

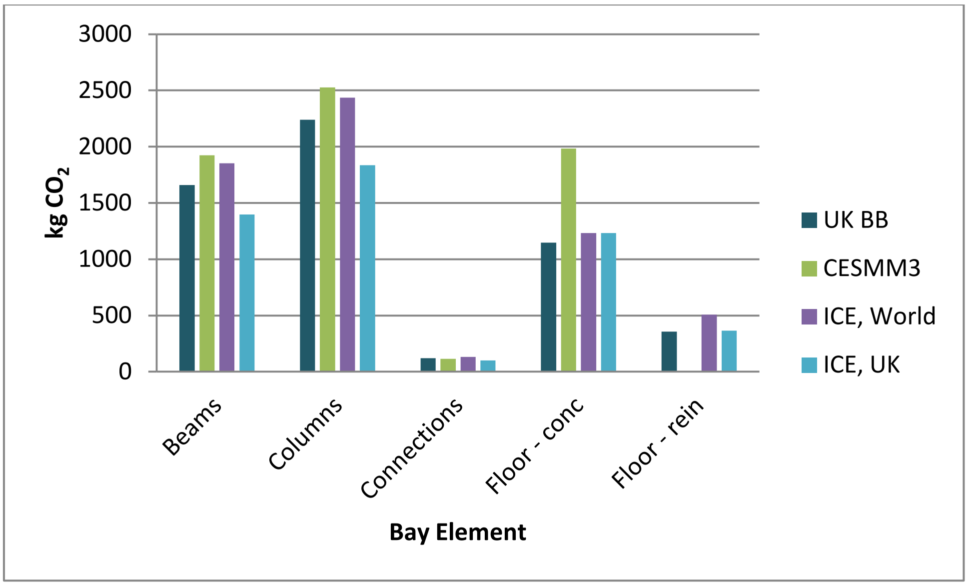


Figure 5.7: Non Composite Bay: the impact of different datasets on the embodied carbon of elements within the bay

The impact of the datasets on the individual elements follows the same pattern as for the other bay types. The CESMM3 embodied carbon value for the concrete looks particularly high because this also includes the reinforcement. The Blackbook results are the lowest for the concrete in this bay, whereas for the other two designs, the ICE estimates are lowest.

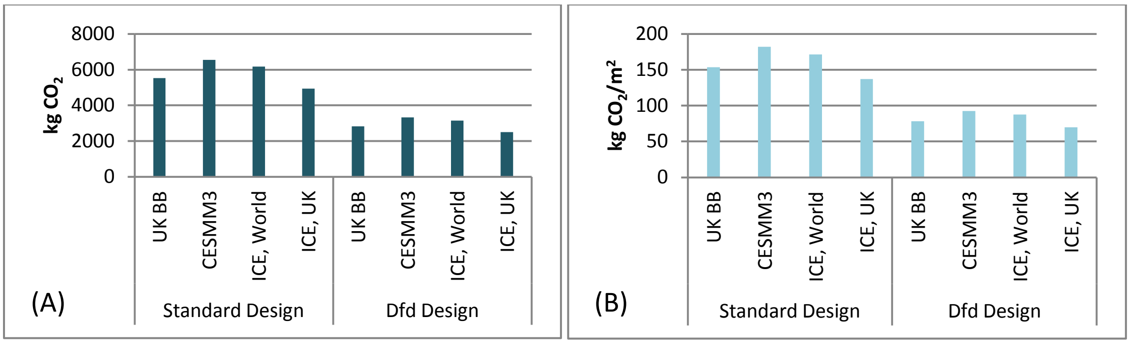


Figure 5.8: Non Composite Bay: the impact of different datasets on the total embodied carbon of the bay, (A) shows the total embodied carbon, (B), the embodied carbon per m^2

The results in Figure 5.8 show that the same pattern is followed as for the other bay types i.e. CESMM3 produces the highest embodied carbon estimates and ICE, UK the lowest. The variation is still significant, highlighting the impact a dataset has on embodied carbon results.

5.6 Conclusions

These preliminary studies demonstrate the potential impact design for deconstruction has on the embodied carbon of three different bay types. The non-composite design benefits the most from this strategy with at 49% reduction in the embodied carbon; it is also the bay type that has the lowest embodied carbon for the DfD design even though the composite bay has the lowest embodied carbon for the standard design. Nonetheless, all bay types did show advantages from design for deconstruction because the columns in all cases could be designed for subsequent reuse.

The sensitivity study highlighted the large variation in results from the use of different datasets, producing up to a 45% increase in the embodied carbon from the lowest set of results to the highest. It is important to be aware of this variation when comparing studies which may have used different datasets.

This chapter demonstrates the feasibility of including design for deconstruction of structures as a means to produce embodied carbon savings. The next step is therefore to develop a tool which can assess this for whole projects and enable designers to explore, at an early design stage, the potential benefits of design for deconstruction within their own projects.

6 Development and use of Sakura

6.1 Introduction

It has been decided that a tool should be developed so that designers can explore the specific benefits of design for deconstruction within their own projects. Quantifying the energy and carbon savings possible makes for a strong case to alter designs where these savings are significant. This tool could have taken a number of different forms: a complex spreadsheet, a program to be installed or a web based application. In order to gain the maximum amount of exposure it was decided that the tool should be available on the internet so that potential users might find it on internet searches, as well as clicking on specific links for it. Whilst any of the described methods could have been linked to a website and downloaded; it was felt that it would be most effective to build the tool into the website so that it could be accessed from anywhere at any time and did not require downloads, which might limit some users. Having the tool integrated into the web site also means that it would be harder for users to alter constant input information that should not be changed.

The tool has been named Sakura, the Japanese word for Cherry Blossom. The cherry tree and its blossom are used within the book 'Cradle to Cradle – Re-making the way we make things' (Braungart & McDonough, 2009) as an example of a cradle to cradle cycle. This tool aspires to encourage cradle to cradle design and so takes its name and inspiration from this exemplar in nature.

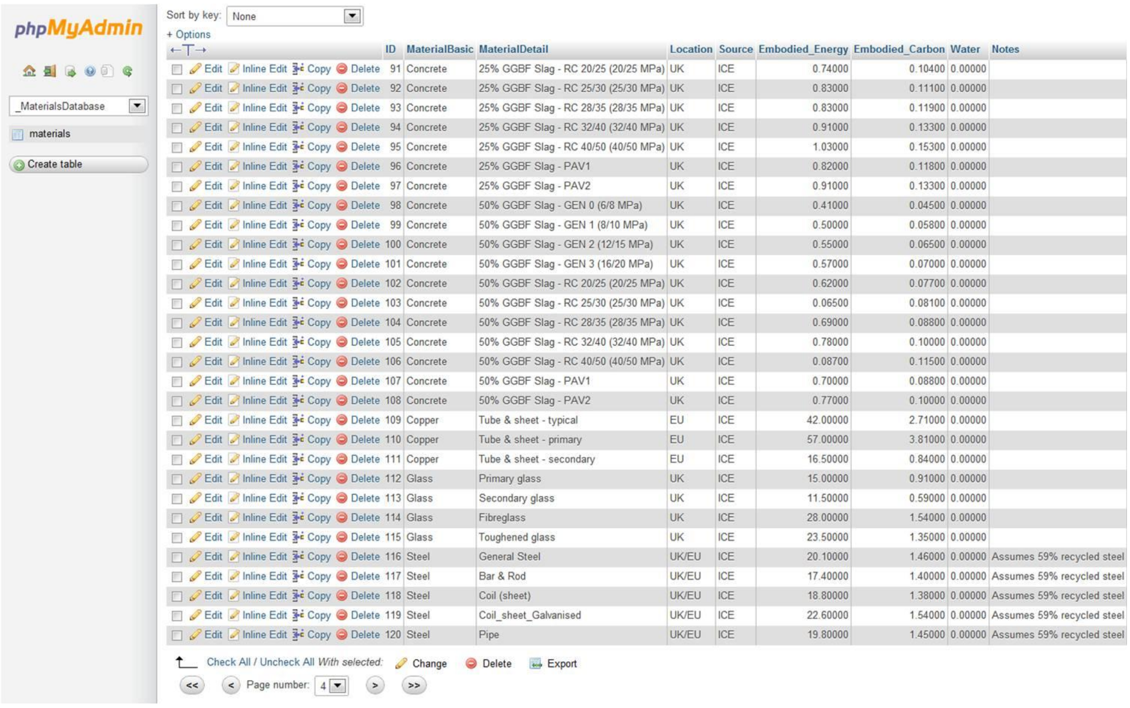
6.2 Technical Background and Setup

The basic website was constructed using HTML coding, with CSS used for the design and visual impact of the website. A database of materials was set up using phpMyAdmin. Information from the Inventory of Carbon and Energy (ICE) (Hammond & Jones, 2011) was manually input into this database. It is acknowledged that there was a risk of typing errors by inputting information in this way, but this was minimised by checking of the entries. The materials table was set up as outlined in Table 6.1.

Database Column	Notes
ID	This is a unique tag for each material
Material Basic	Describes the material, e.g. Steel
Material Detail	Elaborates on above, describing the type of component
Location	Area material data is based on, e.g. UK Specific, Global
Source	The data source used, all ICE at present, but additional sets may be added
Embodied Energy	Embodied energy factor, given in MJ/kg
Embodied Carbon	Embodied carbon factor, given in kg CO_2e/kg
Water	Not currently used, entered for future versions so embodied water can be added
Notes	Lists addition important information, e.g. percentage of recycled steel content

Table 6.1: Description of Materials Database

It should be noted that estimates for the embodied energy and carbon of a suspended ceiling had to be calculated as this information was not readily available. ICE data (Hammond & Jones, 2011) was used for the individual components that make up the suspended ceiling, for the full calculation see Appendix B1. The water column is not used as embodied water data is not currently available, gathering this data forms Recommendation 1674. An example page of the database can be seen in Figure 6.1. The database has been set up so that extra materials and datasets can be easily added.



ID	MaterialBasic	MaterialDetail	Location	Source	Embodied_Energy	Embodied_Carbon	Water	Notes
91	Concrete	25% GGBF Slag - RC 20/25 (20/25 MPa)	UK	ICE	0.74000	0.10400	0.00000	
92	Concrete	25% GGBF Slag - RC 25/30 (25/30 MPa)	UK	ICE	0.83000	0.11100	0.00000	
93	Concrete	25% GGBF Slag - RC 28/35 (28/35 MPa)	UK	ICE	0.83000	0.11900	0.00000	
94	Concrete	25% GGBF Slag - RC 32/40 (32/40 MPa)	UK	ICE	0.91000	0.13300	0.00000	
95	Concrete	25% GGBF Slag - RC 40/50 (40/50 MPa)	UK	ICE	1.03000	0.15300	0.00000	
96	Concrete	25% GGBF Slag - PAV1	UK	ICE	0.82000	0.11800	0.00000	
97	Concrete	25% GGBF Slag - PAV2	UK	ICE	0.91000	0.13300	0.00000	
98	Concrete	50% GGBF Slag - GEN 0 (6/8 MPa)	UK	ICE	0.41000	0.04500	0.00000	
99	Concrete	50% GGBF Slag - GEN 1 (8/10 MPa)	UK	ICE	0.50000	0.05800	0.00000	
100	Concrete	50% GGBF Slag - GEN 2 (12/15 MPa)	UK	ICE	0.55000	0.06500	0.00000	
101	Concrete	50% GGBF Slag - GEN 3 (16/20 MPa)	UK	ICE	0.57000	0.07000	0.00000	
102	Concrete	50% GGBF Slag - RC 20/25 (20/25 MPa)	UK	ICE	0.62000	0.07700	0.00000	
103	Concrete	50% GGBF Slag - RC 25/30 (25/30 MPa)	UK	ICE	0.06500	0.08100	0.00000	
104	Concrete	50% GGBF Slag - RC 28/35 (28/35 MPa)	UK	ICE	0.69000	0.08800	0.00000	
105	Concrete	50% GGBF Slag - RC 32/40 (32/40 MPa)	UK	ICE	0.78000	0.10000	0.00000	
106	Concrete	50% GGBF Slag - RC 40/50 (40/50 MPa)	UK	ICE	0.08700	0.11500	0.00000	
107	Concrete	50% GGBF Slag - PAV1	UK	ICE	0.70000	0.08800	0.00000	
108	Concrete	50% GGBF Slag - PAV2	UK	ICE	0.77000	0.10000	0.00000	
109	Copper	Tube & sheet - typical	EU	ICE	42.00000	2.71000	0.00000	
110	Copper	Tube & sheet - primary	EU	ICE	57.00000	3.81000	0.00000	
111	Copper	Tube & sheet - secondary	EU	ICE	16.50000	0.84000	0.00000	
112	Glass	Primary glass	UK	ICE	15.00000	0.91000	0.00000	
113	Glass	Secondary glass	UK	ICE	11.50000	0.59000	0.00000	
114	Glass	Fibreglass	UK	ICE	28.00000	1.54000	0.00000	
115	Glass	Toughened glass	UK	ICE	23.50000	1.35000	0.00000	
116	Steel	General Steel	UK/EU	ICE	20.10000	1.46000	0.00000	Assumes 59% recycled steel
117	Steel	Bar & Rod	UK/EU	ICE	17.40000	1.40000	0.00000	Assumes 59% recycled steel
118	Steel	Coil (sheet)	UK/EU	ICE	18.80000	1.38000	0.00000	Assumes 59% recycled steel
119	Steel	Coil_sheet_Galvanised	UK/EU	ICE	22.60000	1.54000	0.00000	Assumes 59% recycled steel
120	Steel	Pipe	UK/EU	ICE	19.80000	1.45000	0.00000	Assumes 59% recycled steel

Figure 6.1: Screenshot of single page of materials database

A second database was set up to store user and building information. This database is made up of a series of tables: users, initial information, foundation data, ground floor slab data, column data, beam data, upper floor system data, roof data, ceiling data and embodied data. For the material specific tables there are two of each type of table, one for information that has been input as kg and the other for information that has been entered as kg/m^2. Inputted information is saved to the database so that users can access and edit existing projects after they have run an initial analysis. It also allows users to revisit results if required.

The website communicates, stores and handles information from the databases using PHP and SQL coding. The embodied energy and carbon are calculated using PHP coding which is embedded within each page for the website. A more detailed description of what each page does and calculates is given in section 6.4.

6.3 Design for Deconstruction Website

For Sakura to be most effective it was determined that the users should also be able to learn what design for deconstruction is. Therefore, it is linked to a basic homepage that outlines design for deconstruction and its benefits. The homepage can be found at dfd.group.shef.ac.uk, and a screenshot is shown in Figure 6.2.

Design for Deconstruction (DfD)

Design for deconstruction (DfD) involves planning for the end of a building's life at the design stage (this can also be applied to product design).

Advantages of DfD include:

- maximising future material reuse
- maximising future recycling
- minimising of materials sent to landfill

Reusing materials rather than simply recycling them can:

- reduce the embodied energy/carbon of buildings
- reduce the exploitation of natural resources
- helps to move towards closing the material loop, an important sustainability strategy

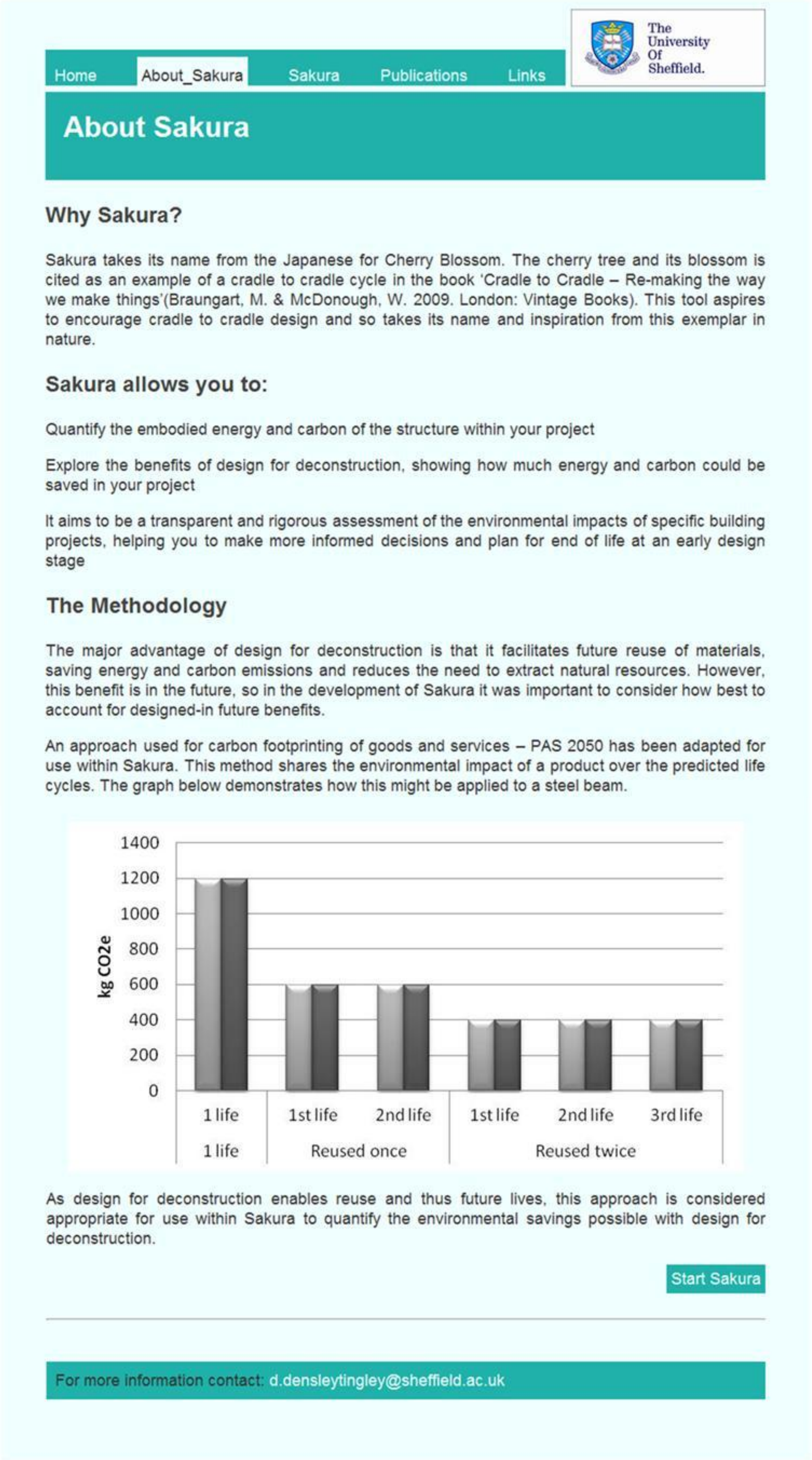
However, a major barrier to material reuse is a fragmented supply chain. Designing all new buildings for deconstruction will increase the future supply of reused materials, thus targeting this barrier.

The purpose of this website is to demonstrate and quantify the environmental benefits of DfD. This is done through the development of a tool to allow designers to explore the impacts of including DfD within their designs.

For more information contact: d.densleytingley@sheffield.ac.uk

Figure 6.2: Screenshot of design for deconstruction homepage

From the homepage users can link to an ‘About Sakura’ page (Figure 6.3) that explains the name of the tool, describes what it does and outlines the basic methodology on which it is based. This enhances the transparency of Sakura, enabling users to understand how the embodied energy and carbon savings by designing for deconstruction are calculated. A graph demonstrating how the future benefits of designed-in reuse is shown, visualising the reuse methodology and so that all users of the website can understand this crucial part of Sakura.



About Sakura

Why Sakura?

Sakura takes its name from the Japanese for Cherry Blossom. The cherry tree and its blossom is cited as an example of a cradle to cradle cycle in the book 'Cradle to Cradle – Re-making the way we make things'(Braungart, M. & McDonough, W. 2009. London: Vintage Books). This tool aspires to encourage cradle to cradle design and so takes its name and inspiration from this exemplar in nature.

Sakura allows you to:

Quantify the embodied energy and carbon of the structure within your project

Explore the benefits of design for deconstruction, showing how much energy and carbon could be saved in your project

It aims to be a transparent and rigorous assessment of the environmental impacts of specific building projects, helping you to make more informed decisions and plan for end of life at an early design stage

The Methodology

The major advantage of design for deconstruction is that it facilitates future reuse of materials, saving energy and carbon emissions and reduces the need to extract natural resources. However, this benefit is in the future, so in the development of Sakura it was important to consider how best to account for designed-in future benefits.

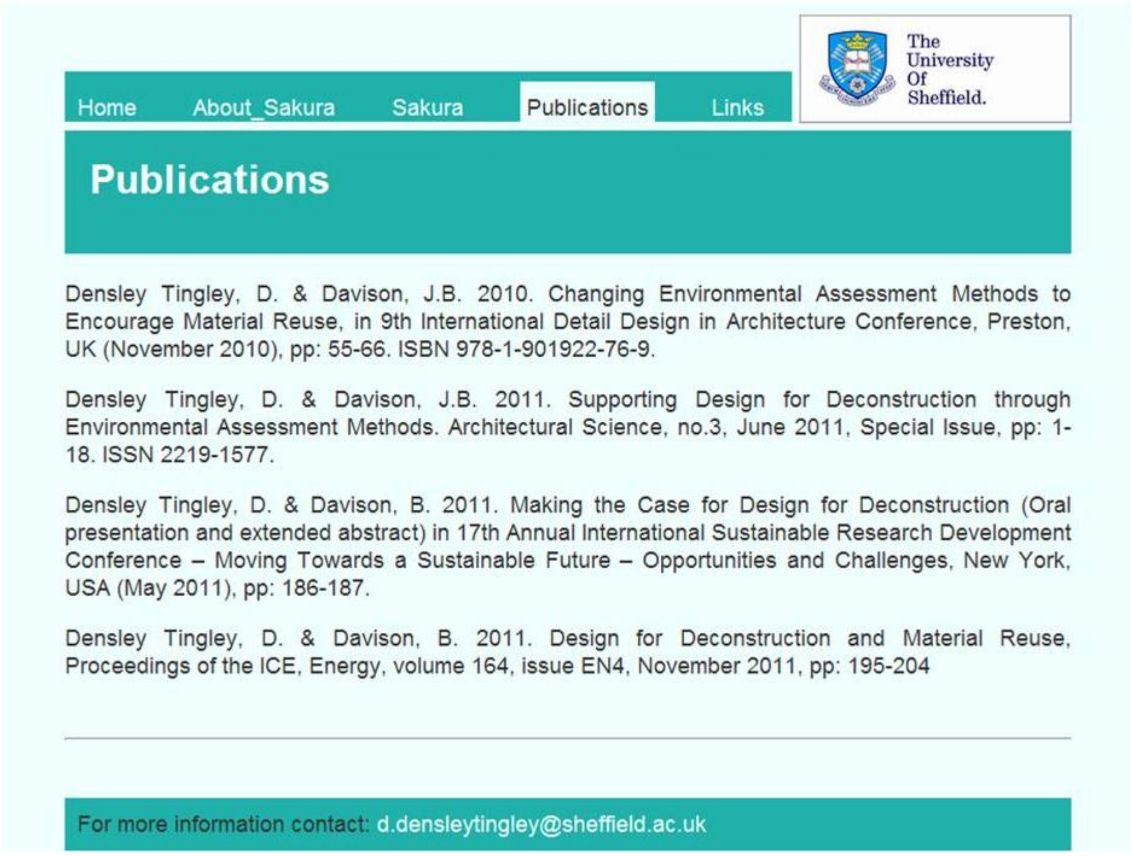
An approach used for carbon footprinting of goods and services – PAS 2050 has been adapted for use within Sakura. This method shares the environmental impact of a product over the predicted life cycles. The graph below demonstrates how this might be applied to a steel beam.

As design for deconstruction enables reuse and thus future lives, this approach is considered appropriate for use within Sakura to quantify the environmental savings possible with design for deconstruction.

For more information contact: d.densleytingley@sheffield.ac.uk

Figure 6.3: Screenshot of About Sakura webpage

Other internal links on the design for deconstruction website are the link to login to Sakura; this will be discussed in more detail in section 6.4.1. There is also a page that outlines the publications associated with this research, shown in Figure 6.4; this enables users to access further more detailed reading on the subject area if they wish. The Links page (Figure 6.5), gives links to a few key websites. The Inventory of Carbon and Energy (Hammond & Jones, 2011) is the dataset that is used within Sakura, this information was extracted from the spreadsheet of version 2, a link to version 1.6 of the Inventory of Carbon and Energy is provided for information. At the time of writing it was not possible to link to version 2, however this would have been preferable so that users could have examined the specific dataset that is being used within Sakura. A link is also provided for those that wish to incorporate design for deconstruction within their designs to the Scottish Ecological Design Association's guide on design for deconstruction. This a very comprehensive guide that outlines a number of strategies on how best to incorporate design for deconstruction into designs. There are also links to the associated research group for this work: Engineering Environmental Buildings and to the author's personal research page.



Publications

Densley Tingley, D. & Davison, J.B. 2010. Changing Environmental Assessment Methods to Encourage Material Reuse, in 9th International Detail Design in Architecture Conference, Preston, UK (November 2010), pp: 55-66. ISBN 978-1-901922-76-9.

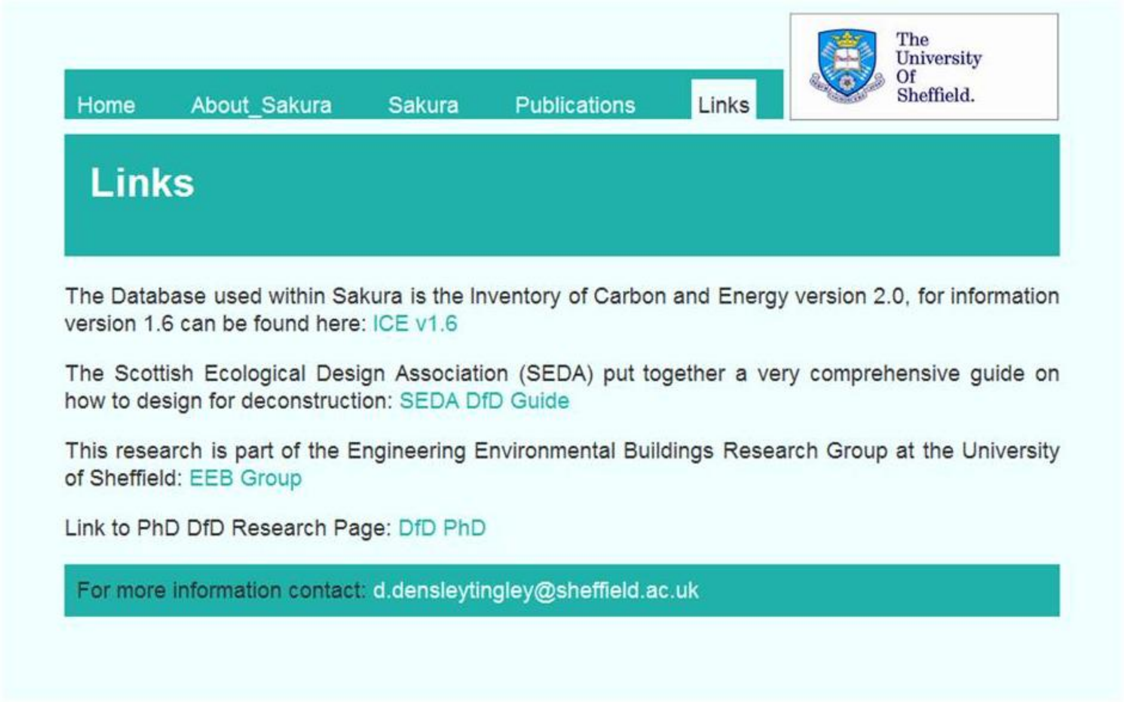
Densley Tingley, D. & Davison, J.B. 2011. Supporting Design for Deconstruction through Environmental Assessment Methods. Architectural Science, no.3, June 2011, Special Issue, pp: 1-18. ISSN 2219-1577.

Densley Tingley, D. & Davison, B. 2011. Making the Case for Design for Deconstruction (Oral presentation and extended abstract) in 17th Annual International Sustainable Research Development Conference – Moving Towards a Sustainable Future – Opportunities and Challenges, New York, USA (May 2011), pp: 186-187.

Densley Tingley, D. & Davison, B. 2011. Design for Deconstruction and Material Reuse, Proceedings of the ICE, Energy, volume 164, issue EN4, November 2011, pp: 195-204

For more information contact: d.densleytingley@sheffield.ac.uk

Figure 6.4: Screenshot of Publication webpage



Links

The Database used within Sakura is the Inventory of Carbon and Energy version 2.0, for information version 1.6 can be found here: ICE v1.6

The Scottish Ecological Design Association (SEDA) put together a very comprehensive guide on how to design for deconstruction: SEDA DfD Guide

This research is part of the Engineering Environmental Buildings Research Group at the University of Sheffield: EEB Group

Link to PhD DfD Research Page: DfD PhD

For more information contact: d.densleytingley@sheffield.ac.uk

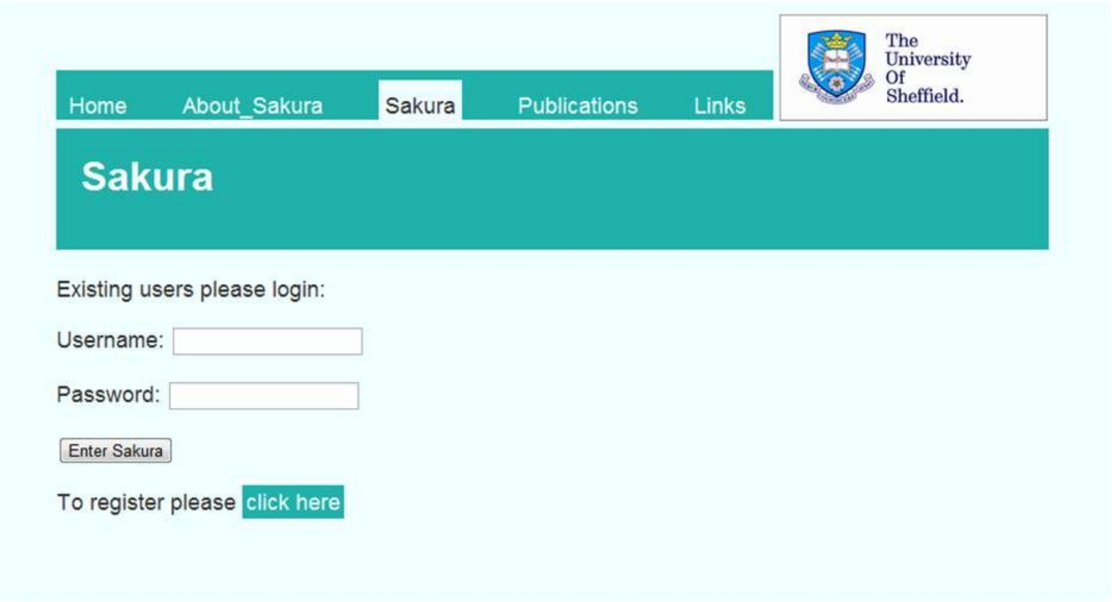
Figure 6.5: Screenshot of Links webpage

6.4 Use of Sakura

An outline of how Sakura is used, what input information is required and the output that is given will now be explained. Sakura is designed to be easy, efficient and intuitive to use so that designers can investigate the benefits of design for deconstruction quickly and effectively, assisting the decision making process.

6.4.1 Login/Registration

When users click on either the Sakura link or the Start Sakura link they will be directed to a page, seen in Figure 6.2Figure 6.6, which invites existing users to login or new users to register. The registration process is as simple as it can be whilst still complying with University regulations about intellectual property. It requires the user to choose and input a username and password and to state the company that they work for, a screenshot of the page can be seen in Figure 6.7. By clicking the register button the user agrees to the terms and conditions of using Sakura, the statement discussing these is linked on the registration page and provided in Appendix B2 for information.



Sakura

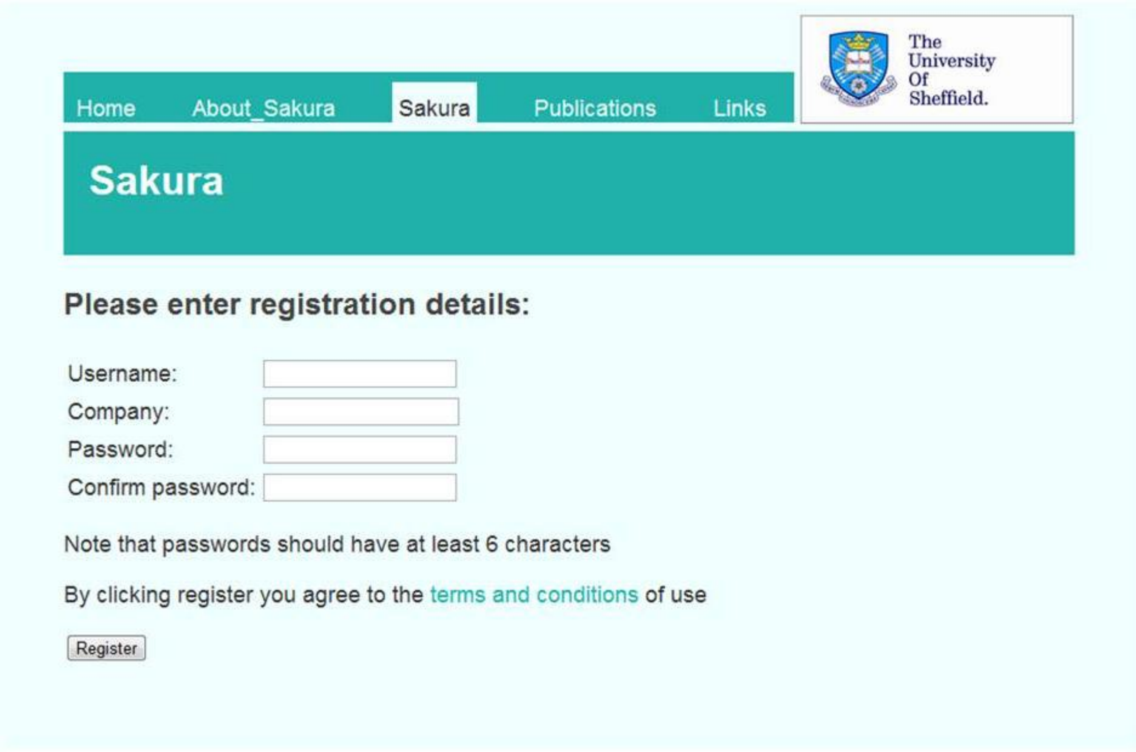
Existing users please login:

Username:

Password:

To register please click here

Figure 6.6: Screenshot of Login page for Sakura



Sakura

Please enter registration details:

Username:

Company:

Password:

Confirm password:

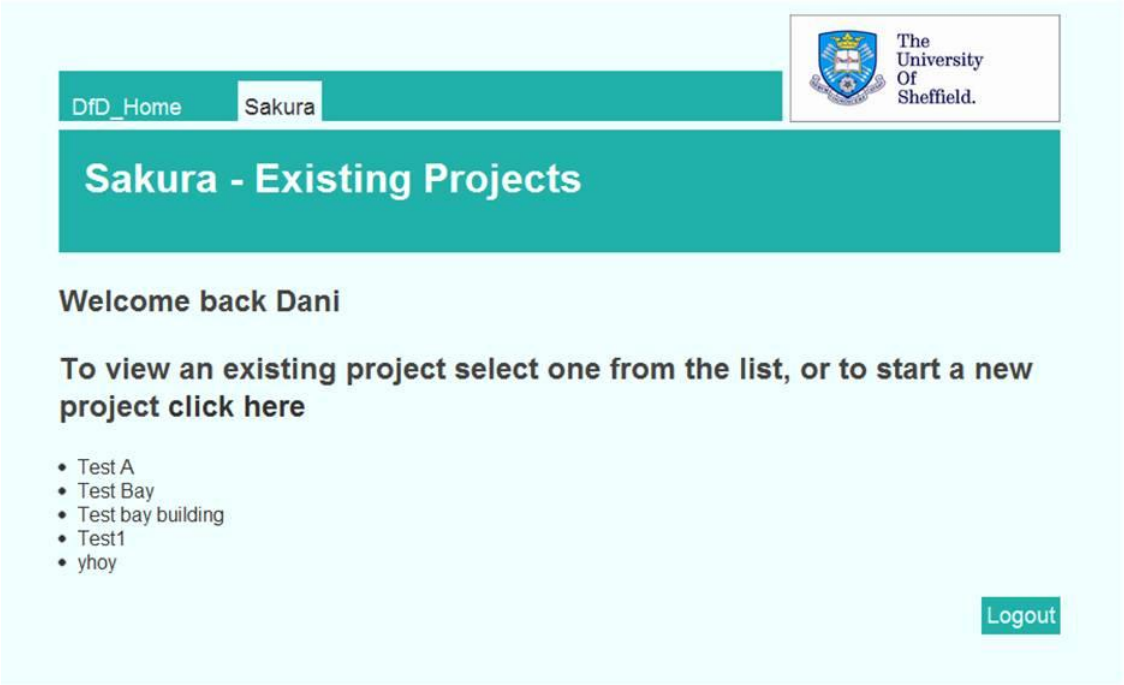
Note that passwords should have at least 6 characters

By clicking register you agree to the terms and conditions of use

Figure 6.7: Screenshot of Registration page for Sakura

6.4.2 The Initial Form

Once users have logged into Sakura they access the welcome page (Figure 6.8), this enables a user to either create a new project or select an existing project from the list. Where users have registered and logged in for the first time they are linked straight to the initial form page (Figure 6.9), so that they can begin inputting information.



Sakura - Existing Projects

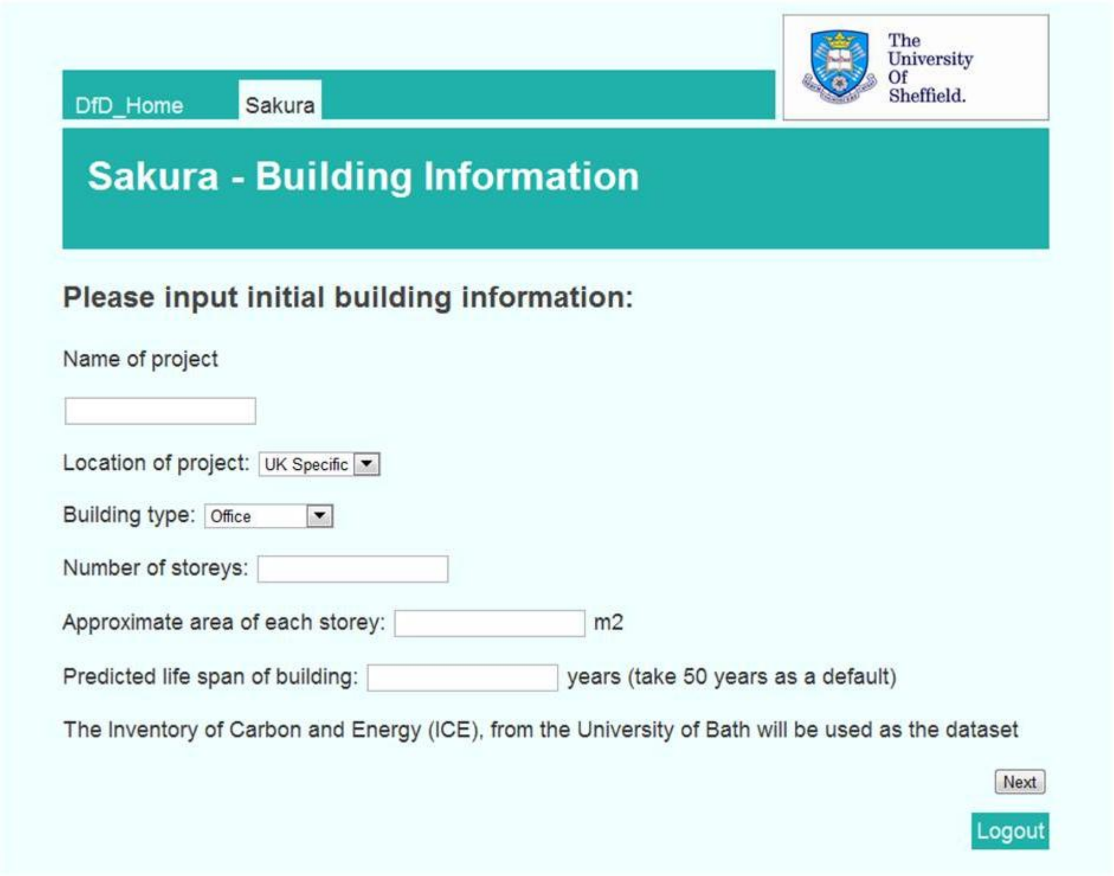
Welcome back Dani

To view an existing project select one from the list, or to start a new project click here

- Test A
- Test Bay
- Test bay building
- Test1
- yhoy

Figure 6.8: Screenshot of initial page in Sakura

Viewing the results and editing an existing project will be discussed in section 6.4.7. If a new project has been selected access is given to the initial form page (Figure 6.9). This asks the user to input a name for the project, select the location of the project: UK, EU or Global; select the building type: office, warehouse, supermarket, school, residential, multi-use or stadia; enter the number of storeys, the approximate area of each storey and the predicted life span of the building. It is suggested that users take fifty years as a default value if they are not sure of the life span; this is consistent with the methodology laid out in Chapter 4. Once this form is completed the user can click next to take then to material input options.



Sakura - Building Information

Please input initial building information:

Name of project

Location of project: UK Specific

Building type: Office

Number of storeys:

Approximate area of each storey: m2

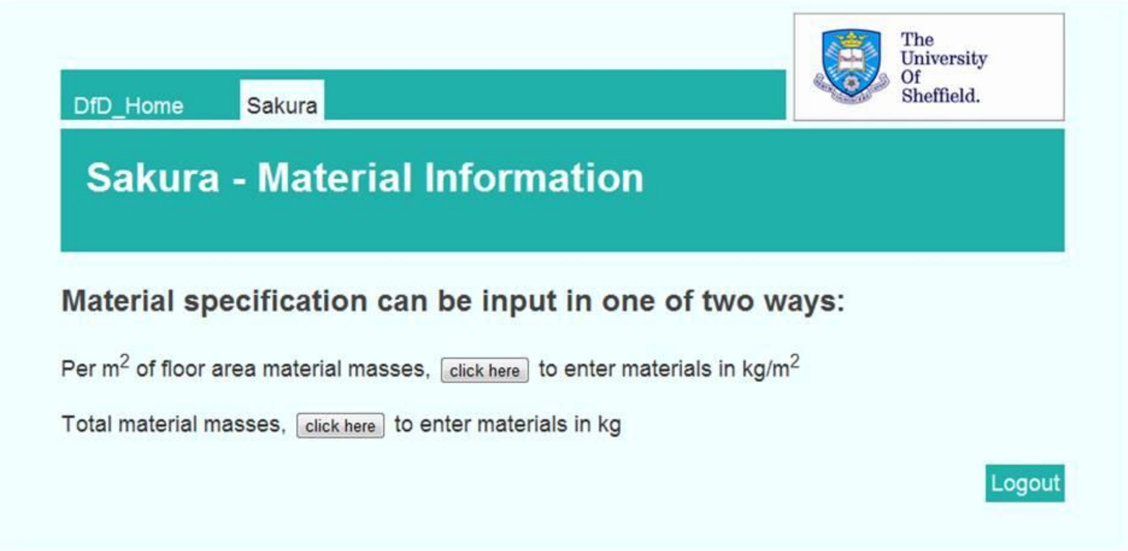
Predicted life span of building: years (take 50 years as a default)

The Inventory of Carbon and Energy (ICE), from the University of Bath will be used as the dataset

Figure 6.9: Screenshot of Initial Form to complete within Sakura

6.4.3 Material Input Options

Material data can be input in one of two ways, kg/m^2 or total material masses, kg, this is shown in Figure 6.10. The first option allows Sakura to be used at an early design stage, where approximate kg/m^2 material amounts will have been calculated for the structure. A conceptual or scheme design stage is the ideal time to use Sakura as it is at this phase that key design decisions are being made, making it the optimal point to incorporate design for deconstruction. However, the results will likely be more accurate with more specific material masses, which is why the second option is available for those projects that have a higher level of detail, for example that in a bill of quantities. A sensitivity study exploring the different input methods' impact on results forms Recommendation 14.



Sakura - Material Information

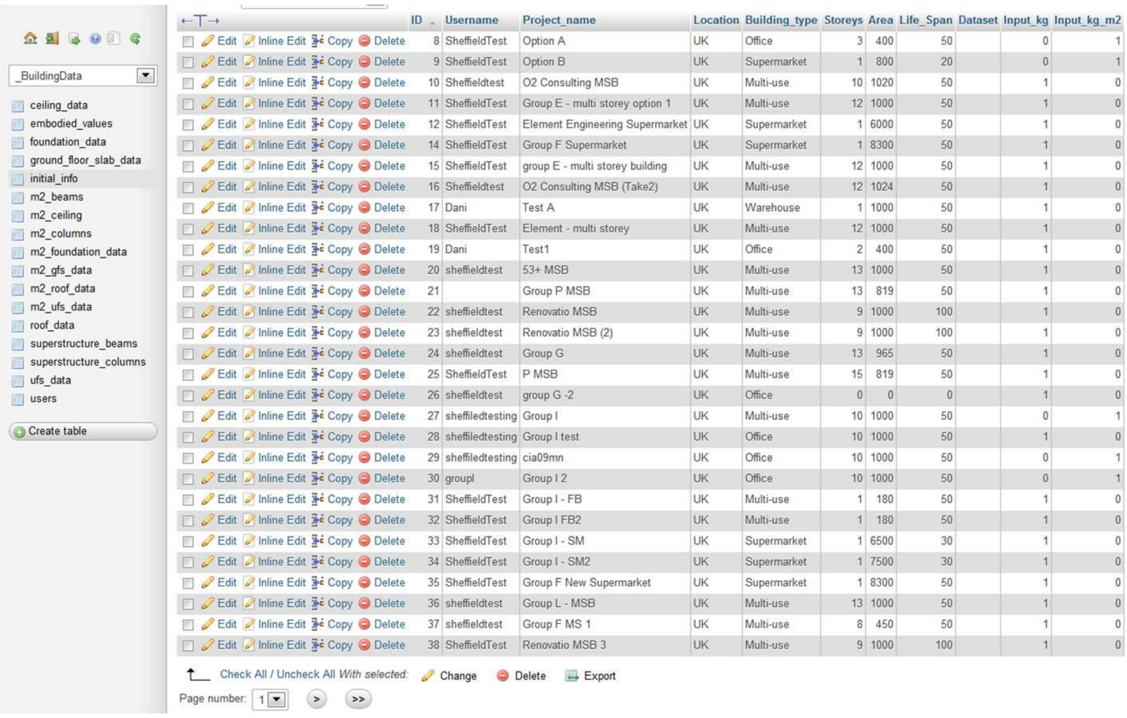
Material specification can be input in one of two ways:

Per m^2 of floor area material masses, click here to enter materials in kg/m^2

Total material masses, click here to enter materials in kg

Figure 6.10: Screenshot of Sakura, showing two different input options

Within this page is some embedded coding that saves the submitted data from the last page into a table, within the Building Data database, this table can be seen in Figure 6.11. This enables some of this data to be used later for the embodied energy and carbon calculations. Storing this information also means it is possible to analyse which building types and sizes appear to be most suitable for design for deconstruction when this information is combined with embodied values. Whether material specification is input per m^2 or as total masses is also saved within this table, the coding for this is embedded at the being of the material specification page which Figure 6.10 links to.

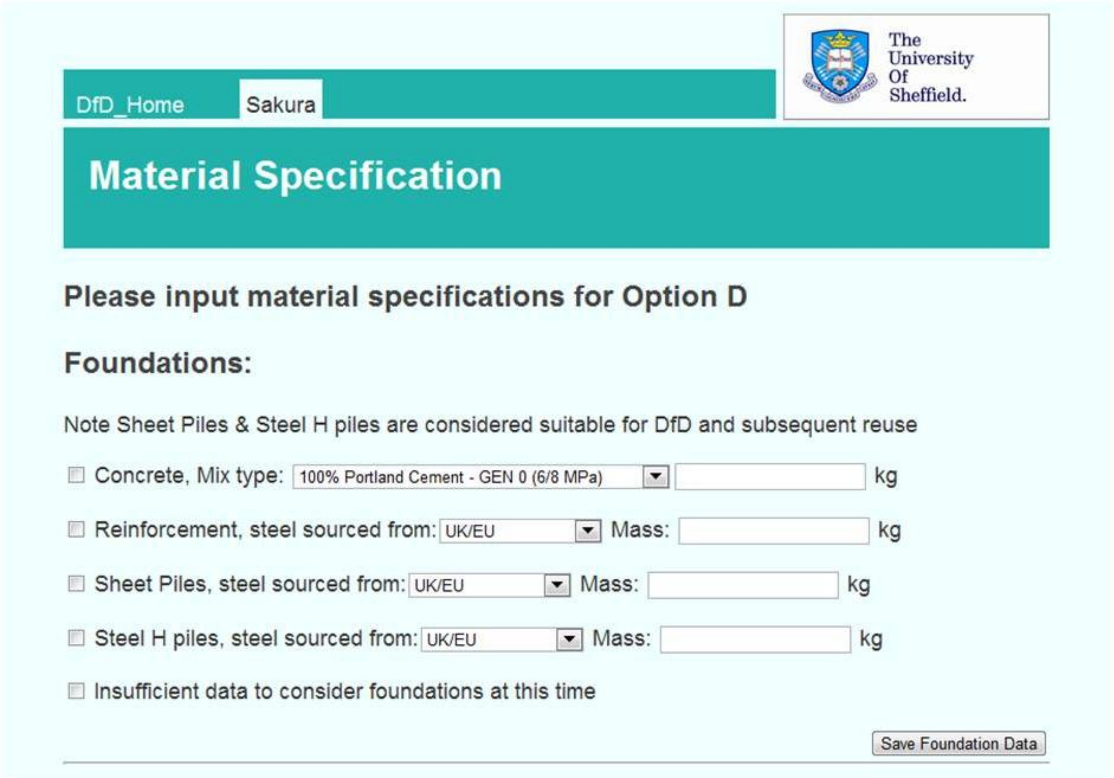


←T→	ID	Username	Project_name	Location	Building_type	Storeys	Area	Life_Span	Dataset	Input_kg	Input_kg_m2
☐ Edit Inline Edit Copy Delete	8	SheffieldTest	Option A	UK	Office	3	400	50		0	1
☐ Edit Inline Edit Copy Delete	9	SheffieldTest	Option B	UK	Supermarket	1	800	20		0	1
☐ Edit Inline Edit Copy Delete	10	Sheffieldtest	O2 Consulting MSB	UK	Multi-use	10	1020	50		1	0
☐ Edit Inline Edit Copy Delete	11	SheffieldTest	Group E - multi storey option 1	UK	Multi-use	12	1000	50		1	0
☐ Edit Inline Edit Copy Delete	12	SheffieldTest	Element Engineering Supermarket	UK	Supermarket	1	6000	50		1	0
☐ Edit Inline Edit Copy Delete	14	SheffieldTest	Group F Supermarket	UK	Supermarket	1	8300	50		1	0
☐ Edit Inline Edit Copy Delete	15	SheffieldTest	group E - multi storey building	UK	Multi-use	12	1000	50		1	0
☐ Edit Inline Edit Copy Delete	16	Sheffieldtest	O2 Consulting MSB (Take2)	UK	Multi-use	12	1024	50		1	0
☐ Edit Inline Edit Copy Delete	17	Dani	Test A	UK	Warehouse	1	1000	50		1	0
☐ Edit Inline Edit Copy Delete	18	SheffieldTest	Element - multi storey	UK	Multi-use	12	1000	50		1	0
☐ Edit Inline Edit Copy Delete	19	Dani	Test1	UK	Office	2	400	50		1	0
☐ Edit Inline Edit Copy Delete	20	sheffieldtest	53+ MSB	UK	Multi-use	13	1000	50		1	0
☐ Edit Inline Edit Copy Delete	21		Group P MSB	UK	Multi-use	13	819	50		1	0
☐ Edit Inline Edit Copy Delete	22	sheffieldtest	Renovatio MSB	UK	Multi-use	9	1000	100		1	0
☐ Edit Inline Edit Copy Delete	23	sheffieldtest	Renovatio MSB (2)	UK	Multi-use	9	1000	100		1	0
☐ Edit Inline Edit Copy Delete	24	sheffieldtest	Group G	UK	Multi-use	13	965	50		1	0
☐ Edit Inline Edit Copy Delete	25	SheffieldTest	P MSB	UK	Multi-use	15	819	50		1	0
☐ Edit Inline Edit Copy Delete	26	sheffieldtest	group G -2	UK	Office	0	0	0		1	0
☐ Edit Inline Edit Copy Delete	27	sheffiledtesting	Group I	UK	Multi-use	10	1000	50		0	1
☐ Edit Inline Edit Copy Delete	28	sheffiledtesting	Group I test	UK	Office	10	1000	50		1	0
☐ Edit Inline Edit Copy Delete	29	sheffiledtesting	cia09mn	UK	Office	10	1000	50		0	1
☐ Edit Inline Edit Copy Delete	30	groupl	Group I 2	UK	Office	10	1000	50		0	1
☐ Edit Inline Edit Copy Delete	31	SheffieldTest	Group I - FB	UK	Multi-use	1	180	50		1	0
☐ Edit Inline Edit Copy Delete	32	SheffieldTest	Group I FB2	UK	Multi-use	1	180	50		1	0
☐ Edit Inline Edit Copy Delete	33	SheffieldTest	Group I - SM	UK	Supermarket	1	6500	30		1	0
☐ Edit Inline Edit Copy Delete	34	SheffieldTest	Group I - SM2	UK	Supermarket	1	7500	30		1	0
☐ Edit Inline Edit Copy Delete	35	SheffieldTest	Group F New Supermarket	UK	Supermarket	1	8300	50		1	0
☐ Edit Inline Edit Copy Delete	36	sheffieldtest	Group L - MSB	UK	Multi-use	13	1000	50		1	0
☐ Edit Inline Edit Copy Delete	37	sheffieldtest	Group F MS 1	UK	Multi-use	8	450	50		1	0
☐ Edit Inline Edit Copy Delete	38	SheffieldTest	Renovatio MSB 3	UK	Multi-use	9	1000	100		1	0

Figure 6.11: Screenshot of initial info table

6.4.4 Material Specification

The material specification page allows the user to input specifications for all the major structural components; this is all input on one page, although can be saved step by step if this is preferred by the user. The examples shown within the report are for total material mass input. Figure 6.12 shows the material specification options for the foundations, the user should tick the boxes for those materials that are specified for the project and enter the appropriated masses. The foundation options are: reinforced concrete, sheet piles and steel H piles. Different concrete strengths and mixes can be selected from the dropdown menu next to mix type, there are a large range of options for the strength; fly ash and ground granulated blast furnace slag are replacement options for cement with different percentage replacements available. The location that the steel is sourced from should be selected from the dropdown menu; this can be either ‘UK/EU’ or ‘rest of the world’. This is because the recycled content within the steel will vary depending on where the steel has been sourced from and therefore the embodied values will differ. According to the ICE (Hammond & Jones, 2011) steel from the UK and/or the EU has a 59% recycled content and steel sourced from the rest of the world has 35.5% recycled content. There will be a greater variation within this depending on specific sources. This is generalised data, however, more specific data is not widely available at this time but the database could be updated to include this if and when it becomes available. These dropdown menus are the same wherever concrete and steel are options. For the foundations both the sheet piles and steel H piles are considered suitable for design for deconstruction and future reuse, as mentioned in Figure 6.12.



Material Specification

Please input material specifications for Option D

Foundations:

Note Sheet Piles & Steel H piles are considered suitable for DfD and subsequent reuse

☐ Concrete, Mix type: 100% Portland Cement - GEN 0 (6/8 MPa) kg

☐ Reinforcement, steel sourced from: UK/EU Mass: kg

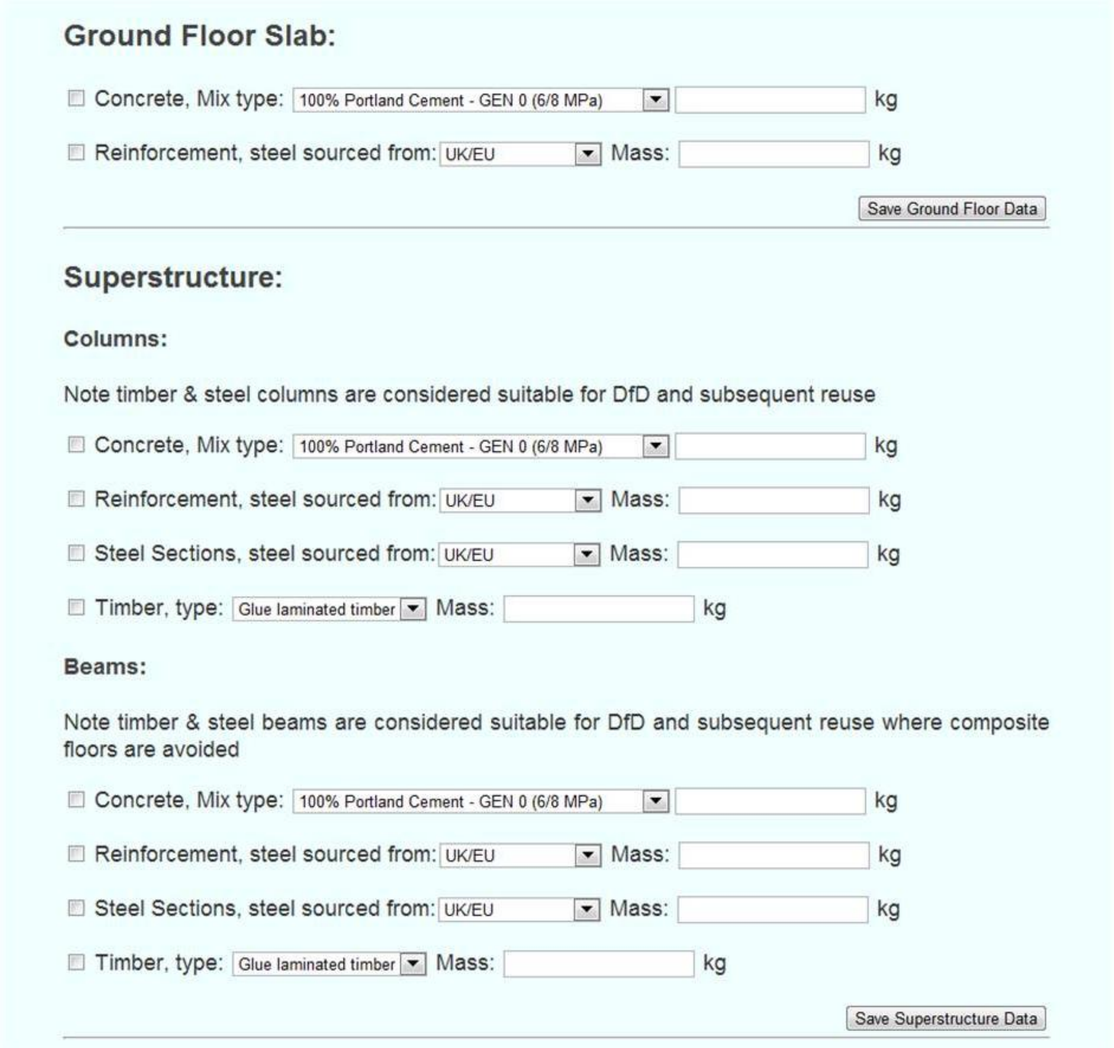
☐ Sheet Piles, steel sourced from: UK/EU Mass: kg

☐ Steel H piles, steel sourced from: UK/EU Mass: kg

☐ Insufficient data to consider foundations at this time

Figure 6.12: Screenshot showing foundation input section

The ground floor slab will likely be reinforced concrete construction and the input requirements based on this can be seen in Figure 6.13. The ground floor slab is not considered suitable for design for deconstruction. The superstructure specification options can also be seen in Figure 6.13. Reinforced concrete, steel sections and timber are all options for both columns and beams. As can be seen column and beam data should be input separately. The type of timber can be chosen from the drop down menu, options include, glue laminated timber, sawn hardwood and sawn softwood. Both the steel and timber columns and beams are considered suitable for design for construction and subsequent reuse. However, if a composite floor is specified then the steel beams are no longer fit for future reuse as the shear studs cause too much damage to them.



Ground Floor Slab:

☐ Concrete, Mix type: 100% Portland Cement - GEN 0 (6/8 MPa) kg

☐ Reinforcement, steel sourced from: UK/EU Mass: kg

Superstructure:

Columns:

Note timber & steel columns are considered suitable for DfD and subsequent reuse

☐ Concrete, Mix type: 100% Portland Cement - GEN 0 (6/8 MPa) kg

☐ Reinforcement, steel sourced from: UK/EU Mass: kg

☐ Steel Sections, steel sourced from: UK/EU Mass: kg

☐ Timber, type: Glue laminated timber Mass: kg

Beams:

Note timber & steel beams are considered suitable for DfD and subsequent reuse where composite floors are avoided

☐ Concrete, Mix type: 100% Portland Cement - GEN 0 (6/8 MPa) kg

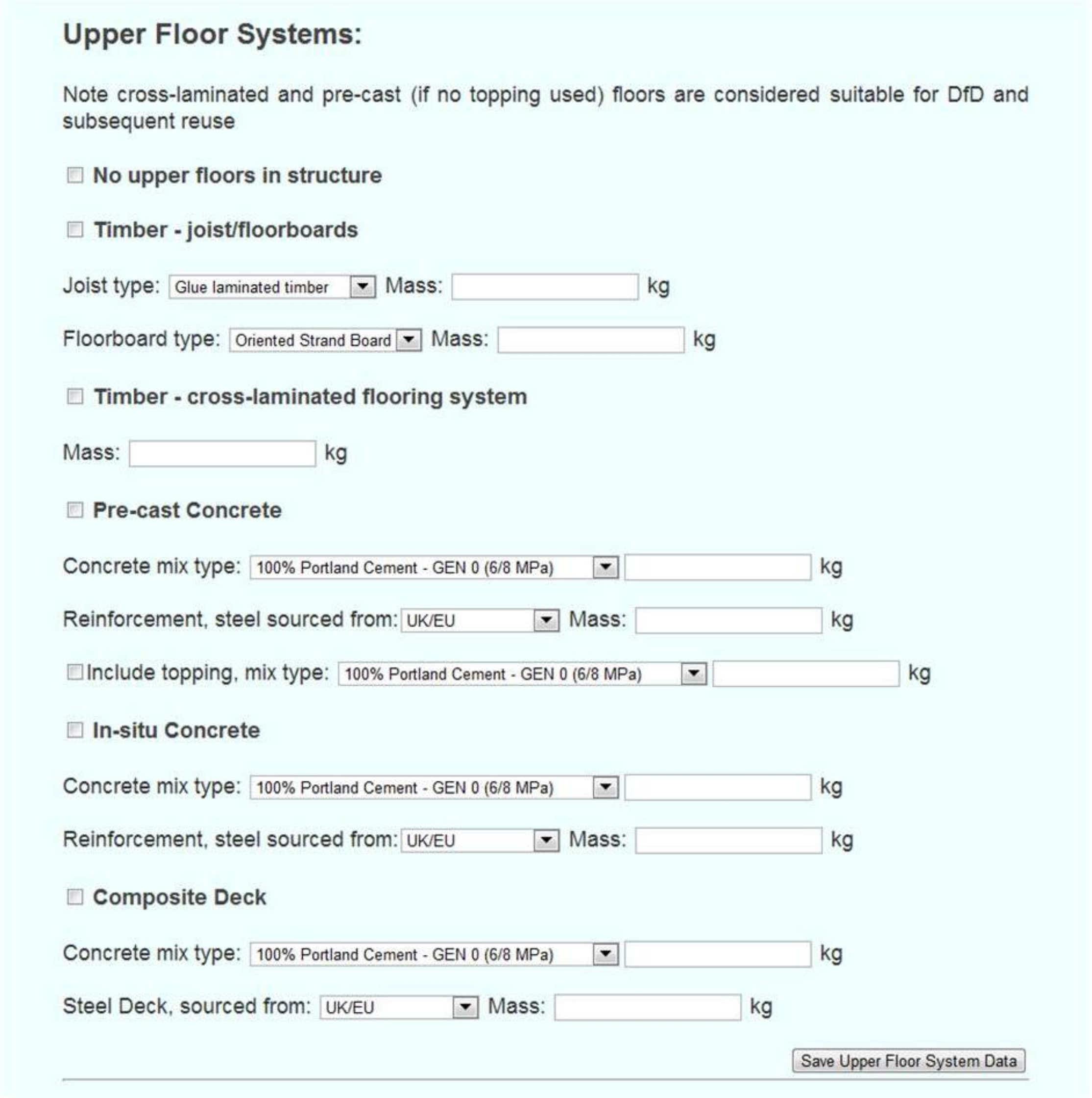
☐ Reinforcement, steel sourced from: UK/EU Mass: kg

☐ Steel Sections, steel sourced from: UK/EU Mass: kg

☐ Timber, type: Glue laminated timber Mass: kg

Figure 6.13: Screenshot showing ground floor slab & superstructure input sections

The input options for the upper floor systems are shown in Figure 6.14, these include: timber joists/floorboards, cross-laminated timber, pre-cast concrete, with or without topping, in-situ concrete, and composite deck. The dropdown options are the same as described before. The floorboard type can be chosen from the dropdown menu next to type, options: oriented strand board, particle board, plywood, sawn hardwood, and sawn softwood. If no topping is used the pre-cast concrete floor is considered suitable for design for deconstruction and subsequent reuse; as is the cross-laminated floor.



Upper Floor Systems:

Note cross-laminated and pre-cast (if no topping used) floors are considered suitable for DfD and subsequent reuse

☐ **No upper floors in structure**

☐ **Timber - joist/floorboards**

Joist type: Glue laminated timber Mass: kg

Floorboard type: Oriented Strand Board Mass: kg

☐ **Timber - cross-laminated flooring system**

Mass: kg

☐ **Pre-cast Concrete**

Concrete mix type: 100% Portland Cement - GEN 0 (6/8 MPa) kg

Reinforcement, steel sourced from: UK/EU Mass: kg

☐ Include topping, mix type: 100% Portland Cement - GEN 0 (6/8 MPa) kg

☐ **In-situ Concrete**

Concrete mix type: 100% Portland Cement - GEN 0 (6/8 MPa) kg

Reinforcement, steel sourced from: UK/EU Mass: kg

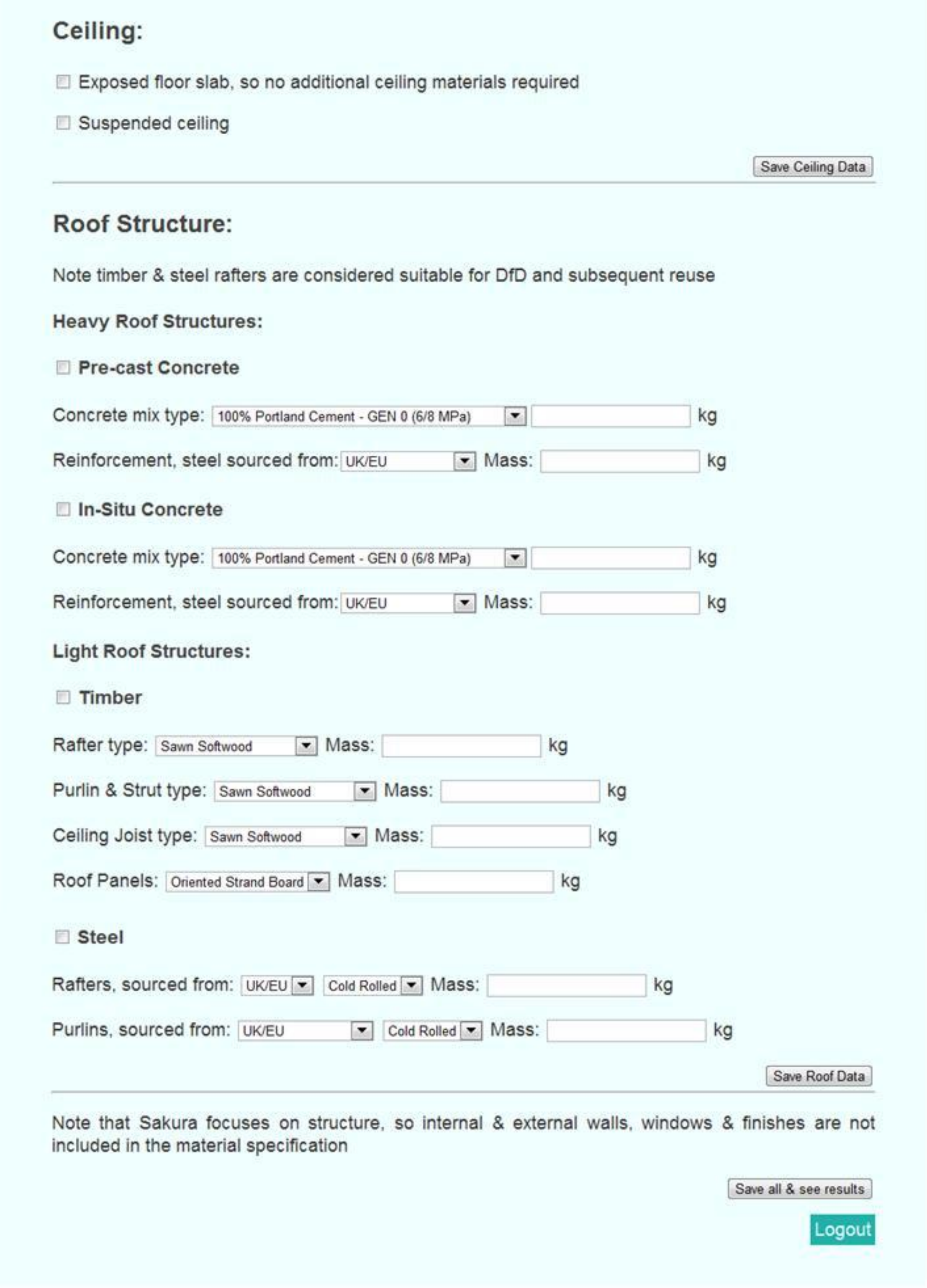
☐ **Composite Deck**

Concrete mix type: 100% Portland Cement - GEN 0 (6/8 MPa) kg

Steel Deck, sourced from: UK/EU Mass: kg

Figure 6.14: Screenshot of upper floor systems input section

The specification for the ceiling is simple: either an exposed floor slab is chosen, so there are no ceiling materials or a suspected ceiling is chosen, this can be seen in Figure 6.15. The roof material options are also shown in Figure 6.15 and are divided into two types: heavy and light roof structures. The heavy roof structures are pre-cast and in-situ concrete. The light roof structures are timber and steel. For the timber option rafters, purlins, struts, ceiling joists and roof panels can all be specified. The timber options for the rafters, purlins, struts and joists are sawn softwood, sawn hardwood and glue laminated timber. The roof panel options include: oriented strand board, particle board, plywood, sawn hardwood and sawn softwood. For the steel option, as well as specifying the source of the steel, it is necessary to select whether the steel is cold or hot rolled.



Ceiling:

☐ Exposed floor slab, so no additional ceiling materials required

☐ Suspended ceiling

Roof Structure:

Note timber & steel rafters are considered suitable for DfD and subsequent reuse

Heavy Roof Structures:

☐ **Pre-cast Concrete**

Concrete mix type: 100% Portland Cement - GEN 0 (6/8 MPa) kg

Reinforcement, steel sourced from: UK/EU Mass: kg

☐ **In-Situ Concrete**

Concrete mix type: 100% Portland Cement - GEN 0 (6/8 MPa) kg

Reinforcement, steel sourced from: UK/EU Mass: kg

Light Roof Structures:

☐ **Timber**

Rafter type: Sawn Softwood Mass: kg

Purlin & Strut type: Sawn Softwood Mass: kg

Ceiling Joist type: Sawn Softwood Mass: kg

Roof Panels: Oriented Strand Board Mass: kg

☐ **Steel**

Rafters, sourced from: UK/EU Cold Rolled Mass: kg

Purlins, sourced from: UK/EU Cold Rolled Mass: kg

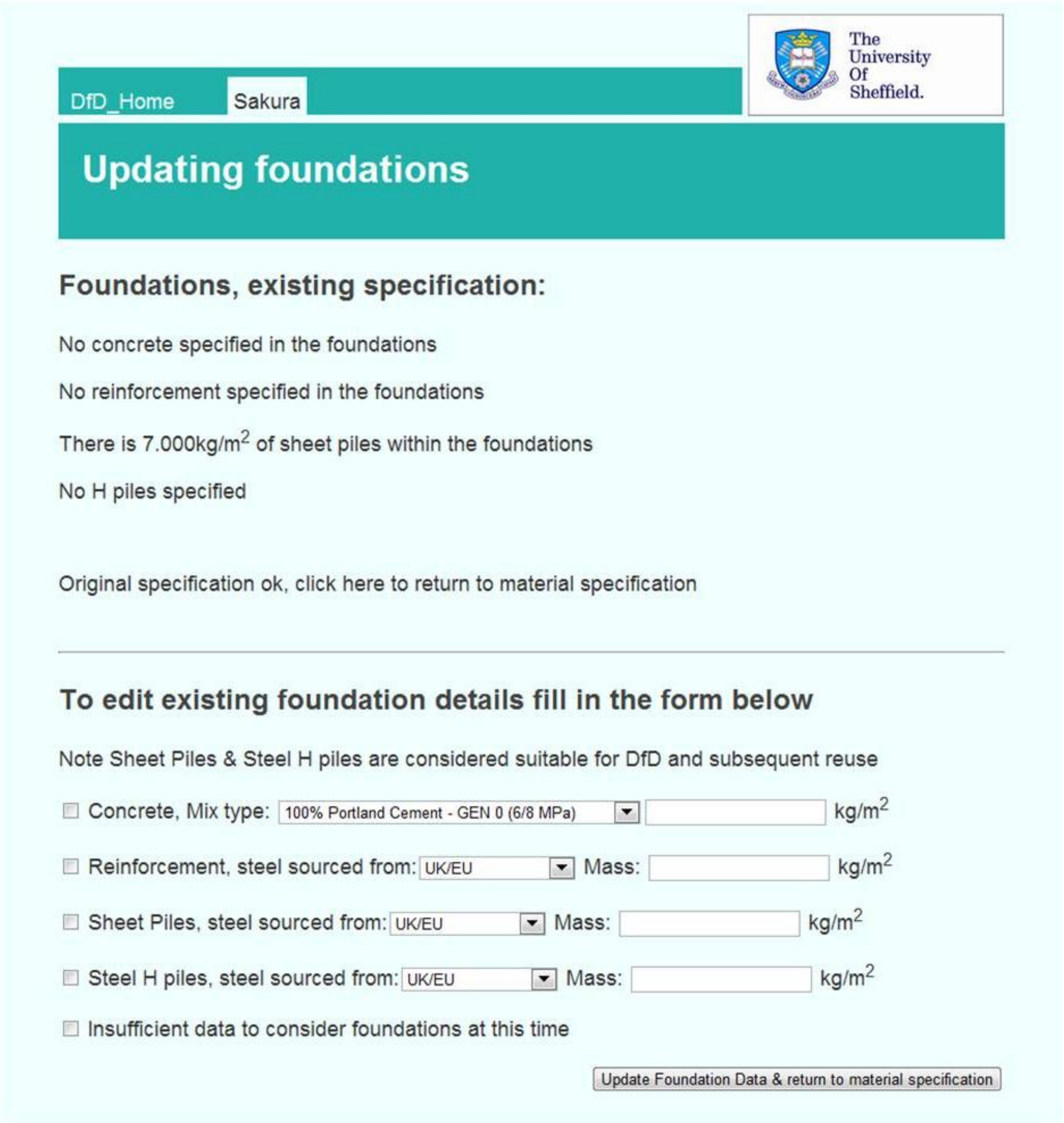
Note that Sakura focuses on structure, so internal & external walls, windows & finishes are not included in the material specification

Figure 6.15: Screenshot of ceiling and roof input sections

Once all the material specification has been input the user can click to see the results. The data is saved into a number of different tables, as described in section 6.2.

6.4.5 Editing Option

As each of the material specification steps is taken it is also possible to return to a saved section and edit it. Figure 6.16 shows the editing page for the foundations, there is an editing page as such for each of the different sections. These can be accessed at any time during the material specification stage and alterations made.



Updating foundations

Foundations, existing specification:

No concrete specified in the foundations

No reinforcement specified in the foundations

There is 7.000kg/m^2 of sheet piles within the foundations

No H piles specified

Original specification ok, click here to return to material specification

To edit existing foundation details fill in the form below

Note Sheet Piles & Steel H piles are considered suitable for DfD and subsequent reuse

☐ Concrete, Mix type: 100% Portland Cement - GEN 0 (6/8 MPa) kg/m^2

☐ Reinforcement, steel sourced from: UK/EU Mass: kg/m^2

☐ Sheet Piles, steel sourced from: UK/EU Mass: kg/m^2

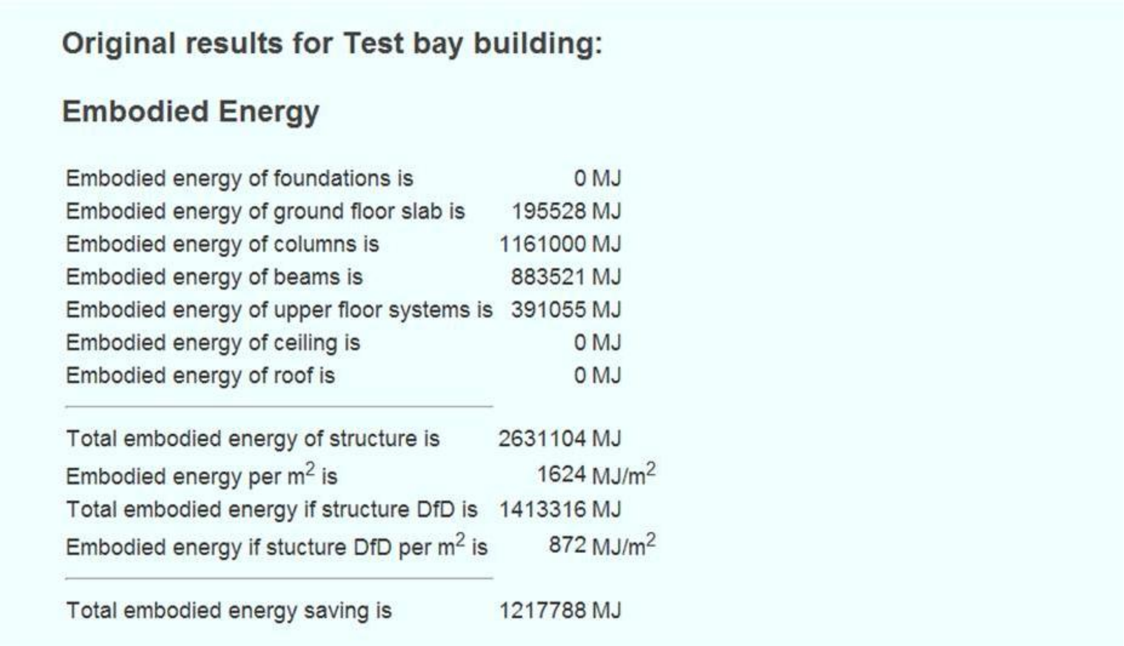
☐ Steel H piles, steel sourced from: UK/EU Mass: kg/m^2

☐ Insufficient data to consider foundations at this time

Figure 6.16: Screenshot of editing page for the foundations

6.4.6 Embodied Energy and Carbon Results Page

Once materials are specified results are available. The potential savings accrued by designing for deconstruction as well as embodied energy and carbon estimates are presented as in Figure 6.17 and Figure 6.18. If the user of Sakura considers the saving to be significant the design may be amended to facilitate deconstruction thereby potentially yielding construction products for reuse in the future. Quantifying savings for specific projects provides strong evidence for decision making and may help to influence designers and clients.

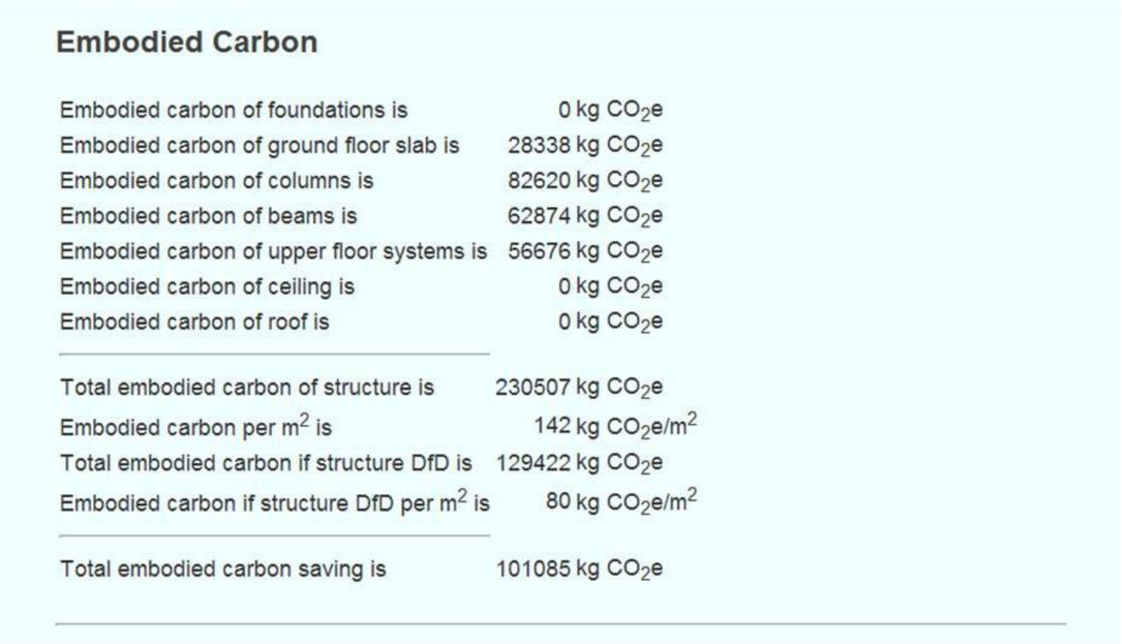


Original results for Test bay building:

Embodied Energy

Embodied energy of foundations is	0 MJ
Embodied energy of ground floor slab is	195528 MJ
Embodied energy of columns is	1161000 MJ
Embodied energy of beams is	883521 MJ
Embodied energy of upper floor systems is	391055 MJ
Embodied energy of ceiling is	0 MJ
Embodied energy of roof is	0 MJ
Total embodied energy of structure is	2631104 MJ
Embodied energy per m^2 is	1624 MJ/m^2
Total embodied energy if structure DfD is	1413316 MJ
Embodied energy if stucture DfD per m^2 is	872 MJ/m^2
Total embodied energy saving is	1217788 MJ

Figure 6.17: Screenshot showing example results for the Embodied Energy

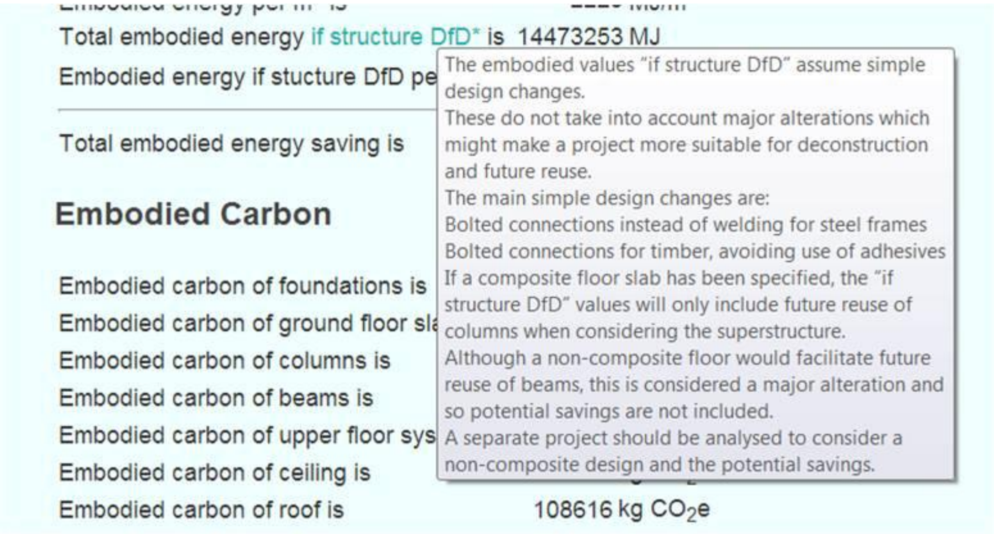


Embodied Carbon

Embodied carbon of foundations is	0 kg CO_2e
Embodied carbon of ground floor slab is	28338 kg CO_2e
Embodied carbon of columns is	82620 kg CO_2e
Embodied carbon of beams is	62874 kg CO_2e
Embodied carbon of upper floor systems is	56676 kg CO_2e
Embodied carbon of ceiling is	0 kg CO_2e
Embodied carbon of roof is	0 kg CO_2e
Total embodied carbon of structure is	230507 kg CO_2e
Embodied carbon per m^2 is	142 kg CO_2e/m^2
Total embodied carbon if structure DfD is	129422 kg CO_2e
Embodied carbon if structure DfD per m^2 is	80 kg CO_2e/m^2
Total embodied carbon saving is	101085 kg CO_2e

Figure 6.18: Screenshot showing example results for the Embodied Carbon

An explanation of what ‘if structure DfD’ means is given in a box that appears when the user hovers the mouse over ‘if structure DfD’, as illustrated in Figure 6.19. Essentially, ‘if structure DfD’ requires simple detailing changes, such as bolted connections rather than welds. It does not take into account major design changes, such as avoiding composite construction, as this would alter the structure design. To explore the benefits of non-composite over composite construction the user should run the two options through Sakura separately and compare the two results.



Total embodied energy if structure DfD* is 14473253 MJ

Embodied energy if stucture DfD pe

Total embodied energy saving is

Embodied Carbon

Embodied carbon of foundations is

Embodied carbon of ground floor sla

Embodied carbon of columns is

Embodied carbon of beams is

Embodied carbon of upper floor sys

Embodied carbon of ceiling is

Embodied carbon of roof is 108616 kg CO_2e

The embodied values "if structure DfD" assume simple design changes.
These do not take into account major alterations which might make a project more suitable for deconstruction and future reuse.
The main simple design changes are:
Bolted connections instead of welding for steel frames
Bolted connections for timber, avoiding use of adhesives
If a composite floor slab has been specified, the "if structure DfD" values will only include future reuse of columns when considering the superstructure.
Although a non-composite floor would facilitate future reuse of beams, this is considered a major alteration and so potential savings are not included.
A separate project should be analysed to consider a non-composite design and the potential savings.

Figure 6.19: Hover box explaining 'if structure DfD'

Once the results have been displayed it is expected that users will logout of Sakura, this ends the session. To see project details again login details have to be re-entered. Figure 6.20 shows the logout page that is displayed once users logout. The results are saved to the database and users can access these at a later date, see section 6.4.7 for more details. At the present time, if users want to save the results to their own computer a screenshot should be taken of the page and this saved. This ensures that the results are linked to Sakura. An alternative output may be developed for later versions of the tool, see recommendation within Chapter 9 for a discussion regarding future developments and alterations.

Sakura

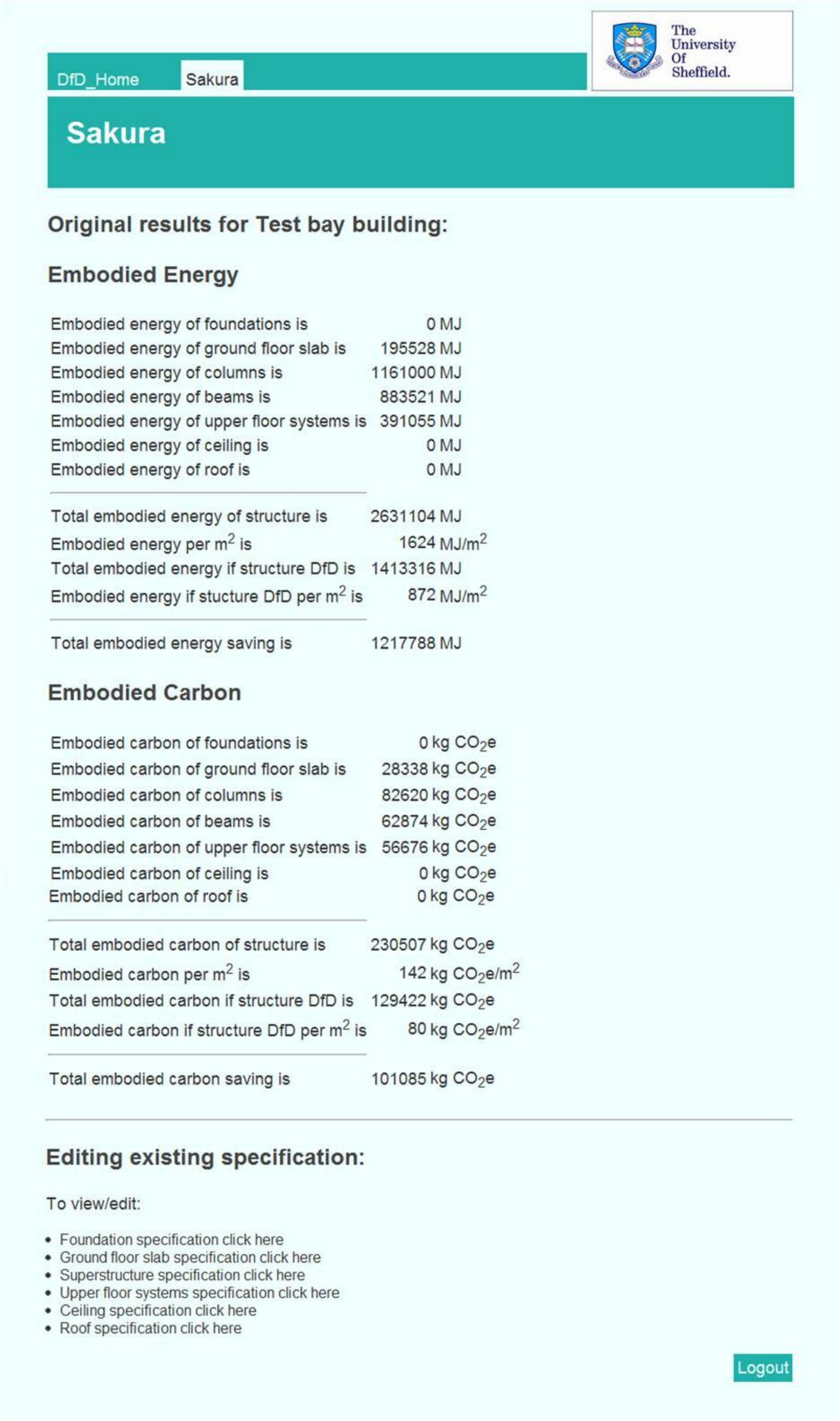
You have logged out of Sakura, to log back in click here

For more information contact: d.densleytingley@sheffield.ac.uk

Figure 6.20: Screenshot showing logout page

6.4.7 Accessing and Altering Existing Projects

Existing users may want to access projects they have already inputted into to Sakura, either to revisit results or to make alterations to projects that have progressed and changed during the design stage. As can be seen in Figure 6.8, when an existing user logs in, the names of their current projects are listed. By clicking on the project name an existing project can be accessed. This then shows the original results for the project and gives the option to edit the existing specification, as can be seen in Figure 6.21. The individual material specification areas can be selected for alteration. Figure 6.22 shows the page to update the foundations as an example. The existing specification is listed for information; in this case no foundations have been specified. If the user decides that this specification is correct then it is possible to click to return to the results page. Alternatively, new foundation information can be entered. The next step is either clicking to save the information and then see the updated results page, or saving the information and proceeding to edit the project. The latter option returns to the edit option page, shown in Figure 6.23, where users can then continue to edit different areas of the project. The former shows the new results in the same format as those shown in Figure 6.17 and Figure 6.18.



Sakura

Original results for Test bay building:

Embodied Energy

Embodied energy of foundations is	0 MJ
Embodied energy of ground floor slab is	195528 MJ
Embodied energy of columns is	1161000 MJ
Embodied energy of beams is	883521 MJ
Embodied energy of upper floor systems is	391055 MJ
Embodied energy of ceiling is	0 MJ
Embodied energy of roof is	0 MJ
Total embodied energy of structure is	2631104 MJ
Embodied energy per m^2 is	1624 MJ/m^2
Total embodied energy if structure DfD is	1413316 MJ
Embodied energy if stucture DfD per m^2 is	872 MJ/m^2
Total embodied energy saving is	1217788 MJ

Embodied Carbon

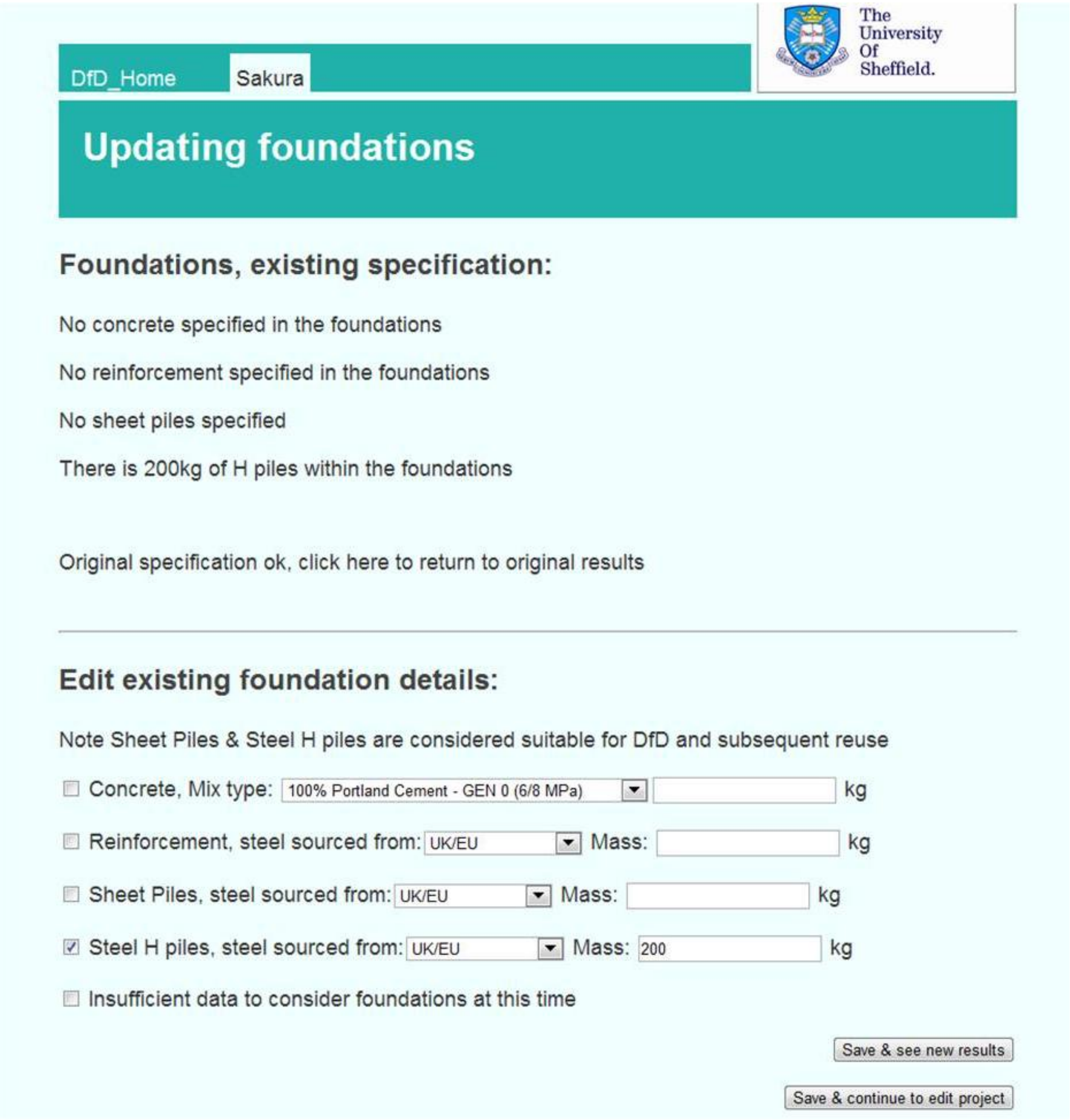
Embodied carbon of foundations is	0 kg CO_2e
Embodied carbon of ground floor slab is	28338 kg CO_2e
Embodied carbon of columns is	82620 kg CO_2e
Embodied carbon of beams is	62874 kg CO_2e
Embodied carbon of upper floor systems is	56676 kg CO_2e
Embodied carbon of ceiling is	0 kg CO_2e
Embodied carbon of roof is	0 kg CO_2e
Total embodied carbon of structure is	230507 kg CO_2e
Embodied carbon per m^2 is	142 kg CO_2e/m^2
Total embodied carbon if structure DfD is	129422 kg CO_2e
Embodied carbon if structure DfD per m^2 is	80 kg CO_2e/m^2
Total embodied carbon saving is	101085 kg CO_2e

Editing existing specification:

To view/edit:

- Foundation specification click here
- Ground floor slab specification click here
- Superstructure specification click here
- Upper floor systems specification click here
- Ceiling specification click here
- Roof specification click here

Figure 6.21: Screenshot showing existing project in Sakura and the option to edit the specification



Updating foundations

Foundations, existing specification:

No concrete specified in the foundations

No reinforcement specified in the foundations

No sheet piles specified

There is 200kg of H piles within the foundations

Original specification ok, click here to return to original results

Edit existing foundation details:

Note Sheet Piles & Steel H piles are considered suitable for DfD and subsequent reuse

☐ Concrete, Mix type: 100% Portland Cement - GEN 0 (6/8 MPa) kg

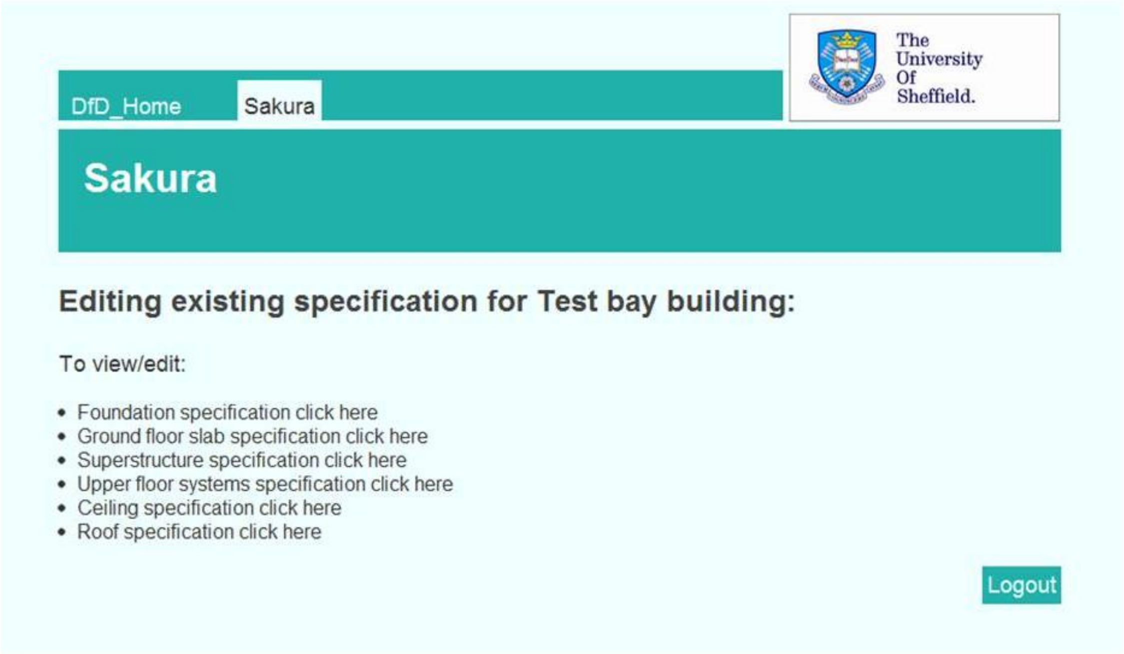
☐ Reinforcement, steel sourced from: UK/EU Mass: kg

☐ Sheet Piles, steel sourced from: UK/EU Mass: kg

☑ Steel H piles, steel sourced from: UK/EU Mass: 200 kg

☐ Insufficient data to consider foundations at this time

Figure 6.22: Screenshot showing the page to update information about the foundations



Sakura

Editing existing specification for Test bay building:

To view/edit:

- Foundation specification click here
- Ground floor slab specification click here
- Superstructure specification click here
- Upper floor systems specification click here
- Ceiling specification click here
- Roof specification click here

Figure 6.23: Screenshot showing options to edit the existing project

It is important to allow users to edit designs because is intended that Sakura be used at an early conceptual design stage, which means that it is likely that alterations will be made after projects have been initially modelled. As part of the design process designers may want to explore how these changes have affected the environmental impact of their project, therefore Sakura has been designed to facilitate this.

6.5 Pilot Trial of Sakura

In order to investigate the effectiveness of Sakura and its ease of use, it was trialled by a group of third students working on a group structural design project. In this case, Sakura was predominantly used as a tool to calculate the embodied carbon of designs; the exploration of the benefits of design for deconstruction was seen to be a secondary benefit. The students were given a short presentation on how to use Sakura and the benefits it might have for their work. As the students were working in groups, generally one student in each group made use of the tool to assess their designs. Some ran several different design solutions through it to compare which had the lowest embodied carbon.

After the students had completed their projects they were sent a questionnaire to gauge their opinions of Sakura. For a full discussion of the questions and results of the questionnaire see Appendix B3. The key points are discussed here. A large percentage of students had already included design for deconstruction within their projects, this may well be because they were lectured about the benefits of this strategy, which raised their awareness of it. However, of those that had not designed for deconstruction, all said that they would now incorporate this strategy having used Sakura and seen the benefits to their projects in terms of embodied energy and carbon savings. This demonstrates that Sakura is effective in altering peoples' opinions and shaping design decisions. All the students said that they were at least moderately likely to recommend use of Sakura to others and the majority found it a very useful tool. There were a few comments on problems within the software and these have been used to make improvements. However, feedback was generally positive, with one comment that 'this tool will be very useful for future work'.

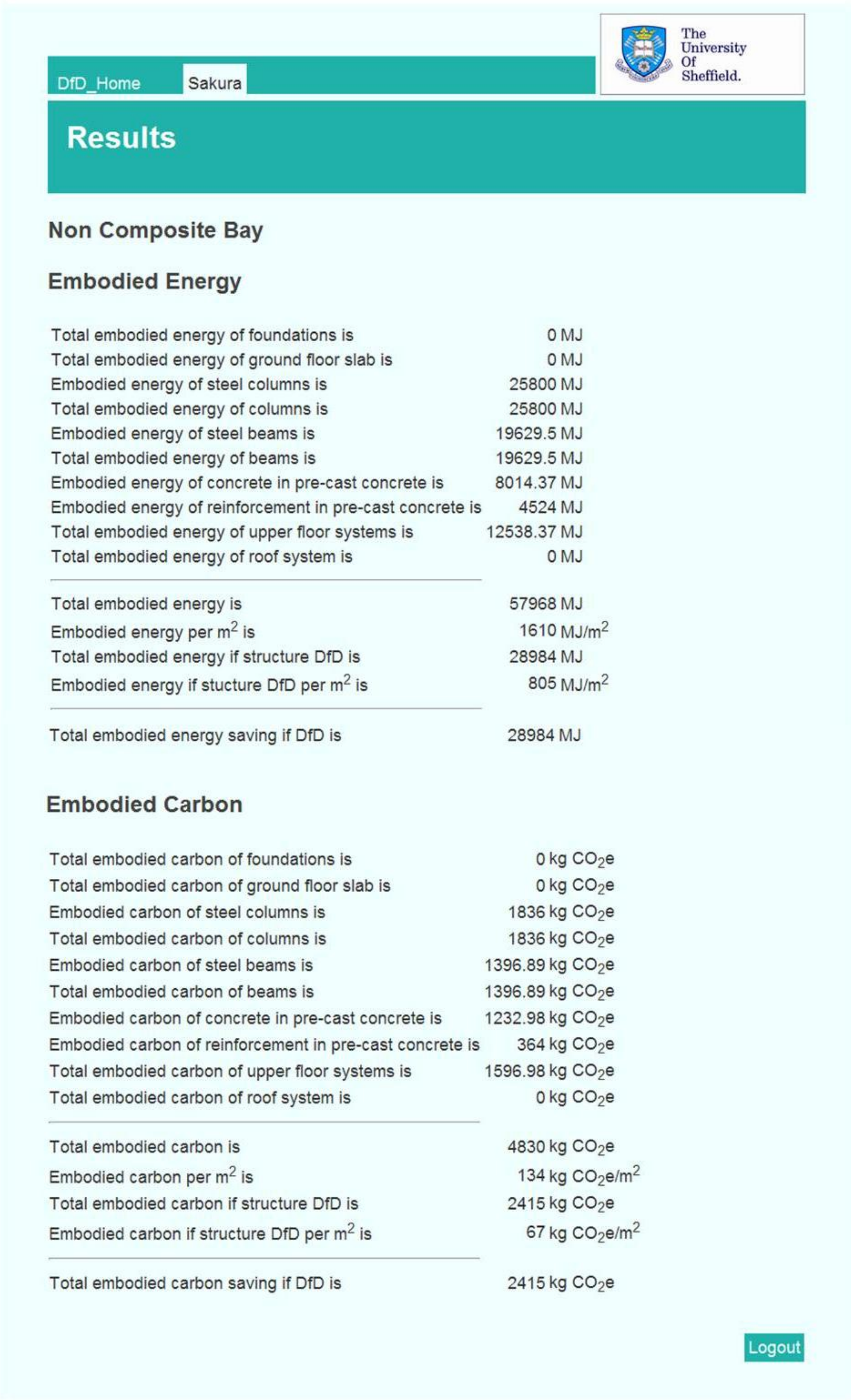
After this initial trial, two MSc students used Sakura as part of their dissertation projects. This was used both to assess embodied carbon of different design options and to explore potential benefits of design for deconstruction to alterative design options. Mammen (2012) used Sakura to great effect, exploring the embodied carbon of different structural types, identifying which of these benefit from design for deconstruction. This is precisely how Sakura was designed to be used, and work within this dissertation demonstrates the value of Sakura.

6.6 Validation of Sakura

In order to ensure that Sakura is running and processing information as expected a validation study was conducted. One of the test bays discussed in Chapter 5, a non-composite bay, was modelled and run within Sakura so that the results could be compared. A summary of the data from the spreadsheet calculation is shown in Table 6.2 and the results from Sakura shown in Figure 6.24.

Element	**Total Mass (kg)**	**EE (MJ)**	**EE if DfD (MJ)**	**EC (kg CO_2e)**	**EC if DfD (kg CO_2e)**
Beams	913.2	19633.8	9816.9	1397.196	698.598
Columns	1200	25800	12900	1836	918
Upper Floors: concrete	8807.339	8014.679	4007.339	1233.028	616.514
Upper Floors: reinforcement	260.098	4525.705	2262.852	364.137	182.069
Total	11181	57974	28987	4830	2415
Total per m^2	**311**	**1610**	**805**	**134**	**67**

Table 6.2: Spreadsheet calculation for the embodied values of non-composite bay



Results

Non Composite Bay

Embodied Energy

Total embodied energy of foundations is	0 MJ
Total embodied energy of ground floor slab is	0 MJ
Embodied energy of steel columns is	25800 MJ
Total embodied energy of columns is	25800 MJ
Embodied energy of steel beams is	19629.5 MJ
Total embodied energy of beams is	19629.5 MJ
Embodied energy of concrete in pre-cast concrete is	8014.37 MJ
Embodied energy of reinforcement in pre-cast concrete is	4524 MJ
Total embodied energy of upper floor systems is	12538.37 MJ
Total embodied energy of roof system is	0 MJ
Total embodied energy is	57968 MJ
Embodied energy per m^2 is	1610 MJ/m^2
Total embodied energy if structure DfD is	28984 MJ
Embodied energy if stucture DfD per m^2 is	805 MJ/m^2
Total embodied energy saving if DfD is	28984 MJ

Embodied Carbon

Total embodied carbon of foundations is	0 kg CO_2e
Total embodied carbon of ground floor slab is	0 kg CO_2e
Embodied carbon of steel columns is	1836 kg CO_2e
Total embodied carbon of columns is	1836 kg CO_2e
Embodied carbon of steel beams is	1396.89 kg CO_2e
Total embodied carbon of beams is	1396.89 kg CO_2e
Embodied carbon of concrete in pre-cast concrete is	1232.98 kg CO_2e
Embodied carbon of reinforcement in pre-cast concrete is	364 kg CO_2e
Total embodied carbon of upper floor systems is	1596.98 kg CO_2e
Total embodied carbon of roof system is	0 kg CO_2e
Total embodied carbon is	4830 kg CO_2e
Embodied carbon per m^2 is	134 kg CO_2e/m^2
Total embodied carbon if structure DfD is	2415 kg CO_2e
Embodied carbon if structure DfD per m^2 is	67 kg CO_2e/m^2
Total embodied carbon saving if DfD is	2415 kg CO_2e

Figure 6.24: Screenshot showing results of non-composite bay in Sakura

Both sets of results are calculated using the UK ICE dataset (Hammond & Jones, 2011) and the same material masses for the structural bay are input. Results for the columns, beam, concrete and reinforcement in the upper floor systems are comparable. This demonstrates that Sakura is processing information correctly and that results are reliable estimates for embodied energy and carbon.

It should be noted at this point that for the time being the ICE approach to using standard reinforcement factors for reinforcement strands within precast concrete (Hammond & Jones, 2011) is adopted within Sakura. Recommendation 9 suggests that a more accurate estimate for the embodied values of reinforcement strands needs to be calculated. Once this information is available, Sakura will be updated to reflect it.

6.7 Conclusions

A web-based tool, Sakura, has been developed to quantify the benefits of design for deconstruction for individual projects. It is designed to be quick and easy to use, quantifying the embodied energy and carbon for projects as well as computing the energy and carbon benefits of design for deconstruction, which no other tools of this type currently do. Importance is placed on designers being able to assess potential benefits of design for deconstruction at an early design stage; therefore a material input option is kg/m^2. There are many decisions to be made when designing holistically sustainable buildings and Sakura aims to raise awareness of the advantages of design for deconstruction and aid users in assessing the embodied energy and carbon savings that can occur using this tactic thus providing assistance in this step of the decision making process. There is an aspiration that use of Sakura within industry will increase the amount of projects that are designed for deconstruction, thereby increasing future supply chains of reused materials and advancing sustainability of the build environment.

Sakura has been used to explore the potential gains of design for deconstruction in several case studies to help to more conclusively identify materials and buildings types particularly suited to this design strategy. The subsequent chapter outlines these case studies and reports the results.

7 Case Studies

7.1 Introduction

The case study buildings, investigated during the course of this chapter, encompass a range of building types and different structural forms. Each building type includes a steel structural option because the feasibility studies presented in Chapter 5 demonstrated substantial savings when designing a steel structural bay for deconstruction. Steel is therefore investigated for each building type to explore if and how significant the savings shown for a single bay translate to savings on a whole structure. Sakura has been used to quantify the potential environmental benefits that occur from design for deconstruction, estimating the energy and carbon savings that are possible. This work is an extension of the feasibility studies in chapter 5 and explores the impact design for deconstruction can have on the structure of an entire building.

The material breakdown is shown in detail for the initial case study, a stadium, and reflects the process of collating the information from the construction drawings. It should be noted that Sakura is not designed to assess information at this stage of the design process as it would be too late to make design alterations and incorporate design for deconstruction. Collecting the level of detail available in construction drawings is time consuming and would not be recommended for designers. However, it was in this form that information was available for the stadium and a detailed study ensured that opportunities from design for deconstruction could be identified. Information for the subsequent case studies (from section 7.4 to section 7.7) was derived from bills of quantities prepared by others. Material information collated is shown in Appendix C. In this chapter, the emphasis is placed on analysing the results. Nine case studies are analysed in this way: two warehouses, three schools, two office buildings and two supermarkets.

7.2 Aims and Objectives

This chapter explores the embodied energy and carbon of a number of different case studies, quantifying the potential savings in these areas achieved by designing for deconstruction. An analysis of five different building types examines their suitability for design for deconstruction and identifies building types that benefit most from this strategy. Each of the building types is categorised into a material construction type so that the savings calculated can be assessed and the construction types appraised for their appropriateness with design for deconstruction. Furthermore, Sakura is used for each of the calculations thus further testing the software prior to release.

7.3 Stadium Case Study

7.3.1 Background

The 25,000-seat stadium is situated within England and was opened in 2002 and is home to both a football and a rugby club and also hosts concerts (Carr & Reynolds, 2007). It is an asymmetric bowl form with single tier stands on three sides and a two-tier main stand on the fourth. A gently sloping roof joins these, bridging the height difference with small increases between columns up to the apex. There are four stair towers which are situated outside the main footprint of the stadium to maximise space within. The structure uses a combination of composite construction and steel elements, more detail is given in section 7.3.2.

7.3.2 Methods & key data

Information for this case study has been collated from construction drawings, a summary for each element is shown in the subsequent sections.

7.3.2.1 Foundations

The foundations to the stadium are continuous flight auger (CFA) piles, with RC30 concrete. Pile caps are placed on top of these; loads are transferred from ground beams to the pile caps through to the piles. From construction drawings the number of piles was counted, see Table 7.1 for a summary. The length and reinforcement of the piles was determined by the sub-contractor so there was no detailed information regarding this, however the average pile length was 16.3m (Carr & Reynolds, 2007). This was used in combination with the cut off levels given on drawings to calculate the pile lengths. For the reinforcement in the piles an assumption has been made that minimal reinforcement would have been provided. From this data the mass of concrete and reinforcement in the piles has been calculated, see Table 7.1 for a summary and Appendix C1 for detailed calculations.

The piles are topped with pile caps, the materials in these have been included within the study. Table 7.1 summarises the number of pile caps within the different areas of the stadium and shows the quantities of concrete and steel reinforcement that are contained within the pile caps.

Piles and pile caps are both considered to be part of the foundations, these have been added together for input into Sakura, the total masses can be seen in Table 7.10.

Stand	**Quantity of Piles**	**Mass of Concrete in Piles (kg)**	**Mass of Rebar in Piles (kg)**	**Quantity of Pile Caps**	**Mass of Concrete in Pile Caps (kg)**	**Mass of Rebar in Pile Caps (kg)**
North	155	1014087	21836	102	489831	489831
East	194	1275468	27465	88	342171	342171
South	159	1040886	22413	99	486793	486793
West	364	2383215	51318	112	677048	677048
Total	872	5713657	123032	401	1995843	1995843

Table 7.1: Summary of information for piles and pile caps

7.3.2.2 Ground Beams

Dimensions of ground beams were taken from plan drawings and sections, from this the mass of concrete within the ground beams was calculated, which can be seen in Table 7.3. The reinforcement sizes, lengths and quantities were worked out from reinforced concrete detail drawings and schedules of reinforcement. A summary of the reinforcement in the different stands can be seen in Table 7.2 and in Table 7.3 it can be seen that reinforcement makes up 11% of the total mass within the ground beams. For the detailed calculations see Appendix C1.

Stand	**Mass (kg)**
East	34029
N & S East Corners	31464
North	20792
South	21368
North West Corner	14554
South West Corner	14414
West	49262
Perimeter & Stairs	50769
Total	**236654**

Table 7.2: Summary table showing mass of reinforcement within the ground beams

	Mass (kg)	% of total
Concrete	1872130	89
Reinforcement	236654	11
Total	2108784	100

Table 7.3: Masses of concrete and reinforcement in the ground beams

For input into Sakura the ground beams will be considered as part of the ground floor slab.

7.3.2.3 Ground Floor Slabs

The ground floor slabs are 200mm deep pre-cast units. The total area that these cover was calculated, then the volume and the mass of concrete required estimated, see Appendix C1 for the details. The mass of reinforcement was estimated in a similar manner, see Appendix C1 for full details, Table 7.4 shows the summary information. These units have a concrete topping, which prevents future reuse. However, this topping has not been included within the estimates of mass for the study due to uncertainty in the quantity used; whilst 50mm cover was specified, the depth of cover may be much greater in some areas due to the camber of the units.

Stand	Area of slab (m^2)	Mass, Concrete (kg)	Mass, Rebar (kg)
South	2576.400	787889.908	19848.586
Corners	2180.840	666923.547	16801.191
East	3089.683	944857.187	23802.918
North	2576.400	787889.908	19848.586
West	3596.874	1099961.468	27710.317
Total		**4287522**	**108012**

Table 7.4: Summary showing the mass of materials within the ground floor slab

7.3.2.4 Columns

Information about the columns was gathered from plan drawings showing column positions and from sections showing column heights, in places the column height had to be estimated using trigonometry as the information was not otherwise available.

The majority of the columns in the stadium are steel UC sections, however, on the perimeter of the main (west) stand the steel sections are encased in 1.2m of concrete and act compositely to support the high loads in this area. For aesthetic reasons the perimeter columns in the other stands are also encased in concrete, this is non-structural and half the diameter. Where the columns have been encased in concrete they are not suitable for reuse. It is not possible within Sakura to specify composite columns; therefore the results will be adjusted afterwards, reflecting the reduced reuse potential. This will be based on the estimates in Table 7.5 which shows the percentage of composite and non-composite columns, both by quantity and mass.

Column Type	Quantity	% of total	Mass of Steel (kg)	% of Mass total
Composite	93	25	91566	33
Non-composite	284	75	189144	67
Total	377	100	280710	100

Table 7.5: Inventory of columns in stadium, showing which are composite and non-composite

It can be seen from Table 7.5 that the majority of columns are non-composite. However, concrete contributes 86.4% of the total mass of materials within the columns, see Table 7.6.

	Mass (kg)	% of mass total
Steel Sections	280710	12.2
Concrete	1995186	86.4
Reinforcement	33394	1.4
Total	2309290	100

Table 7.6: Masses of Steel and Concrete Columns

7.3.2.5 Beams

The beams throughout the stadium are steel sections, the majority form part of a composite floor slab. Information regarding the beam type was gathered from plan drawings, the lengths were obtained from sections and steelwork elevations, although in some places, where dimensions were not given, estimations were calculated using trigonometry or by scaling off the drawing. See Appendix C1 for details on the beam types, quantities and where estimations have been used. The beams are situated on six different levels. All the stands have a lower concourse and lower terrace level, however in the west stand there is also a hospitality level, an upper concourse level, a plant room level and an upper terracing level. The beams work compositely with the slabs to support each of these floors. Cross bracing is included within the beam masses, in places this crosses several levels, for details on which bracing has been included on which level see Appendix C1. Table 7.7 shows a summary of the steel masses, for the detailed information see Appendix C1.

Level	**Mass (kg)**
Lower Concourse	357210
Lower Terracing	335779
Hospitality	82761
Upper Concourse	84764
Plant Room	42082
Upper Tier Terracing	86542
Stair Towers	68757
Total Mass of Beams	**1057895**

Table 7.7: Masses of Steel Beams within Stadium, showing the different levels they're situated on

7.3.2.6 Upper Floor Slabs

The upper floor slabs are composite construction, details of these were taken from plan drawings which outline the specification and details. Areas of the different parts of the slabs were calculated using dimensions from sections and geometrical equations. For the detailed breakdown, calculations and assumptions see Appendix C1. The composite slab is made up of six different elements, concrete, reinforcement mesh, metal deck, u-bars, shear studs and reinforcement, Table 7.8 shows the breakdown of the mass of each of these elements. From this it can be seen that the concrete makes up a substantial amount of the total mass, although the individual smaller elements will still have an impact once added together for the whole project and are therefore included within the study.

Stand/Level	Concrete (kg)	Mesh (kg)	Deck (kg)	U-Bars (kg)	Shear Studs (kg)	Rebar (kg)
South - LC	318368	3100	14480	720	885	3335
S/W Corner -LC	70983	691	3228	563	384	1590
West -LC	495667	4826	22544	1383	1605	6448
N/W Corner - LC	70983	691	3228	563	384	1590
North - LC	318368	3100	14480	720	885	3335
N/E Corner -LC	70983	691	3228	551	342	1060
East - LC	591711	5761	26912	1175	1241	5512
S/E Corner - LC	70983	691	3228	551	342	1060
Perimeter LC	N/A	N/A	N/A	N/A	4318	N/A
Hospitality Level	409155	3984	18609	829	1254	7266
Upper Concourse	285978	2785	13007	1755	631	5594
Plant Room	144195	1404	6558	928	287	1848
Perimeter -upper	N/A	N/A	N/A	N/A	2405	N/A
All	**2847372**	**27724**	**129505**	**9738**	**6068**	**23929**

Table 7.8: Summary table showing the mass breakdown within the floor slabs in different stands and different levels

7.3.2.7 Roof Structure

The roof structure is predominately made up of large steel sections, and steel purlins. There are also several A-frames which are found to the rear of the West Stand and two trusses, one of which to the upstand between the West and North stand roofs and the other to the upstand between the West and South stand roofs. Table 7.9 shows the mass of steel beams and the mass of steel purlins within the roof structure (the A-frames and trusses are included within this). The beams and purlins are kept separate as this is how they are input into Sakura. For the detailed workings see Appendix C1.

Element	Mass (kg)	% of Total
Beams	1076281	83.3
Purlins	216475	16.7
Total	1292756	100

Table 7.9: Summary table showing the masses of the roof beams and purlins

7.3.3 Mass Breakdown for the whole structure

A breakdown of the mass of the different elements that make up the structure is shown in Table 7.10. This shows the ground floor slab's substantial contribution to the total mass, 24.5% of the total. Elements with the potential for reuse, the columns and roof structure, make up less, 13.2% for the columns and only 7.4% for the roof structure. This data is shown graphically in Figure 7.1.

	Mass (kg)	Mass (tonnes)	% of Total
Piles	1041045	1041	5.9
Pile Caps	2383579	2384	13.6
Ground Beams	2108784	2109	12.0
Ground Floor Slabs	4287522	4288	24.5
Columns	2309290	2309	13.2
Beams	1057895	1058	6.0
Upper Floor Slabs	3044337	3044	17.4
Roof Structure	1292756	1293	7.4
Total	17525208	17525	100

Table 7.10: Mass breakdown of the different elements within the stadium, showing the contribution of each

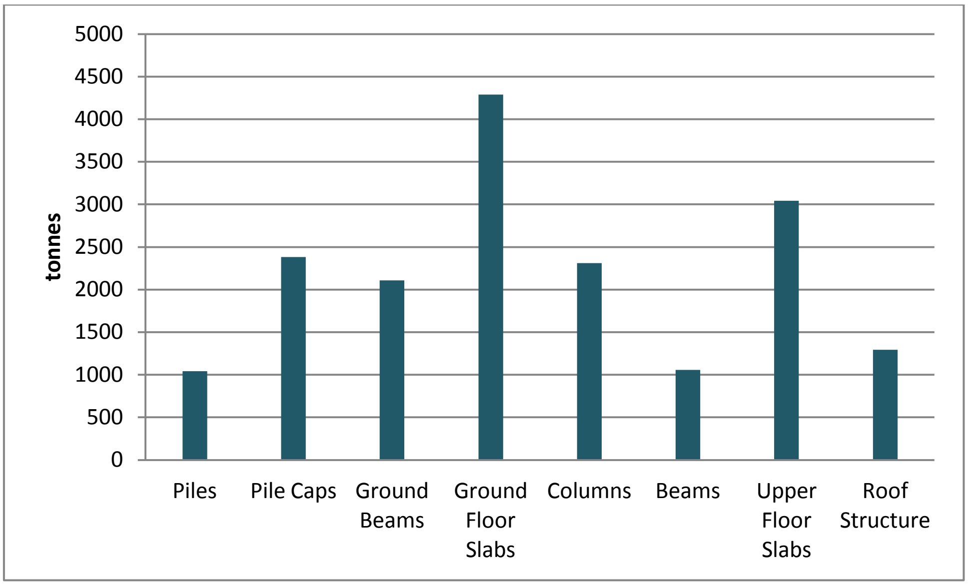


Figure 7.1: Mass breakdown of the different elements in the stadium

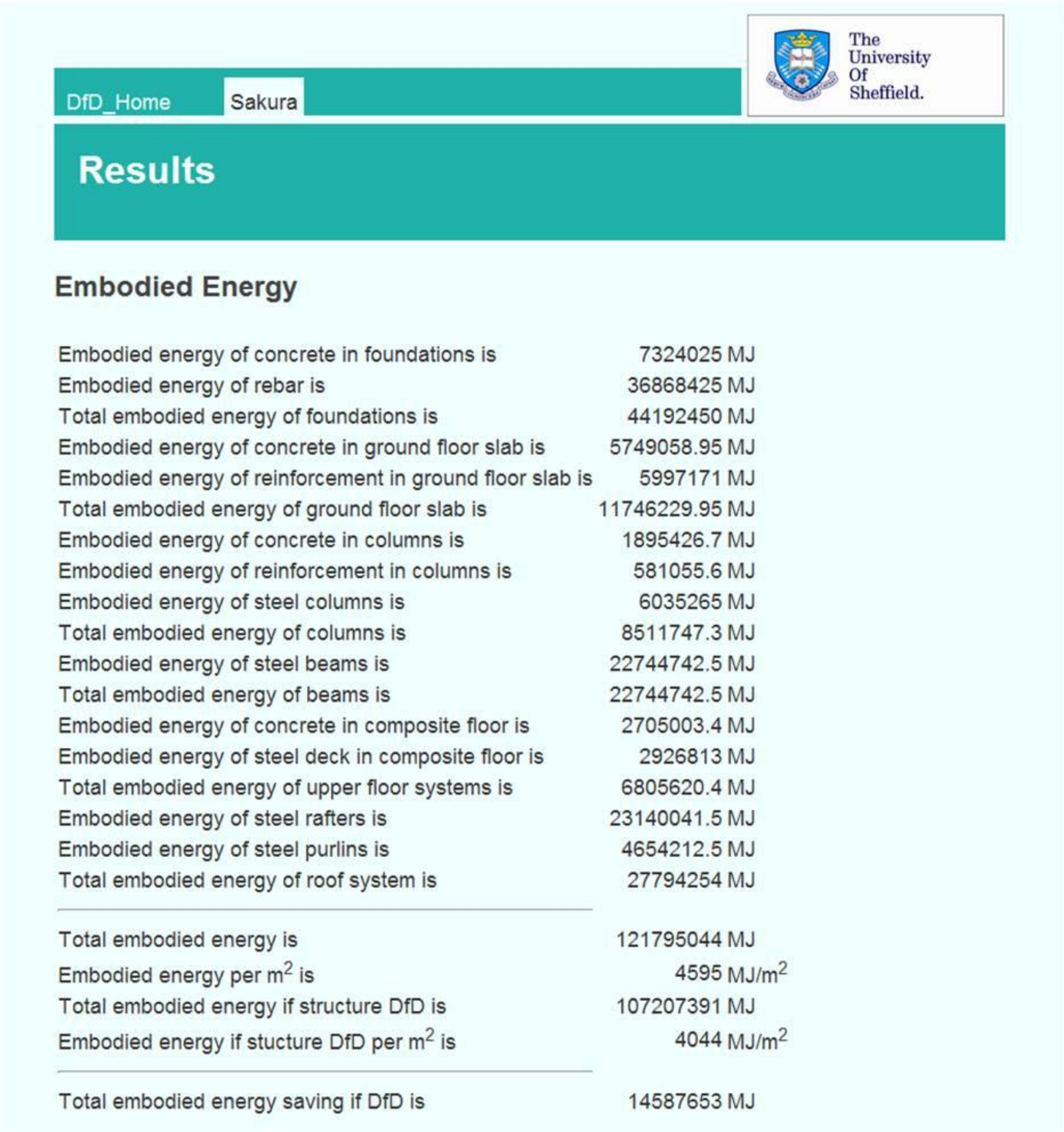
The different material contributions to the total mass are displayed in Table 7.11, showing that concrete makes up the majority of the mass at 78% of the total. This corresponds with those structural elements that make up a large percentage of the mass, they are generally concrete based.

	Mass (kg)	Mass (tonnes)	% of Total
Concrete	18603699	18604	78
Steel Sections	2631360	2631	11
Steel Reinforcement	2564394	2564	11
Total	23799453	23799	100

Table 7.11: Mass of different materials in the stadium

7.3.4 Utilising Sakura for the Stadium Case Study

All the structure details were input into Sakura, for screenshots of the input see Appendix C1. Screenshots of the results are shown in Figure 7.2 and Figure 7.3.

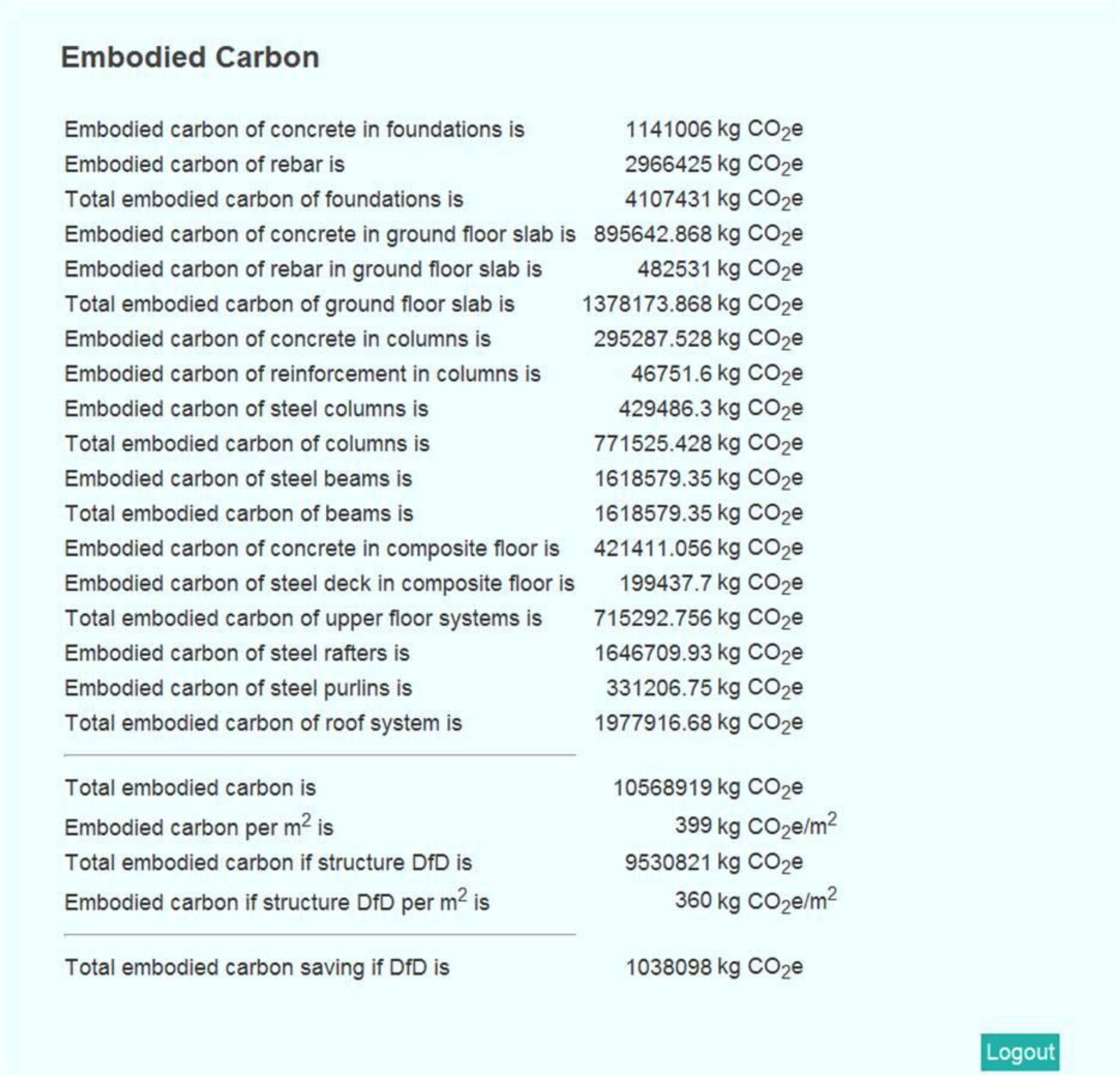


Results

Embodied Energy

Embodied energy of concrete in foundations is	7324025 MJ
Embodied energy of rebar is	36868425 MJ
Total embodied energy of foundations is	44192450 MJ
Embodied energy of concrete in ground floor slab is	5749058.95 MJ
Embodied energy of reinforcement in ground floor slab is	5997171 MJ
Total embodied energy of ground floor slab is	11746229.95 MJ
Embodied energy of concrete in columns is	1895426.7 MJ
Embodied energy of reinforcement in columns is	581055.6 MJ
Embodied energy of steel columns is	6035265 MJ
Total embodied energy of columns is	8511747.3 MJ
Embodied energy of steel beams is	22744742.5 MJ
Total embodied energy of beams is	22744742.5 MJ
Embodied energy of concrete in composite floor is	2705003.4 MJ
Embodied energy of steel deck in composite floor is	2926813 MJ
Total embodied energy of upper floor systems is	6805620.4 MJ
Embodied energy of steel rafters is	23140041.5 MJ
Embodied energy of steel purlins is	4654212.5 MJ
Total embodied energy of roof system is	27794254 MJ
Total embodied energy is	121795044 MJ
Embodied energy per m^2 is	4595 MJ/m^2
Total embodied energy if structure DfD is	107207391 MJ
Embodied energy if stucture DfD per m^2 is	4044 MJ/m^2
Total embodied energy saving if DfD is	14587653 MJ

Figure 7.2: Screenshot showing Embodied Energy results from Sakura for the Stadium case study


Embodied Carbon

Embodied carbon of concrete in foundations is	1141006 kg CO_2e
Embodied carbon of rebar is	2966425 kg CO_2e
Total embodied carbon of foundations is	4107431 kg CO_2e
Embodied carbon of concrete in ground floor slab is	895642.868 kg CO_2e
Embodied carbon of rebar in ground floor slab is	482531 kg CO_2e
Total embodied carbon of ground floor slab is	1378173.868 kg CO_2e
Embodied carbon of concrete in columns is	295287.528 kg CO_2e
Embodied carbon of reinforcement in columns is	46751.6 kg CO_2e
Embodied carbon of steel columns is	429486.3 kg CO_2e
Total embodied carbon of columns is	771525.428 kg CO_2e
Embodied carbon of steel beams is	1618579.35 kg CO_2e
Total embodied carbon of beams is	1618579.35 kg CO_2e
Embodied carbon of concrete in composite floor is	421411.056 kg CO_2e
Embodied carbon of steel deck in composite floor is	199437.7 kg CO_2e
Total embodied carbon of upper floor systems is	715292.756 kg CO_2e
Embodied carbon of steel rafters is	1646709.93 kg CO_2e
Embodied carbon of steel purlins is	331206.75 kg CO_2e
Total embodied carbon of roof system is	1977916.68 kg CO_2e
Total embodied carbon is	10568919 kg CO_2e
Embodied carbon per m^2 is	399 kg CO_2e/m^2
Total embodied carbon if structure DfD is	9530821 kg CO_2e
Embodied carbon if structure DfD per m^2 is	360 kg CO_2e/m^2
Total embodied carbon saving if DfD is	1038098 kg CO_2e

Figure 7.3: Screenshot showing Embodied Carbon results from Sakura for the stadium case study

The only elements that would be suitable for design for deconstruction and future reuse are the majority of the columns and the roof rafters. By designing these elements with bolted connections instead of welding it would be much easier to reuse them in the future. It is these assumptions that the savings are based on. Whilst dramatically altering the design would enable the beams to also be reused, users would need to explore this in a separate study as it is not possible in the current design. Nevertheless, even only reusing columns and rafters, the potential savings are substantial.

7.3.5 Exploration and Discussion of Results

The estimates produced using Sakura are presented in a number of graphs to visually demonstrate where the savings are. Elements with high embodied energy/carbon are also highlighted within these graphs. The saving achieved by designing the columns for deconstruction is adjusted to account for the columns that are composite construction and therefore could not be reused.

Figure 7.4 shows a breakdown of the impacts of the different structural elements for both the embodied energy and carbon. The reinforcement within the foundations makes the biggest contribution to both, with the beams and roof rafters making significant impacts as well. The roof rafters show substantial savings in the DfD design and the steel columns also show some savings. Greater savings could be accrued by altering some of the design to better facilitate design for deconstruction, this is discussed further in Chapter 8, section 8.4.2.

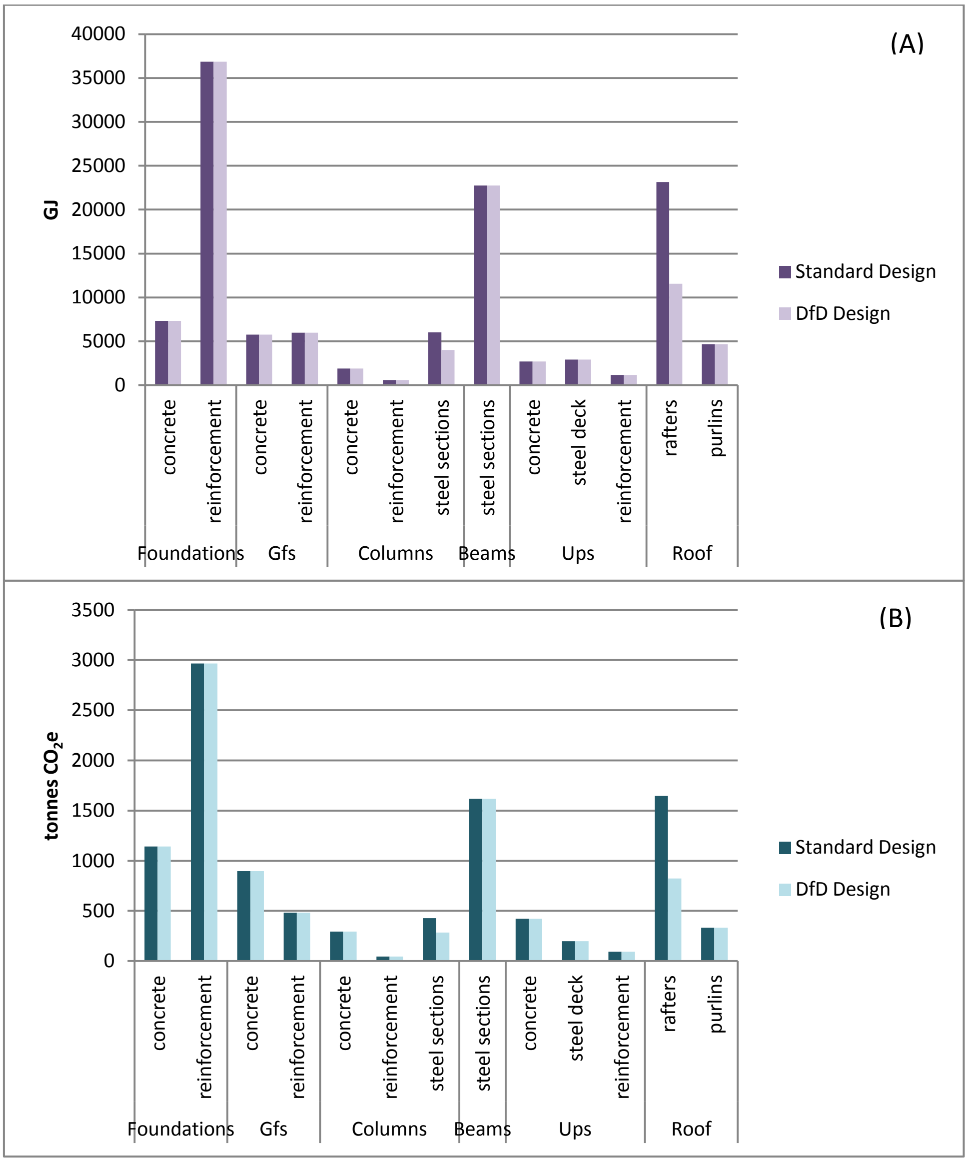


Figure 7.4: Potential savings from design for deconstruction for the individual elements, embodied energy shown in (A) and embodied carbon in (B)

Grouping the materials together into different structural elements it can be seen (Figure 7.5) that the foundations have the greatest impact, then the roof structure, followed closely by the beams. The roof structure benefits from design for deconstruction and for the whole structure a saving of 39 kg CO_2e/m^2 could be achieved through simple design changes to allow for future reuse. The total potential saving amounts to 1000 tonnes of CO_2e which is significant, particularly as this only involves reusing roof rafters and the majority of the columns. Analysing the material breakdown (Figure 7.6) it is the steel sections that provide the benefit from design for deconstruction but no other material types.

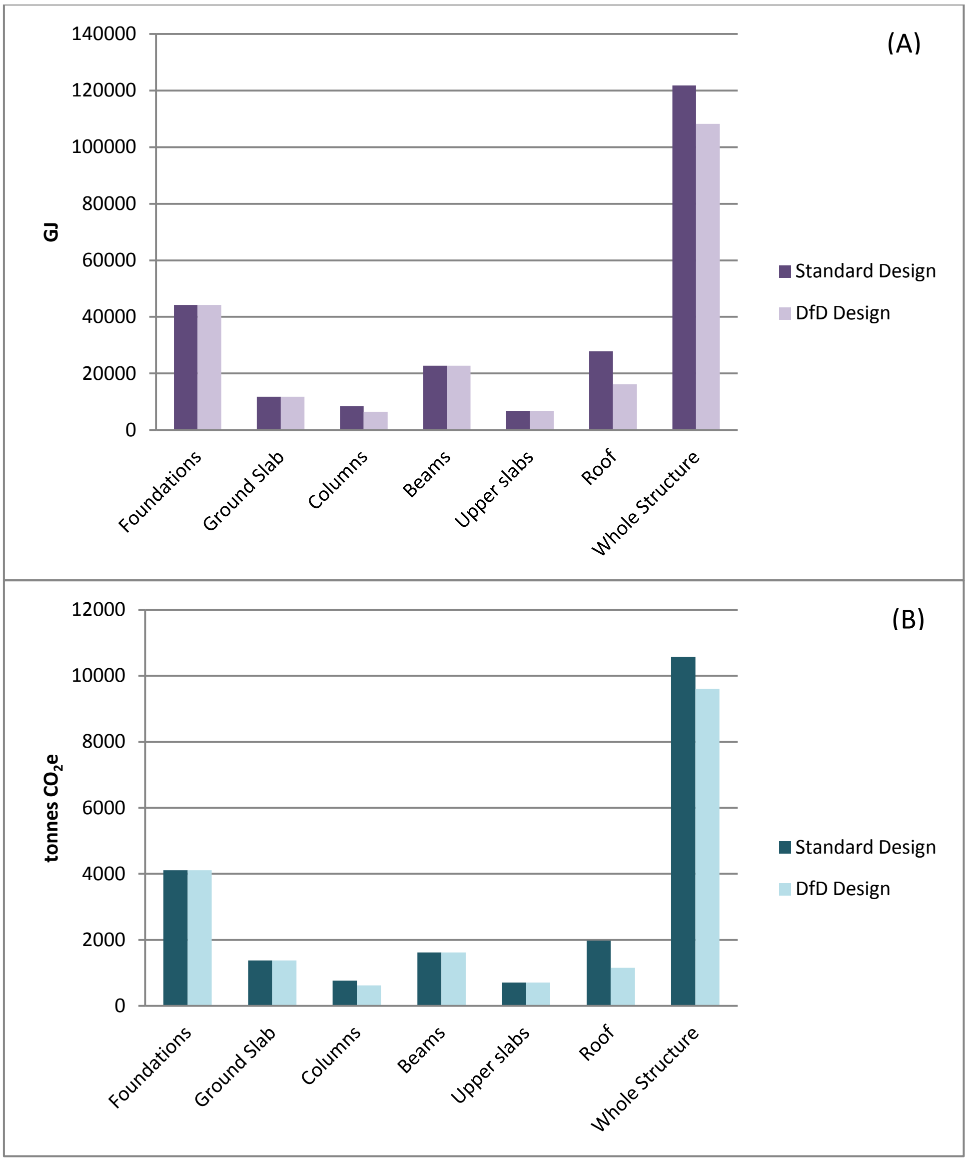


Figure 7.5: Stadium - embodied energy (A) and embodied carbon (B) of the different structural elements showing which benefit for DfD savings

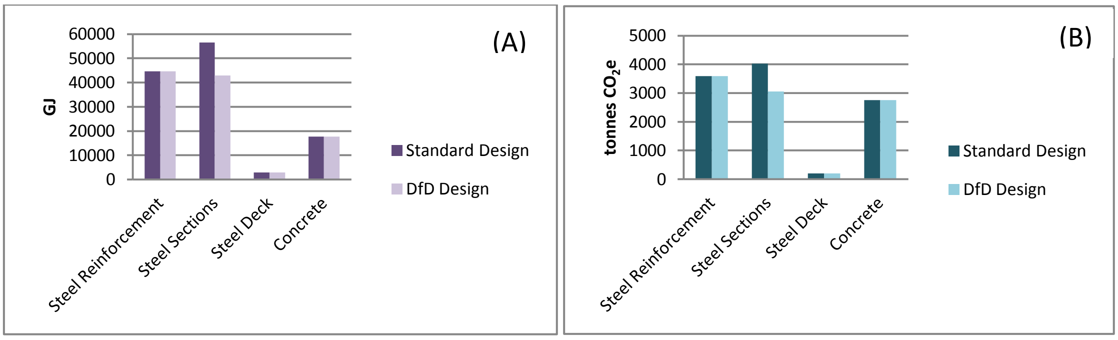


Figure 7.6: The impact of design for deconstruction on different material types, embodied energy shown in (A) and embodied carbon in (B)

In conclusion, whilst the stadium design does not particularly lend itself to design for deconstruction the savings are still significant. This is likely due to the large material quantities within the project and is influenced by the structure providing the majority of materials within the stadium. It is not possible to assess if the embodied energy and carbon figures per m^2 are reasonable as there are no benchmarks of this type for stadiums. Developing benchmarks as guidelines for designers therefore forms Recommendation 3, in Chapter 9.

7.4 Warehouse Case Studies

Both warehouse case studies are based on the same building footprint but incorporate different structural types. The majority of the building forms a large warehouse, with office space contained in the back of house. The total internal floor area amounts to 34,000m^2; the space is predominantly single storey, although the office area is two storeys. Both options are supported on pad foundations and are steel clad. (Target Zero, 2011).

7.4.1 Warehouse 1, steel frame

The first design consists of a portal steel frame structure in both the warehouse space and the office area. The upper floor in the office space is constructed from pre-cast concrete units (Target Zero, 2011). For a breakdown of material masses see Appendix C2. The superstructure in this design is ideal for design for deconstruction, both the steel frame and pre-cast units can be designed appropriately for future reuse. In-situ topping should be avoided for the pre-cast units to maximise reuse.

7.4.2 Warehouse 2, concrete & timber frame

The second design uses pre-cast concrete columns and beams for the structure throughout the warehouse and office spaces. However, glulam beams are used for the roof structure. Foundations and ground floor slab design are the same as option 1 (Target Zero, 2011). The masses input into Sakura can be found in Appendix C2. Within the superstructure only the glulam beams would be suitable for design for deconstruction and future reuse. Using bolted connections and avoiding the use of adhesives will facilitate this reuse.

7.4.3 Results

An overview of results is presented in this section, the two design options are compared and standard designs versus DfD designs are also evaluated. Screenshots showing the input and output from Sakura can be examined in Appendix C2.

7.4.3.1 Comparison of Options

Table 7.12 displays the results from Sakura, showing the two warehouse options side by side. Graphs visually comparing results can be found from Figure 7.7 to Figure 7.10.

		Warehouse, steel frame		Warehouse, concrete frame	
Element	**Material**	**EE (MJ)**	**EC (kg CO2e)**	**EE (MJ)**	**EC (kg CO2e)**
Foundations	**Concrete**	1421109	224894	2062666	326422
	Reinforcement	766313	61657	983239	79111
	Total	2187422	286551	3045905	405533
GFS	**Concrete**	14426149	2282973	14426149	2282973
	Reinforcement	1493303	120151	1493303	120151
	Total	15919452	2403124	15919452	2403124
Columns	**Steel Sections**	9235777	657244		
	PCC concrete			1476017	237172
	PCC reinforcement			1155325	92957
	Total	9235777	657244	2631342	330129
Beams	**Steel Sections**	276533	19679		
	PCC concrete			67503	10847
	PCC reinforcement			52844	4252
	Total	276533	19679	120347	15098
UPS	**Concrete**	226216.8	35799	226217	35799
	Reinforcement	93838.2	7550	93838	7550
	Total	320055	43350	320055	43350
Roof	**Steel Rafters**	9235766	657243		
	Timber Rafters			17776438	622175
Total for the Structure		37175004	4067190	39813539	3819409
Standard Design	**per m2**	1106	125	1125	108
Total if structure DfD		27640939	3728582	30765292	3486647
DfD Design	**per m2**	836	105	869	98
Total saving if structure DfD		9534065	688757	9048247	332762

Table 7.12: Embodied energy and carbon results from Sakura for the two warehouse options

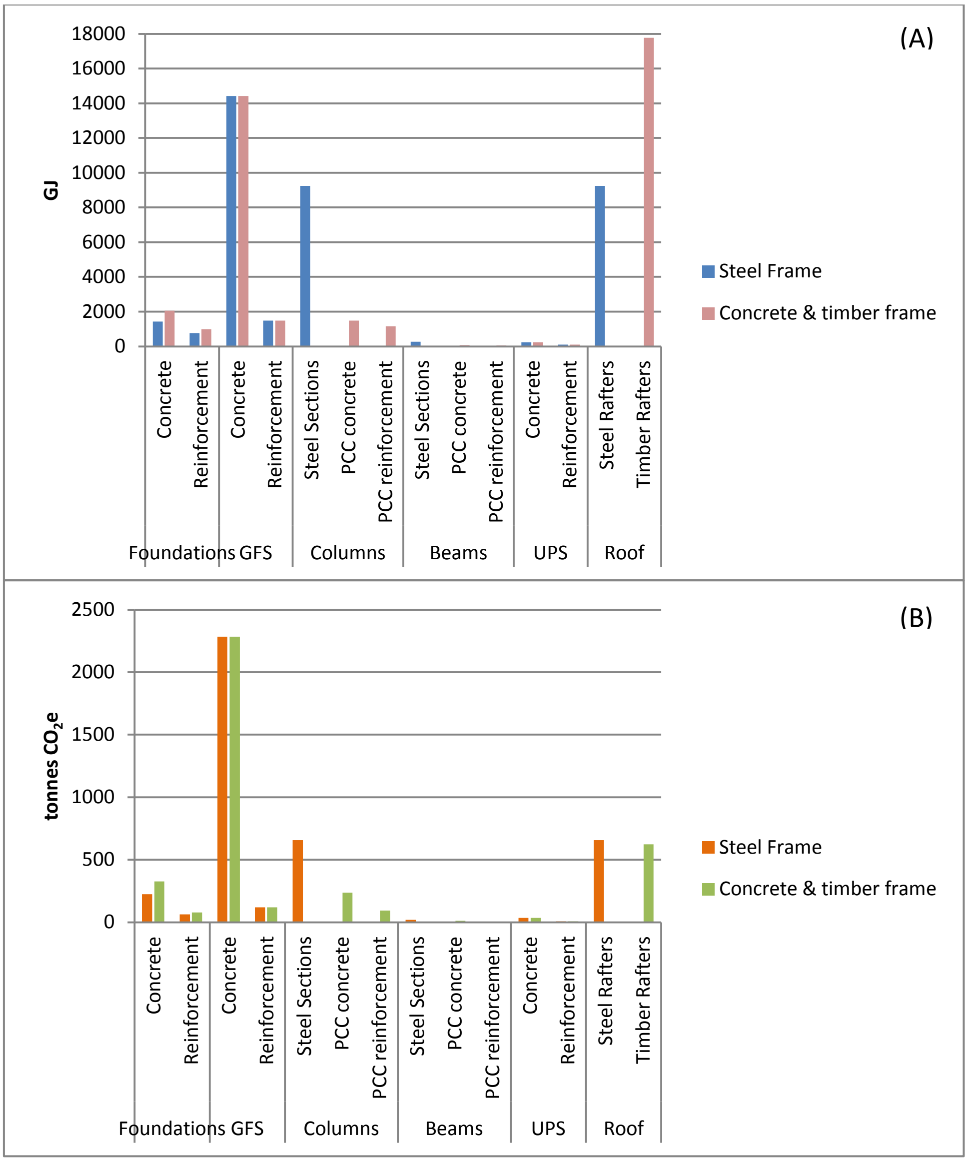


Figure 7.7: Comparison of the 2 standard warehouse design options, (A) shows embodied energy, (B) embodied carbon

In the standard warehouse design (Figure 7.7) the timber rafters have the most impact on the embodied energy of the components in both options. This is closely followed by that of the concrete in the ground floor slab. The latter has a significantly larger impact on the embodied carbon compared to all other elements. The beams and upper floor systems have a negligible effect on the system as a whole. The DfD designs (Figure 7.8) show a similar pattern in the results, but the concrete in the ground floor slab has a proportionally higher impact on both the embodied energy and carbon. The huge impact of the ground floor slab in both designs highlights this as a potential area to target for reduction. A study exploring strategies and alternative designs for ground floor slabs forms Recommendation 12, in Chapter 9.

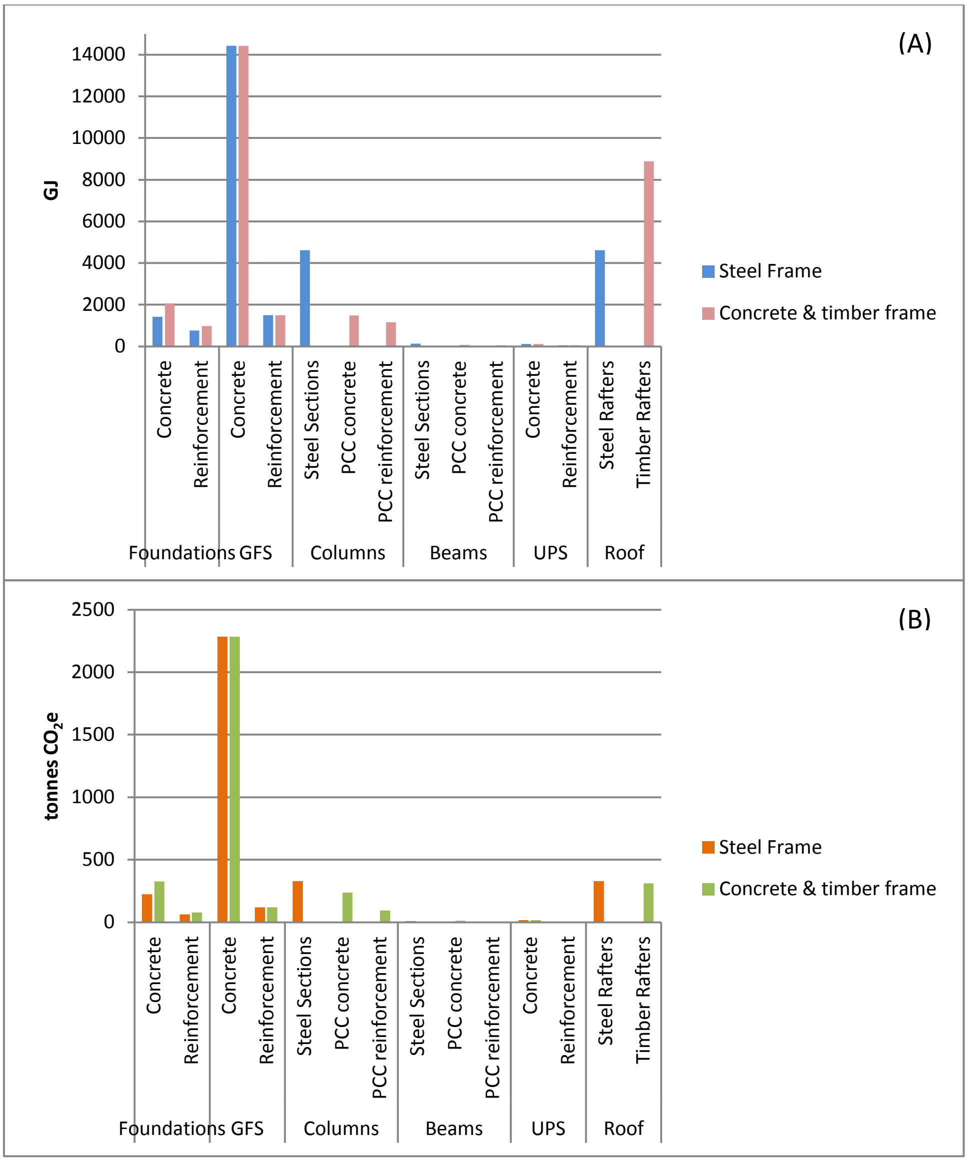


Figure 7.8: Comparison of the 2 warehouse DfD design options, (A) shows embodied energy, (B) embodied carbon

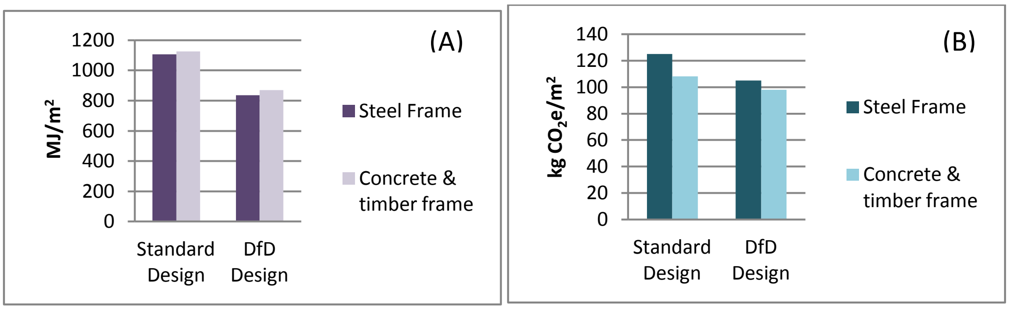


Figure 7.9: Comparison of warehouse options, embodied energy in (A), and embodied carbon in (B)

The concrete & timber frame has a slightly higher embodied energy than the steel frame, as seen in Figure 7.9. The situation is reversed for the embodied carbon with the concrete & timber frame being lower than the steel frame. This reversal is mainly due to the timber roof rafters which have a higher embodied energy than relative embodied carbon when the different elements are compared. As for the stadium case study, there is little benchmark data to compare these per m^2 estimations for the structure of a warehouse, emphasising the importance of developing this, see Recommendation 3 for details. A Faithful+Gould carbon calculator suggests the embodied carbon should fall within a range from 13940 tonnes CO_2e to 9758 tonnes CO_2e for the whole warehouse (Faithful + Gould, 2012). Sakura estimates 4067 tonnes CO_2e for the standard design and 3378 tonnes CO_2e for the DfD design of the structure. Both of these fall significantly below the suggested range. However, Sakura estimates are for the structure, whereas the carbon calculator estimates are for the whole building, including cladding, roofing and internal finishes.

The steel frame incurs significant benefits from design for deconstruction when compared to the concrete and timber frame (Figure 7.10), this is the case for both the embodied energy and carbon. However, the savings for both are significant ranging from around 330 tonnes of CO_2e to nearly 700 tonnes of CO_2e.

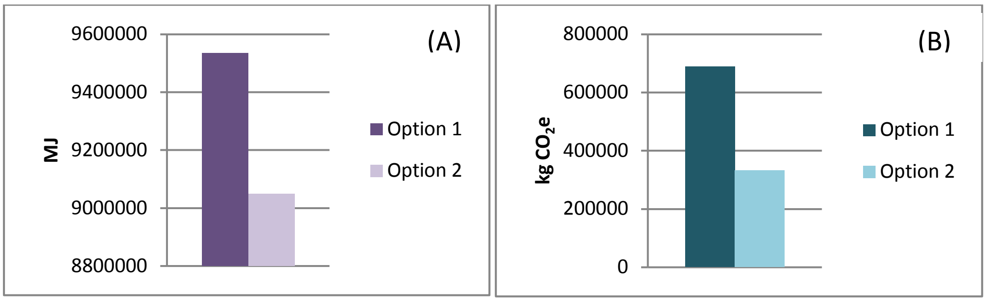


Figure 7.10: Potential savings from DfD of the warehouse options, (A) shows embodied energy, (B) embodied carbon

The potential savings accrued from design from deconstruction suggest that warehouses as a building type benefit from this strategy and that it should be integrated within more designs.

7.4.3.2 Standard versus DfD design

This section explores which elements within the design options benefit most from design for deconstruction.

7.4.3.2.1 Option 1, steel frame

The ground floor slab makes the largest contribution to both the embodied energy and carbon, followed by the roof and columns. Figure 7.11 shows that both the roof and columns benefit from design for deconstruction and displays the overall benefit when the DfD design is compared to the standard design. Figure 7.12 shows the breakdown for the different materials, the steel sections make the most impact to the embodied energy, but also show significant benefits from design for deconstruction. The concrete contributes most to the embodied carbon and the steel section input is considerably reduced by design for deconstruction.

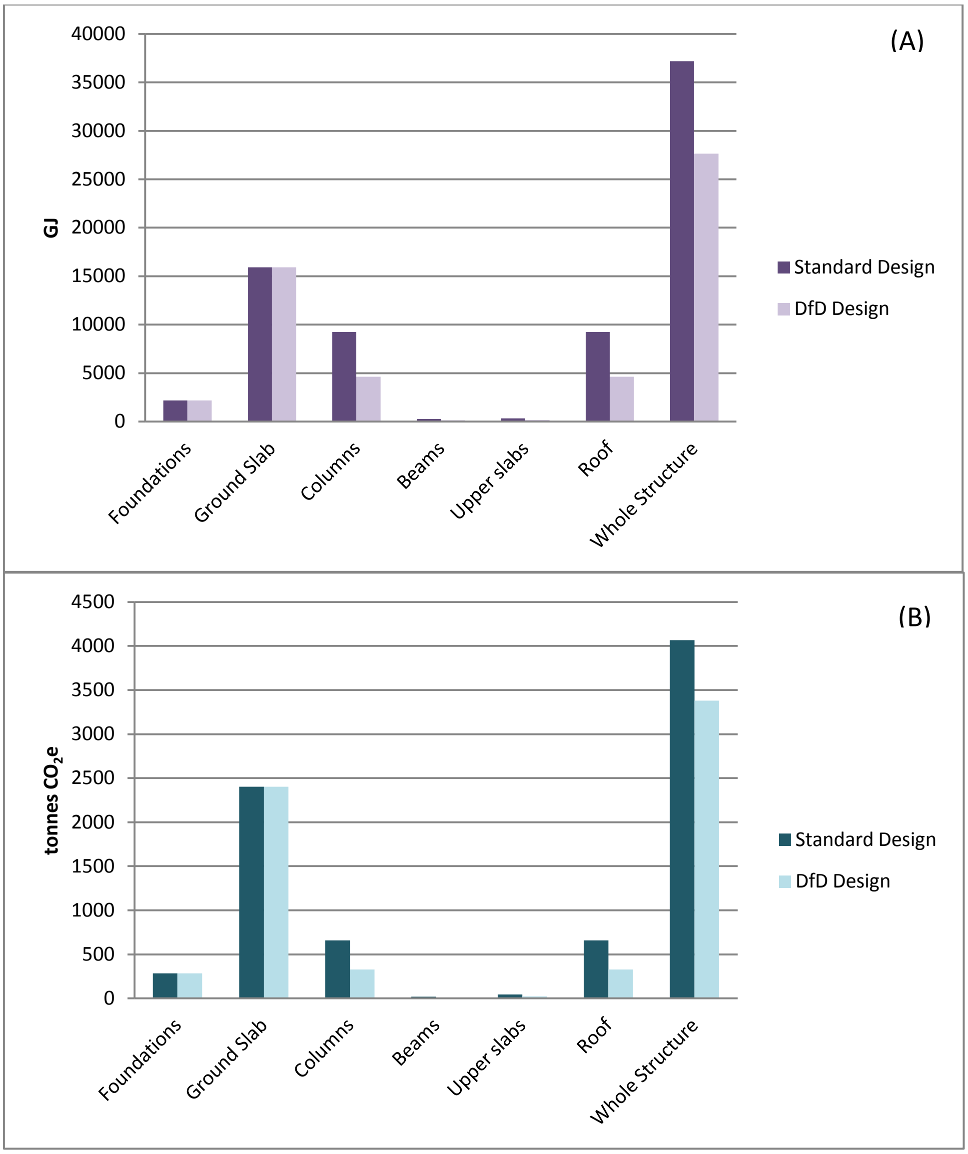


Figure 7.11: Warehouse, steel frame option, distribution of embodied energy (A) and embodied carbon (B) for the structural elements

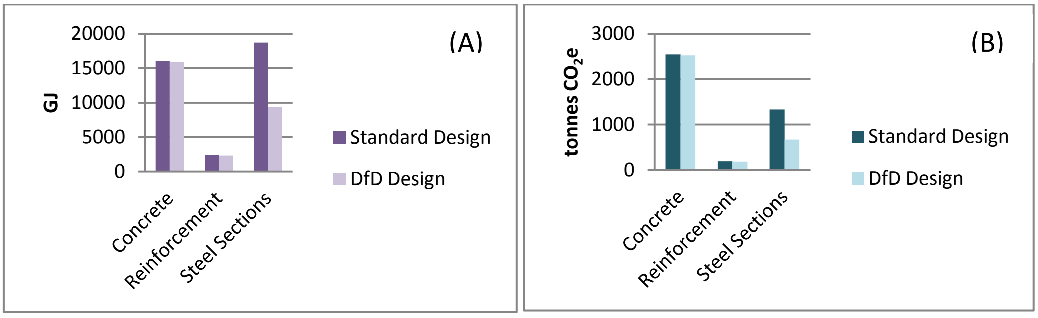


Figure 7.12: Warehouse, steel frame option, distribution of embodied energy (A) and embodied carbon (B) for different material types

From this case study it has emerged that steel framed warehouses with precast upper floors benefit significantly from design for deconstruction. If solely the superstructure is considered, a 50% reduction in the embodied carbon can be achieved.

7.4.3.2.2 Option 2, concrete & timber frame

For this option the roof has the largest impact for the embodied energy, although this reduced significantly through design for deconstruction. The ground slab has a significant impact to the embodied energy and is the highest contributor to the embodied carbon, whereas the roof does not have as high an impact here. Exploring the different materials used it can be seen (Figure 7.14) that concrete and timber have equal impacts on the embodied energy, but only timber benefits from design for deconstruction which substantially reduces its embodied energy. Concrete makes the biggest contribution to the embodied carbon. The impact of timber in the DfD design is almost reduced to the same as that of the reinforcement.

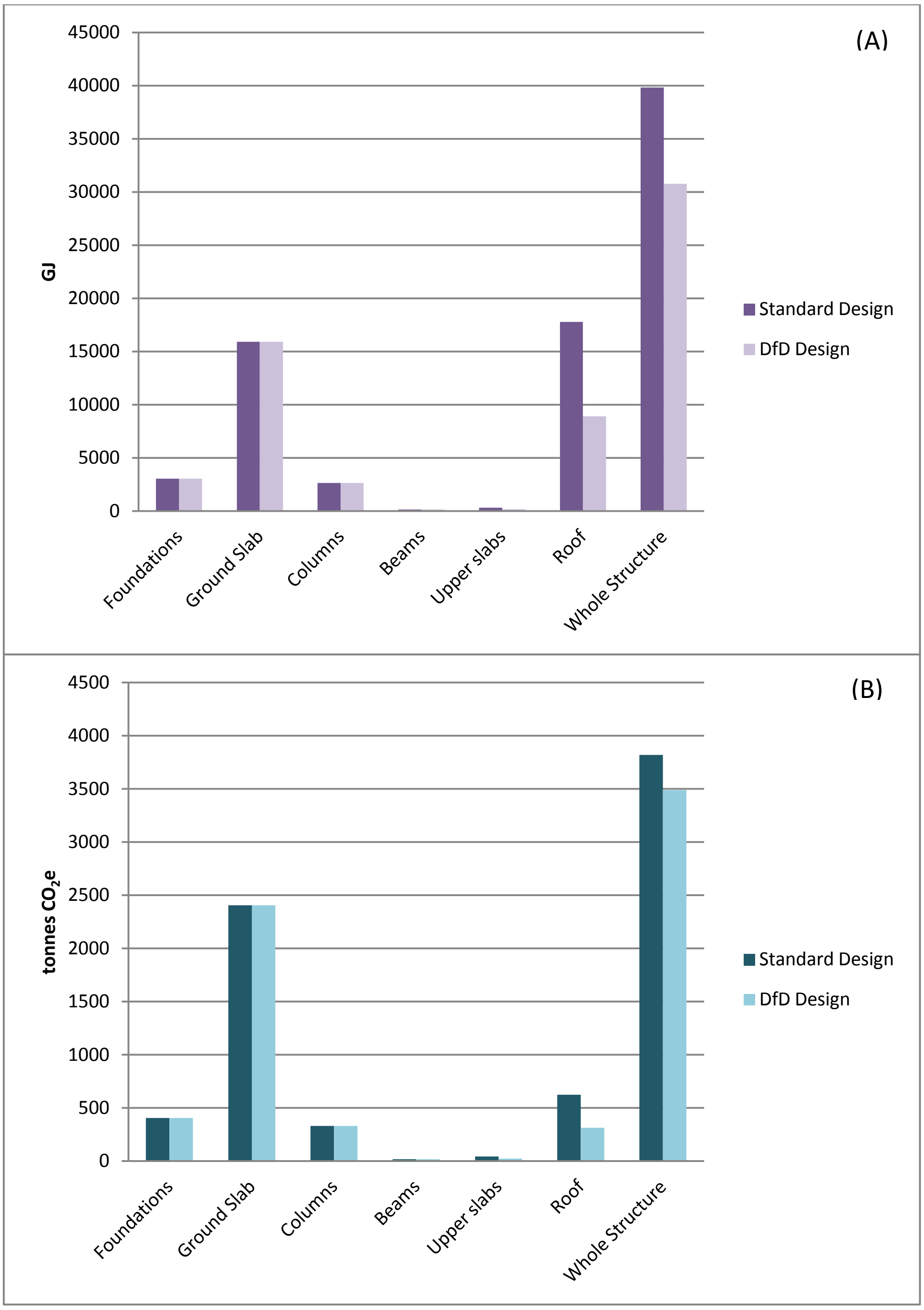


Figure 7.13: Warehouse Option 2, distribution of embodied energy (A) and embodied carbon (B) for the structural elements

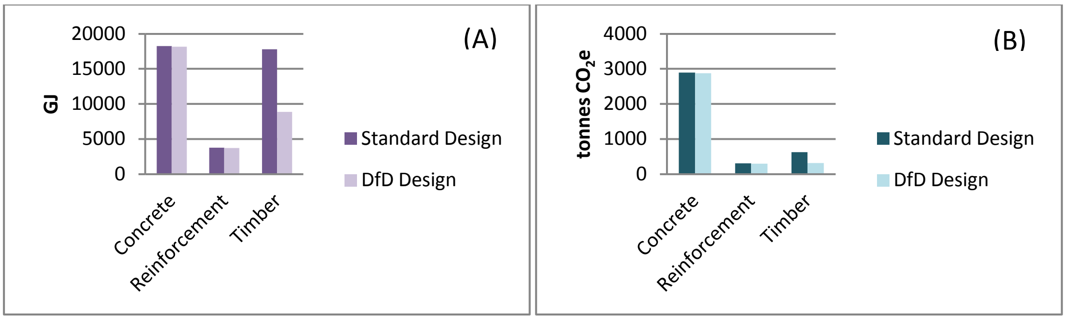


Figure 7.14: Warehouse Option 2, distribution of embodied energy (A) and embodied carbon (B) for different material types

Whilst the concrete and timber frame warehouse does not show the same savings as for the steel frame, if the timber alone is considered design for deconstruction has more of an impact. This suggests that design for deconstruction might be more suitable for a glue-laminated timber warehouse than for the concrete and timber hybrid that is presented here.

7.5 School Case Studies

There are three different school case studies, these are based on the same architectural design of a school but provide different structural options in each case. The internal floor area of the school is 9,637m$^{2.}$ This contains a number of large classrooms, approximately 81m^2 each and a 591m^2 sports hall, as well as other essential facilities (Target Zero, 2010).

7.5.1 School 1, steel frame

The structural design for this option consists of a steel frame with precast hollow core slabs for both floors and the roof. The steel frame in this option is ideal for being designed for deconstruction as the precast slabs can sit on top of the beams, without the use of shear stud connections. A screed topping is specified for the hollow core slabs which would prevent these from being reused. The embodied energy and carbon results from Sakura can be seen in within Table 7.13.

7.5.2 School 2, concrete frame

Option 2 is made from a concrete frame with concrete flat slabs. The roof structure is lightweight steel; the sports hall also has a steel frame. Only the steel frame areas would be suitable for deconstruction and future reuse. Embodied energy and carbon results can be seen summarised in Table 7.13.

7.5.3 School 3, composite steel frame

The design has a different foundation type, steel H piles instead of driven precast concrete piles as in the first two options. The superstructure is mostly a steel frame, but with a concrete composite floor. The sports hall frame is constructed from glulam. In this design, from the steel frame only the columns can be designed for deconstruction and reused as the composite floor means that the beams will be connected using shear bolts which will damage the beams too much for future reuse. The gluam and steel H piles could also be designed for deconstruction and reused. The results of the study can be found in Table 7.13.

7.5.4 Results

The results are split into two sections, the first compares the embodied values of the different options, the latter contrasts the standard designs with the potential DfD design for each option.

7.5.4.1 *Comparison of Options*

Table 7.13 summarises all the embodied energy and carbon results for the three school options produced using Sakura. Option 1 has the lowest embodied energy and carbon both in the standard design and when designed for deconstruction. Figure 7.15 to Figure 7.18 explore and contrast the three designs visually.

		School 1 Steel Frame		School 2 Concrete Frame		School 3 Composite Steel Frame	
Structural Element	**Material**	**EE (MJ)**	**EC (kg CO_2e)**	**EE (MJ)**	**EC (kg CO_2e)**	**EE (MJ)**	**EC (kg CO_2e)**
Foundations	**Concrete**	322675	51064	1087733	172136	457528	72405
	Reinforcement	600944	48352	1468734	118174	291050	23418
	Steel H Piles					2934922	208857
	Total	923619	99416	2556467	290310	3683500	304680
GFS	**Concrete**	2071642	327842	2081044	329330	2089171	330616
	Reinforcement	474829	38205	600074	48282	577767	46487
	Total	2546471	366047	2681118	377612	2666938	377103
Columns	**Concrete**			251878	39860		
	Reinforcement			471888	37968		
	Steel Sections	7012225	499010	3441075	244877	7146256	508548
	Total	7012225	499010	4164841	322705	7146256	508548
Beams	**Concrete**			217958	34492		
	Reinforcement			752567	60551		
	Steel Sections	7012225	499010	3441075	244877	7146256	508548
	Timber					270300	9461
	Total	7012225	499010	4411601	339920	7416556	518008
UFS	**Concrete**	1778645	281475	5268058	833683	1957094	309715
	Reinforcement	640772	51556	4244208	341488	244714	19690
	Concrete topping	786486	120998				
	Steel Deck					2047357	139510
	Total	3205903	454029	9512266	1175171	4249164	468915
Roof	**Concrete**	584272	92462	123563	19554	123563	19554
	Reinforcement	200763	16153	618277	49746	618277	49746
	Total	785035	108616	741840	69301	741840	69301
Total for the Structure		21485478	2026127	24068132	2575019	25904253	2246554
Total per m^2 for the Structure		**2229**	**210**	**2497**	**267**	**2688**	**233**
Total if structure DfD		14473253	1527117	20627057	2330142	20728514	1883121
Total per m^2 if structure DfD		**1502**	**158**	**2140**	**242**	**2151**	**195**
Total saving if structure DfD		7012225	499010	3441075	244877	5175739	363433

Table 7.13: Embodied energy and carbon results for School case studies

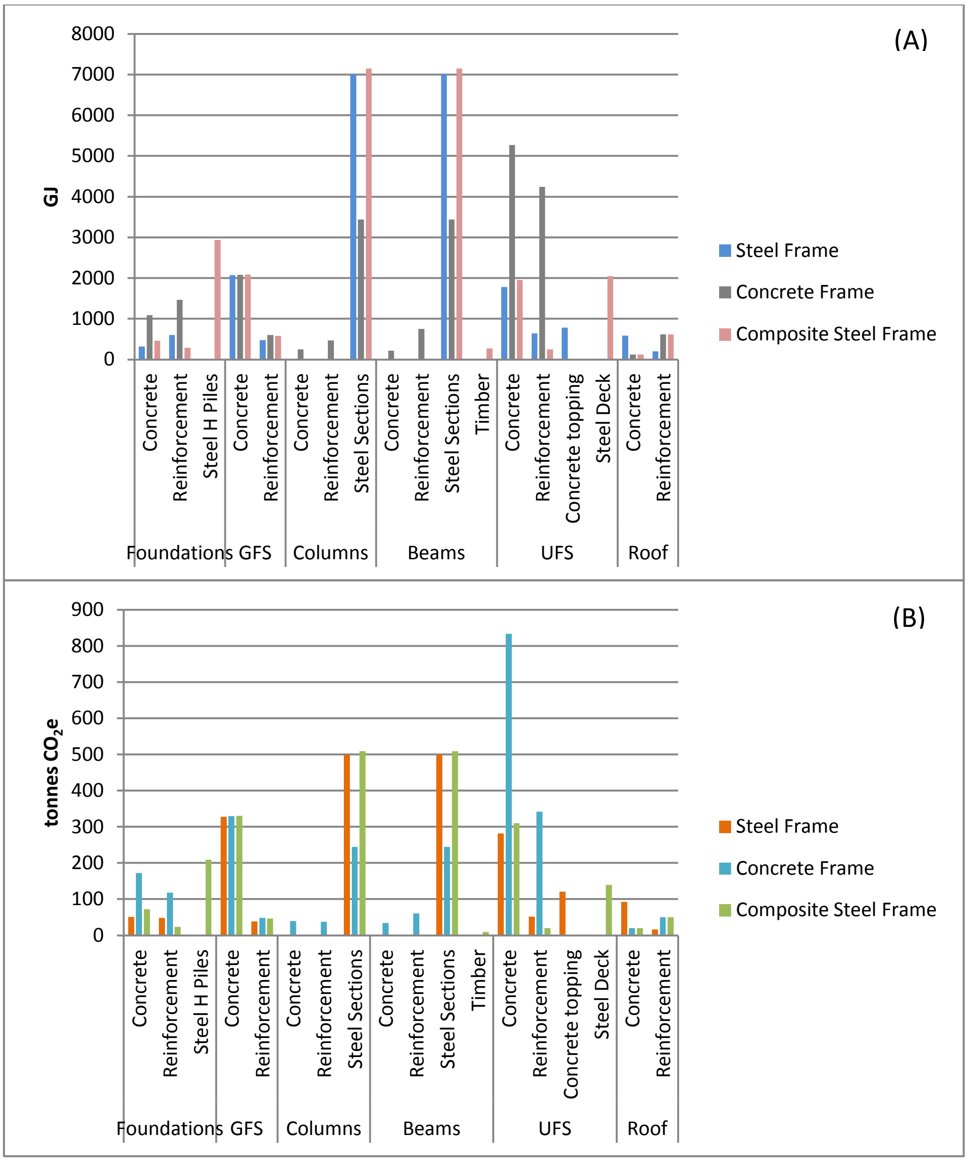


Figure 7.15: Comparison of the 3 standard design options, (A) shows embodied energy, (B) embodied carbon

Figure 7.15 (standard design) and Figure 7.16 (DfD design) display the embodied energy and carbon breakdowns for the individual structural elements. These reflect the different construction types for each of the designs. The two designs with steel frames show high embodied energy and carbon for the steel columns and beams. The design with a concrete frame shows higher levels of embodied energy and carbon for the concrete and reinforcement in beams, columns and the upper floor slabs. Similar patterns can be seen for the embodied carbon, although the concrete in the upper floor slabs of the concrete frame makes a larger relative impact.

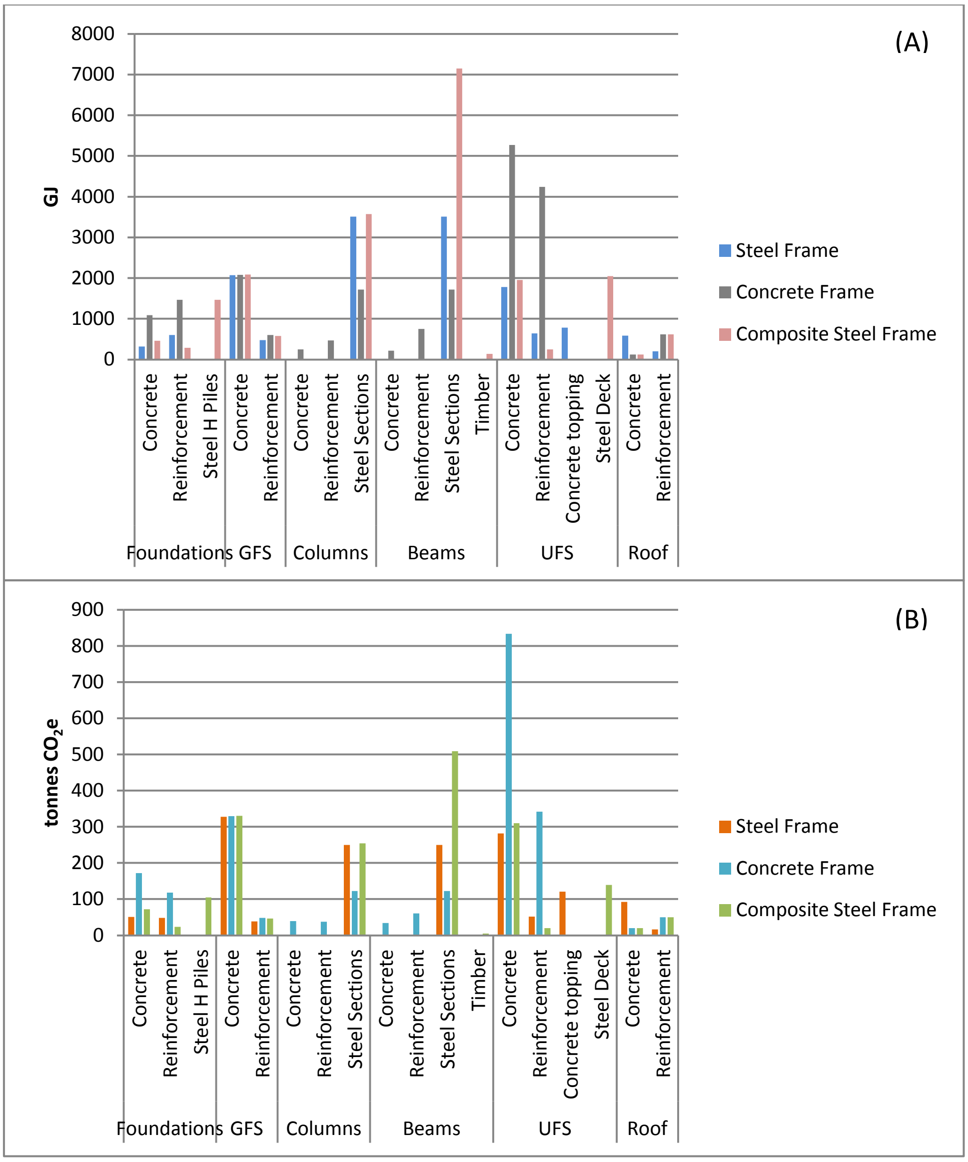


Figure 7.16: Comparison of the 3 DfD design options, (A) shows embodied energy, (B) embodied carbon

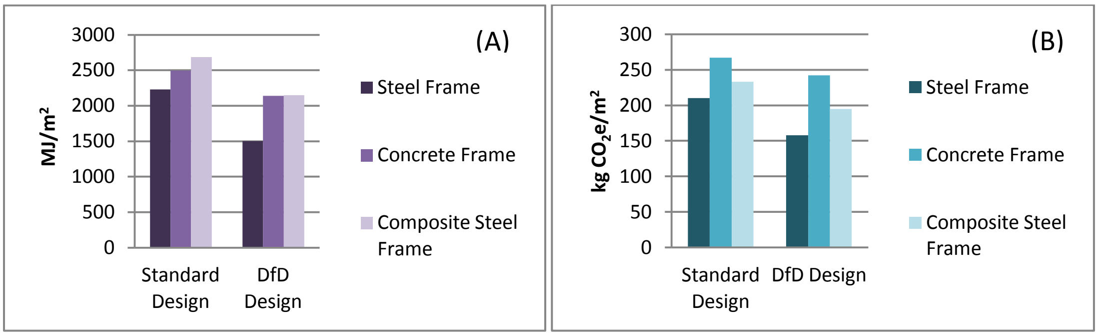


Figure 7.17: Comparison of the school options, (A) shows embodied energy/m^2 and (B) embodied carbon/m^2

From Figure 7.17 it can be seen that overall the steel frame has the lowest embodied energy and carbon for the standard design and the DfD design. The composite design frame has the highest embodied energy for the standard design but this is only slightly higher than the concrete frame for the DfD design. Whereas the concrete frame has the highest embodied carbon for both the standard and DfD designs. Comparing the embodied carbon results to a study by Kaethner and Burridge (2012) all designs fall within the expected range (between 180 and 320 kg CO_2/m^2) of the structure in a school, enhancing the credibility of the calculations. The DfD design for the steel frame even drops slightly lower than this range, demonstrating the significant savings.

Figure 7.18 explores the potential saving that results from the DfD design when compared to the standard design. The pattern is the same for both the embodied energy and carbon; the steel frame benefits the most, then the composite steel frame and finally concrete. All options see significant savings, ranging from approximately 250 tonnes of CO_2e to 500 tonnes of CO_2e, demonstrating the potential for design for deconstruction within this building type.

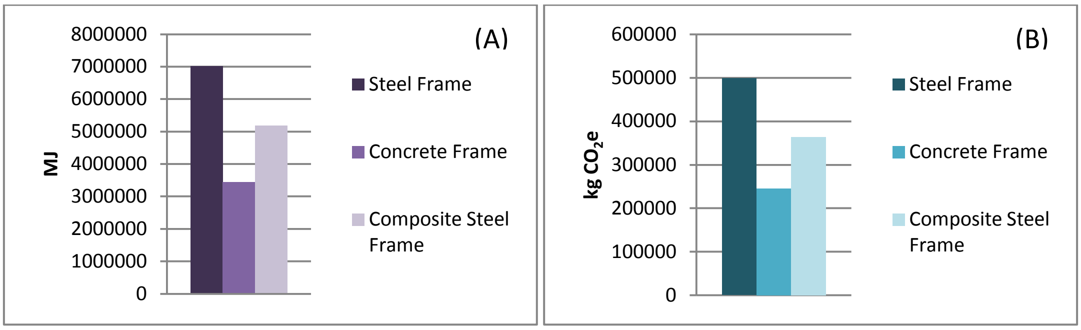


Figure 7.18: Potential savings from DfD of each of the School options, (A) shows embodied energy, (B) embodied carbon

7.5.4.2 Standard versus DfD design

This demonstrates areas of the structure which benefit most from design for deconstruction for each of the school options.

7.5.4.2.1 Option 1, the steel frame

Figure 7.19 shows the distribution of energy and carbon across the different structural elements, it also displays potential savings by design for deconstruction. The beams and columns have both the highest embodied energy and carbon of all the elements. It is also these that can benefit from deconstruction, it brings their embodied energy down to the same as that of the upper floor slabs and below the embodied carbon of these floor slabs. Exploring the impact of different material types (Figure 7.20) it can be seen that the steel sections have the highest embodied energy, if design for deconstruction had been applied to the project this could have been significantly reduced. The embodied carbon of the sections is only slightly higher than that of the concrete. For the DfD design this level is reduced to below that of the concrete.

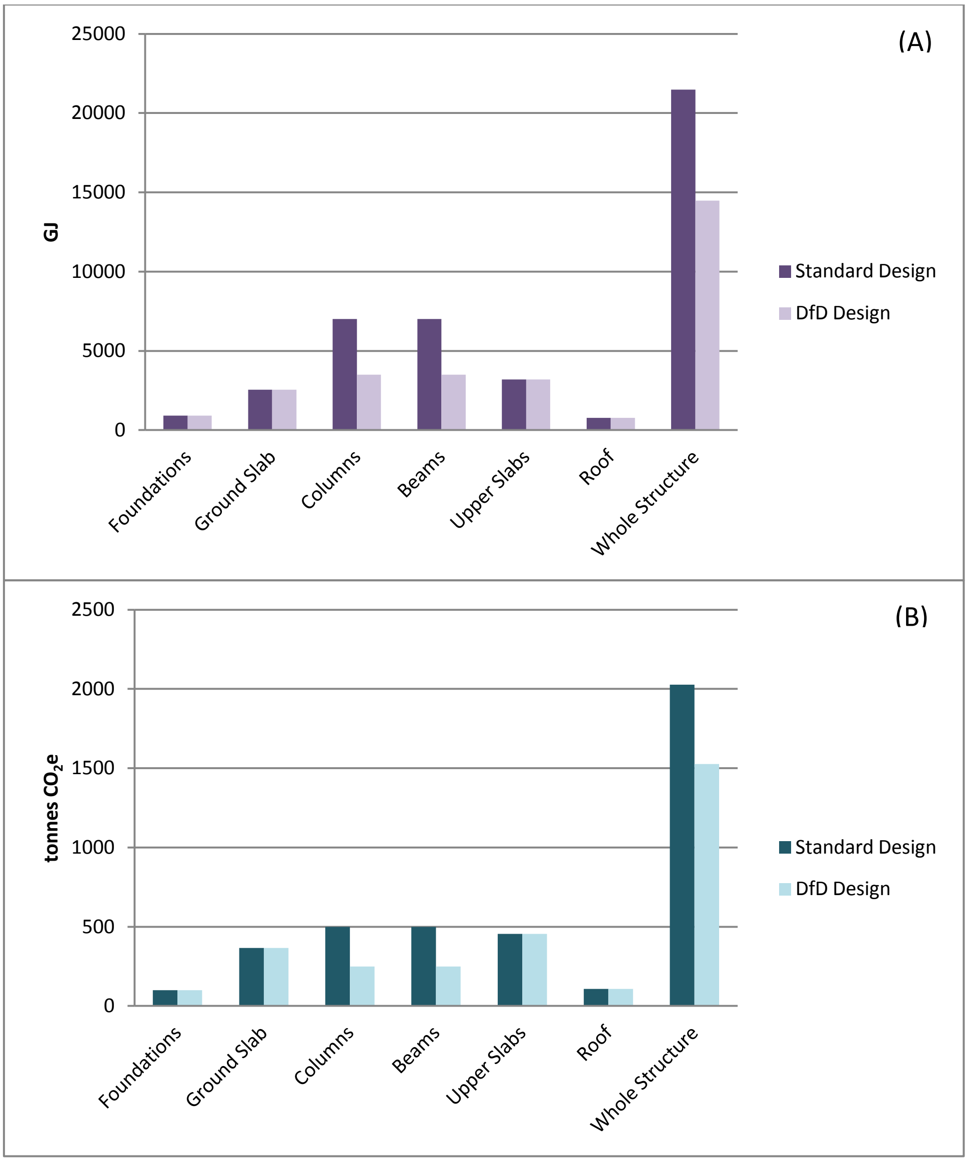


Figure 7.19: School 1, steel frame, distribution of embodied energy (A) and embodied carbon (B) for the structural elements

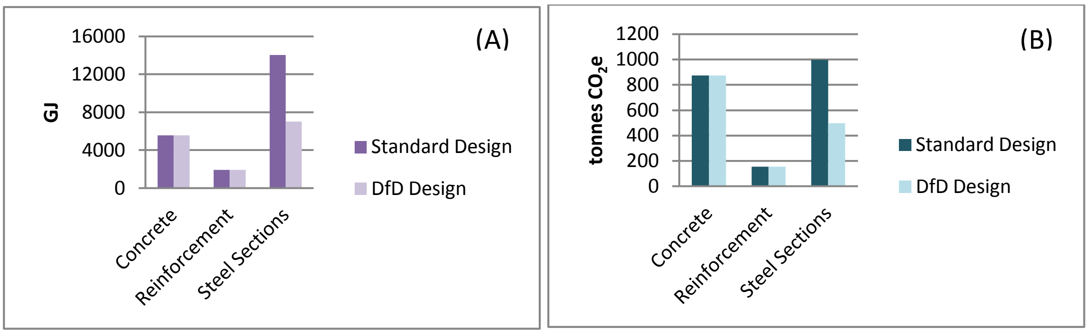


Figure 7.20: School 1, steel frame, distribution of embodied energy (A) and embodied carbon (B) for different material types

The potential for design for deconstruction within this structural type is clear, with substantial savings for the steel sections within the design. Additional alterations could result in savings for the precast units as discussed in Chapter 8.

7.5.4.2.2 Option 2, the concrete frame

For this structural type the main impact is from the upper floor slabs (Figure 7.21). The columns and beams also have a significant impact, although this is reduced in the DfD design. On examination of the material breakdown (Figure 7.22) it can be seen that this reduction is for the steel elements, suggesting that if the frame were only concrete with no steel elements then there would be no benefit from design for deconstruction. Nonetheless, this particular design does show a significant benefit. Concrete makes the biggest impact to both the embodied energy and carbon when the individual materials are considered. This could be reduced through the use of cement replacements like fly ash and ground granulated blast furnace slag, however, detailed discussion of this is considered outside the scope of this thesis.

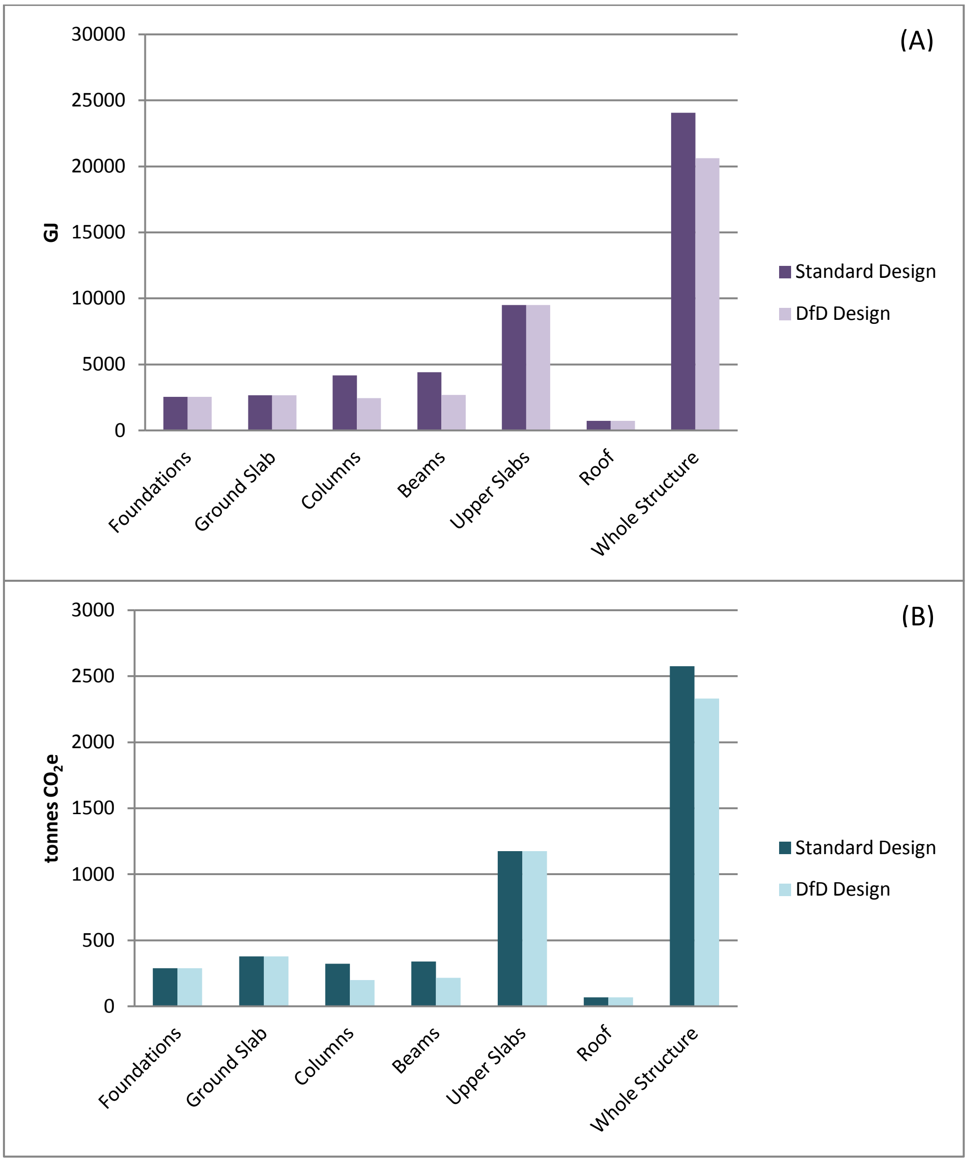


Figure 7.21: School 2, concrete frame distribution of embodied energy (A) and embodied carbon (B) for the structural elements

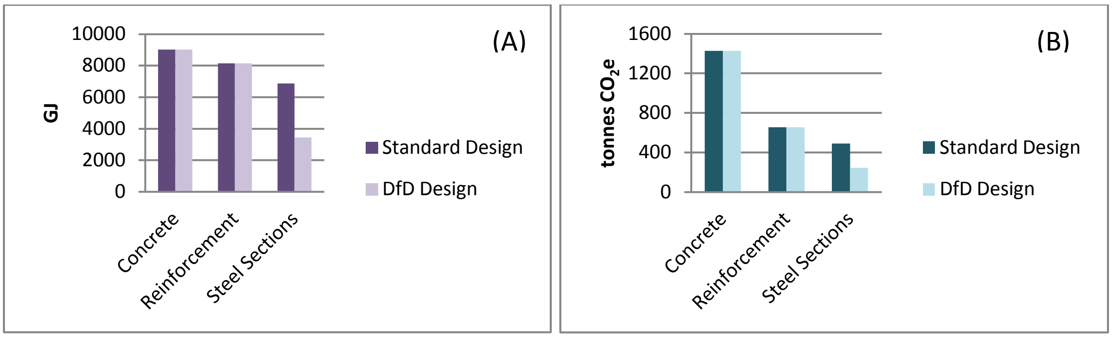


Figure 7.22: School 2, concrete frame, distribution of embodied energy (A) and embodied carbon (B) for different material types

7.5.4.2.3 Option 3, the composite steel frame

A breakdown of the contribution of each structural element is shown in Figure 7.23, columns and beams make the largest impact on the embodied energy and carbon, although the columns' contribution is significantly reduced for the DfD design. The foundations also see the benefit of design for deconstruction. When the material impacts (Figure 7.24) are examined it becomes clear that it is the H-piles in the foundations that benefit from design from deconstruction, substantially reducing their impact.

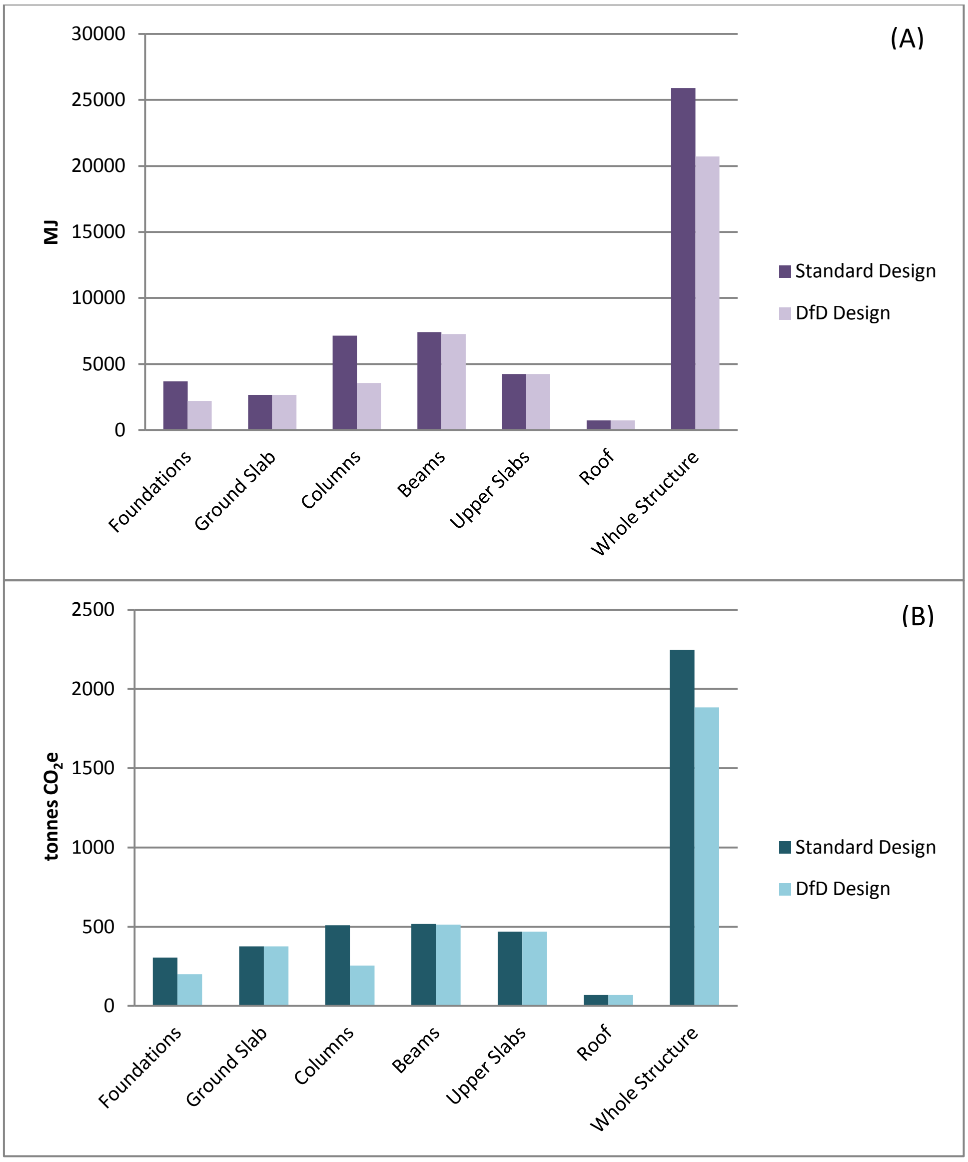


Figure 7.23: School Option 3, distribution of embodied energy (A) and embodied carbon (B) for the structural elements

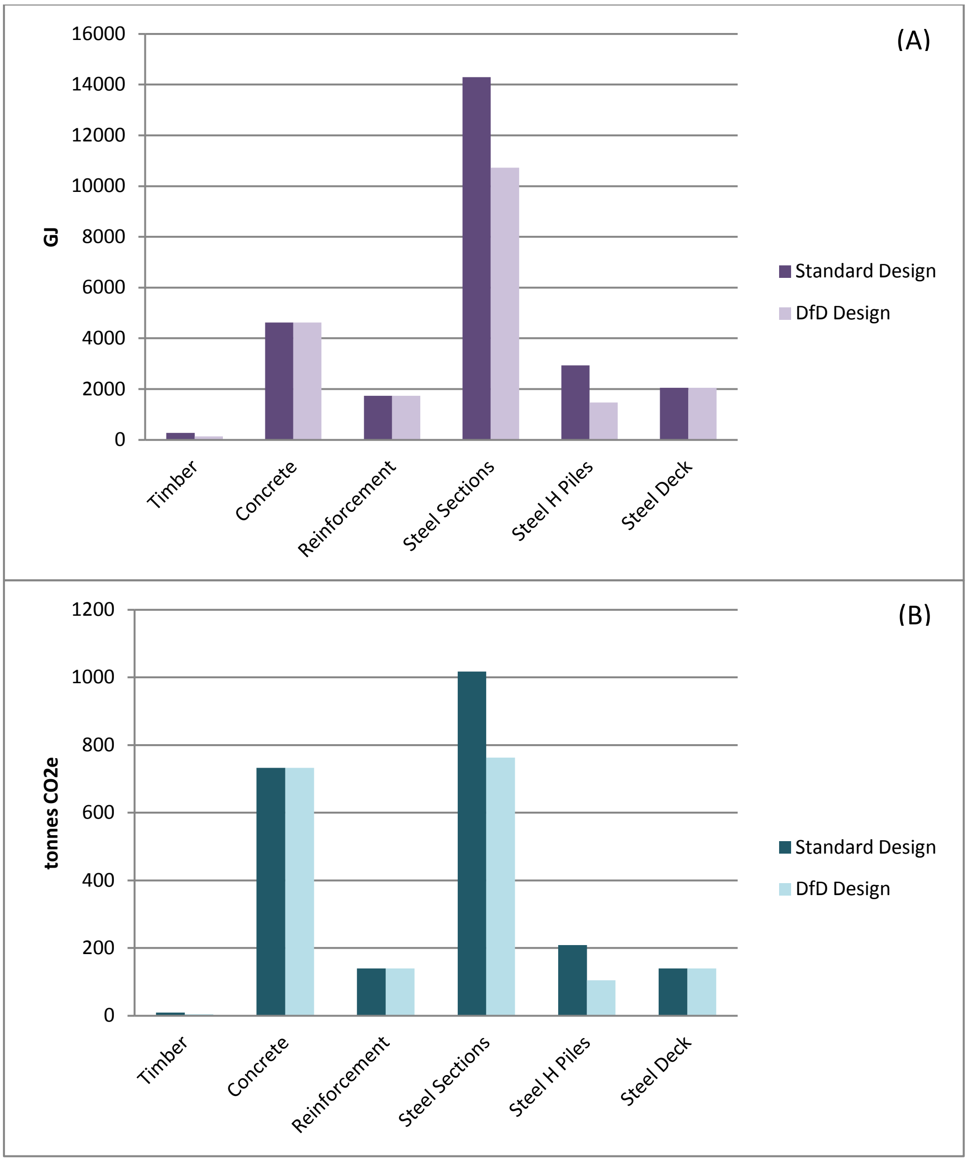


Figure 7.24: School Option 3, distribution of embodied energy (A) and embodied carbon (B) for different material types

This case study demonstrates the reduction in the potential of design for deconstruction when a composite slab is utilised as steel beams can no longer be reused. It also highlights the reuse benefits of steel H piles, an effect way of reducing the embodied energy and carbon on the foundations. If methods could be developed to reduce the need for pile caps or to find replacement materials then the embodied values of the foundations could be reduced even further. This forms Recommendation 10, found in Chapter 9.

7.6 Office Case Studies

Both office case studies investigated are based on the same building; it is the structural design that varies. The case study is a forty metre high building that consists of ten floors of offices, with two basement levels across half of the building for parking. The other half of the building is constructed on a podium transfer structure. The total internal floor area amounts to 33,018m^2. The project incorporates three structural cores and centres around two atria (Target Zero, 2012).

7.6.1 Office 1, composite steel frame

The first option contains a structural steel frame, with cellular beams acting compositely with in-situ concrete on a profiled steel deck. The design is based on a 12m x 10.5m grid, services are integrated within the cellular beams, giving a floor to ceiling height of 2.8m. The upper floors incorporate a suspended ceiling which contains acoustic insulation (Target Zero, 2012). In this design only the steel columns could be designed for deconstruction and subsequently reused. The large spans would have given excellent reuse potential to the beams if it were not for the composite design.

7.6.2 Office 2, concrete frame

This option uses a concrete frame structure, although there is still some steel structure within the building. The upper floors are constructed from post-tensioned concrete slabs. The same structural grid is used as for option 1 (Target Zero, 2011). Due to the higher mass of the concrete frame the foundations are slightly larger. For this construction type only the steel columns are suitable for design for deconstruction and future reuse.

7.6.3 Results

The results are split into two sections, the first compares the embodied values of the two office options. The second section explores the differences between the standard design and the DfD design for both options.

7.6.3.1 Comparison of Options

Table 7.14 contains a summary of the output from Sakura for both office case studies. Screenshots of the results from Sakura, as well as the inputs into Sakura can be found in Appendix C4.

		Office 1, composite steel frame		Office 2, concrete frame	
		EE	EC	EE	EC
Element	**Material**	(MJ)	(kg CO_2e)	(MJ)	(kg CO_2e)
Foundations	**Concrete**	2848143	450725	3163202	500584
	Reinforcement	188755	15187	209635	16867
	Total	3036898	465913	3372837	517452
GFS	**Concrete**	5726666	906259	4224901	668601
	Reinforcement	3720085	299317	4622136	371896
	Total	9446751	1205576	8847037	1040497
Columns	**Steel Sections**	13461236	957939	2294523	163285
	Concrete			2846700	450497
	Reinforcement			3688800	296800
	Total	13461236	957939	8830023	910582
Beams	**Steel Sections**	50707105	3608459	5275756	375438
	Concrete	87920	13914	2183737	345582
	Reinforcement	278400	22400	4611000	371000
	Total	51073425	3644773	12070493	1092019
Shear Cores	**Concrete**	3690254	583992	3475288	544581
	Reinforcement	4889400	393400	4889400	393400
	Total	8579654	977392	8364688	937981
UFS & Roof	**Concrete**	12220848	1933979	24786247	3922484
	Reinforcement	7437473	598417	14871667	1196571
	Steel Deck	12563476	856095	1240921	84558
	Total	32221797	3388492	40898835	5203613
Suspended Ceiling		178506	10467	178506	10467
Total for the Structure		117998267	10650551	82562419	9712611
Standard Design	**per m^2**	3574	323	2500	294
Total if structure DfD		111267649	10171581	81415157	9630969
DfD Design	**per m^2**	3370	308	2466	292
Total saving if structure DfD		6730618	478970	1147262	81642

Table 7.14: Embodied energy and carbon results for Office case studies

A comparison of the embodied energy and carbon of the different elements for the two options are shown in Figure 7.25 for the standard design and Figure 7.26 for the DfD design. There is very little difference in the pattern found within the two sets of graphs. The DfD options show slightly lower values for the steel sections in the columns. The impact of the steel beams is very significant for the composite steel frame for both the embodied energy and carbon. The concrete in the upper floor systems and roof makes a substantial contribution for the concrete frame; this is proportionally higher for the embodied carbon.

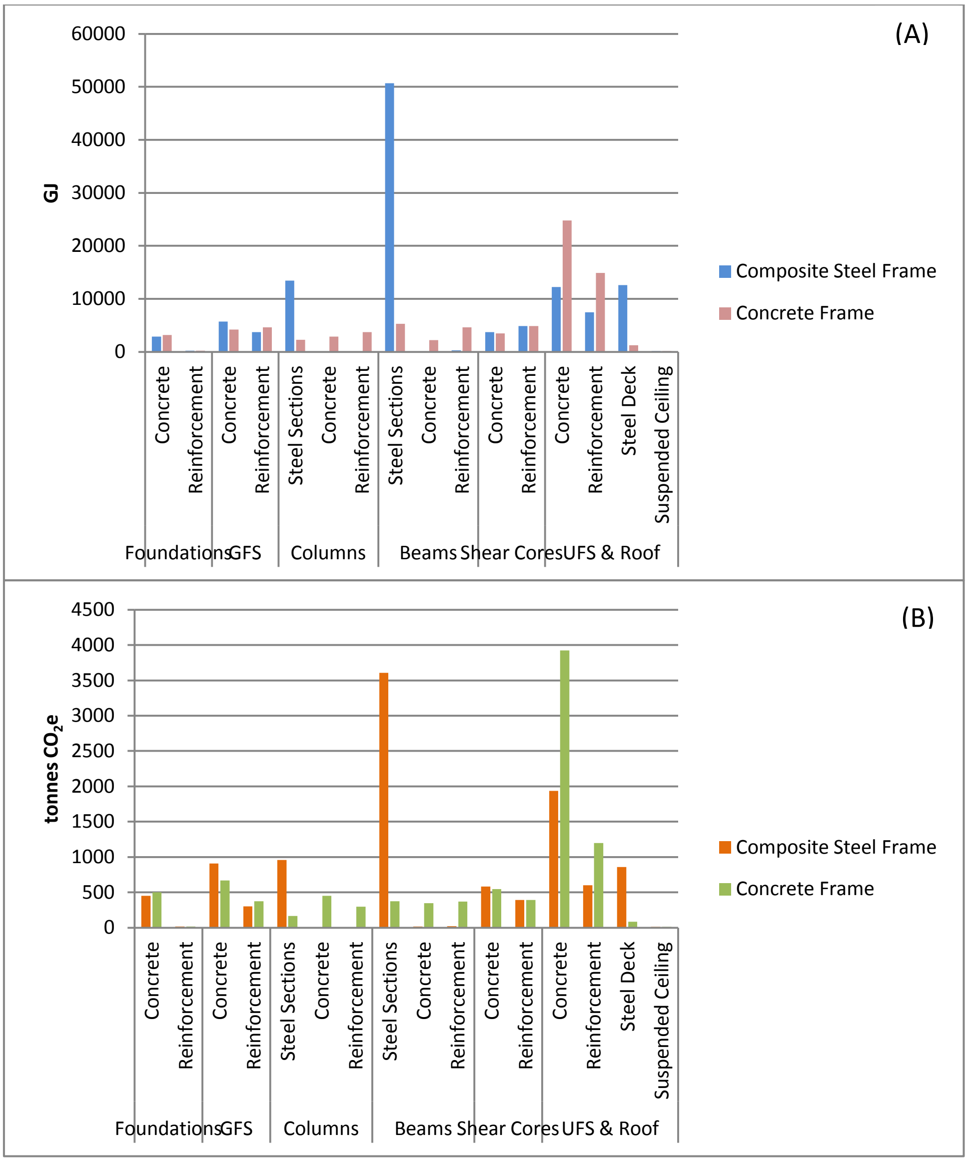


Figure 7.25: Comparison of the 2 standard office design options, (A) shows embodied energy, (B) embodied carbon

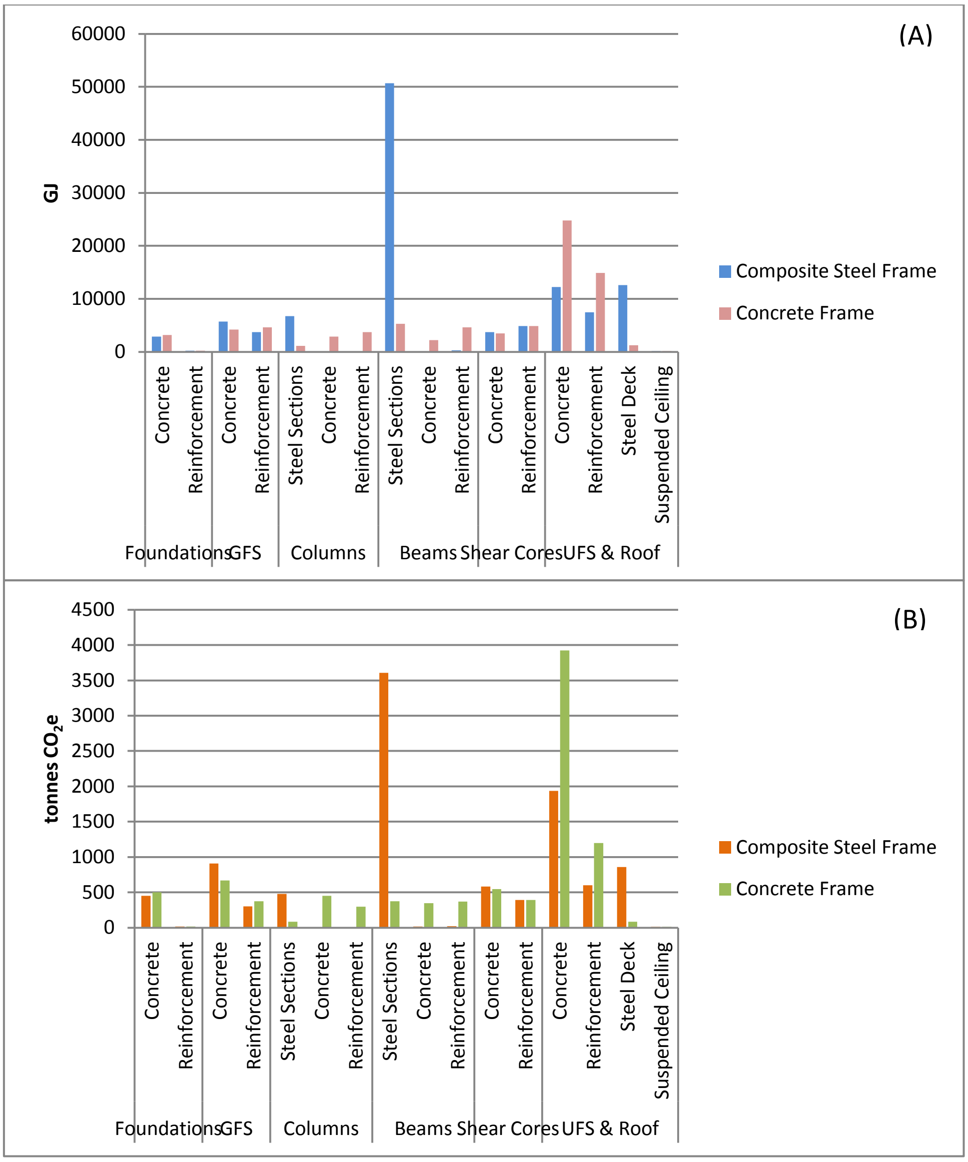


Figure 7.26: Comparison of the 2 office DfD design options, (A) shows embodied energy, (B) embodied carbon

A comparison of the overall embodied values for the two designs can be seen in Figure 7.27. The concrete frame has both the lowest embodied energy and carbon for the standard and DfD designs. Although it can be seen (Figure 7.28) that the composite steel frame accrues much larger savings, nearly 500 tonnes of CO_2e, by designing for deconstruction than the concrete frame, just under 100 tonnes of CO_2e.

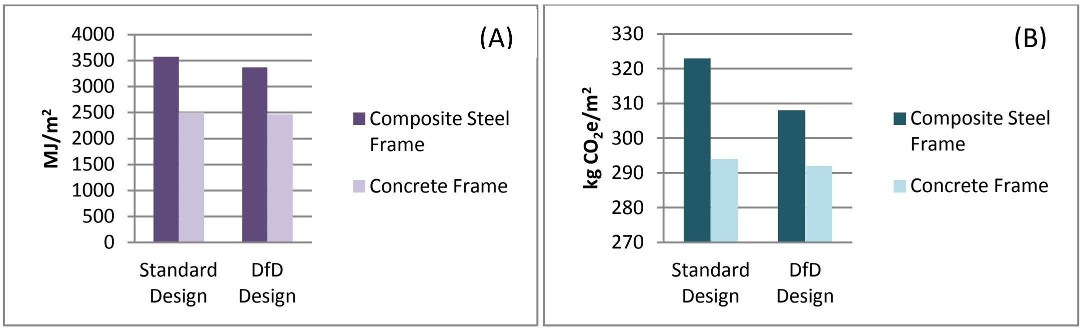


Figure 7.27: Comparison of the office options, (A) shows embodied energy/m^2 and (B) embodied carbon/m^2

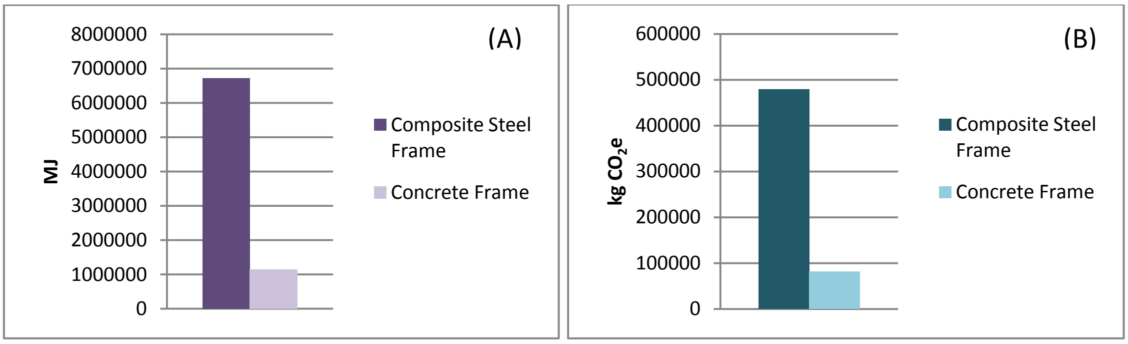


Figure 7.28: Potential savings from DfD of each of the Office options, (A) shows embodied energy, (B) embodied carbon

7.6.3.2 Standard versus DfD design

This discusses which elements of the structure benefit most from design for deconstruction for the two office options.

7.6.3.2.1 Option 1, the composite steel frame

The breakdown for the different elements can be seen in Figure 7.29 and for the different materials in Figure 7.30. The beams make the largest contribution to the embodied energy and carbon. The upper floor slabs and roofs also have a significant impact. The contribution of the suspended ceiling is so small that it doesn't register on either graph. The columns are the only element which benefit for design for deconstruction.

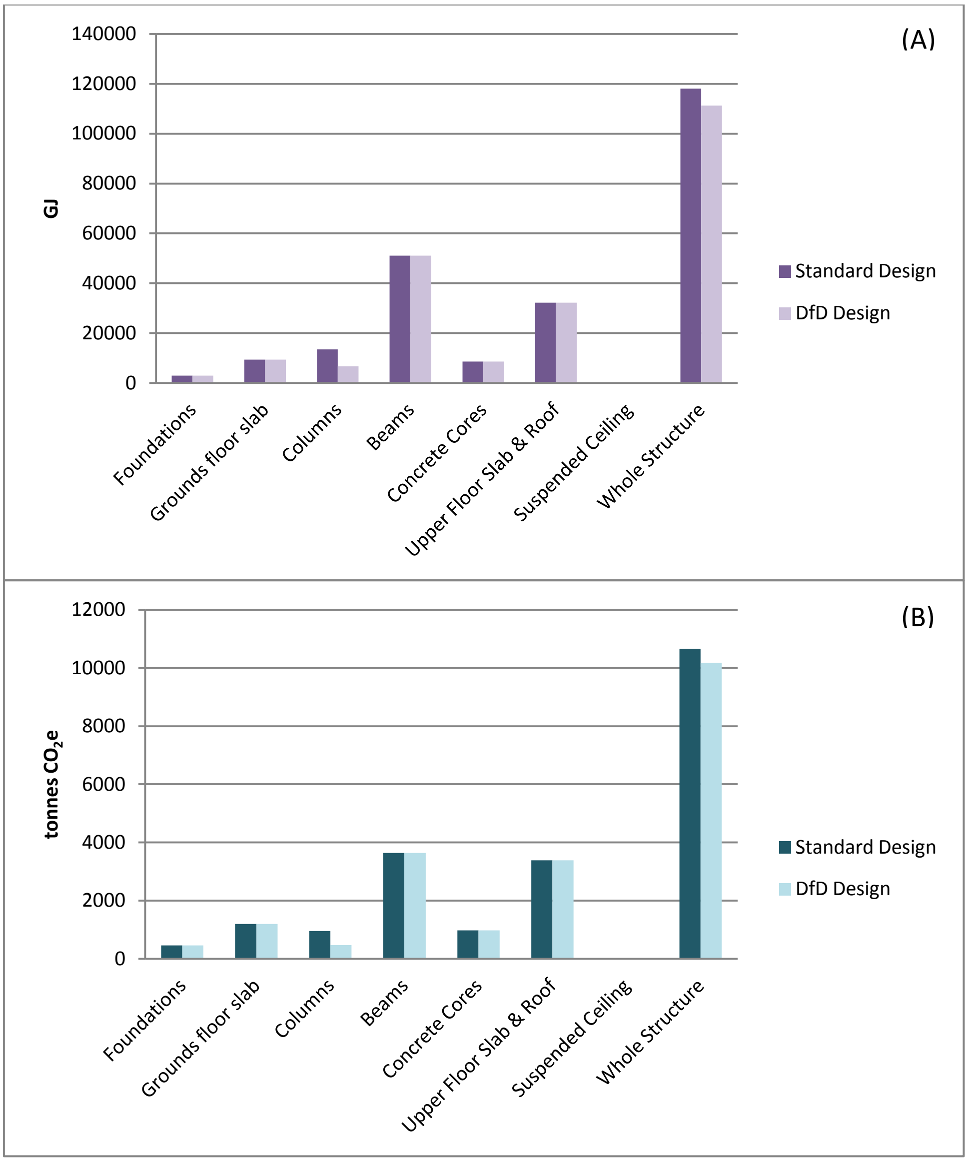


Figure 7.29: Office Option 1, distribution of embodied energy (A) and embodied carbon (B) for the structural elements

Exploring the different material types it can be seen (Figure 7.30) that the steel sections have the biggest impact for both the embodied energy and carbon, however this is reduced by design for deconstruction. Concrete also makes a substantial contribution to the embodied carbon.

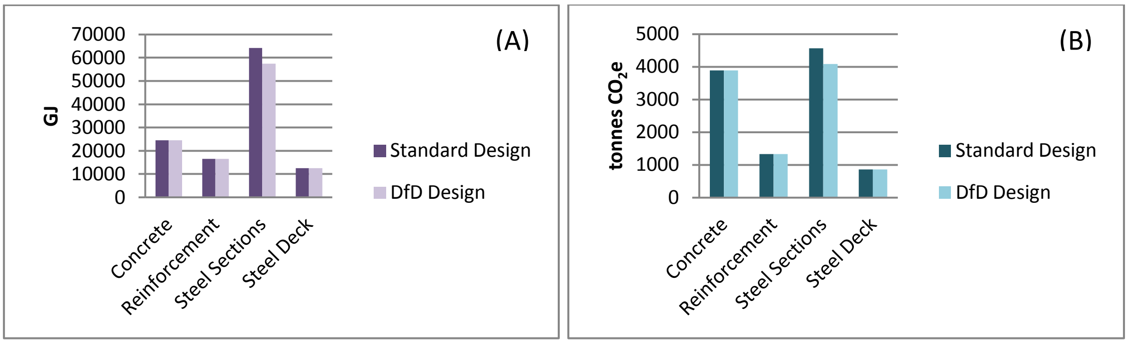


Figure 7.30: Office Option 1, distribution of embodied energy (A) and embodied carbon (B) for different material types

This case study shows that some savings can be made by designing a composite steel frame for deconstruction, these could however be maximised by avoiding composite design as discussed fully in Chapter 8.

7.6.3.2.2 Option 2, the concrete frame

Figure 7.31 shows the breakdown of embodied impacts for the individual elements. The upper floor slabs and roof make the largest contribution to both the embodied energy and carbon. The other elements have similar impacts. Columns slightly benefit from design for deconstruction but only by a small amount.

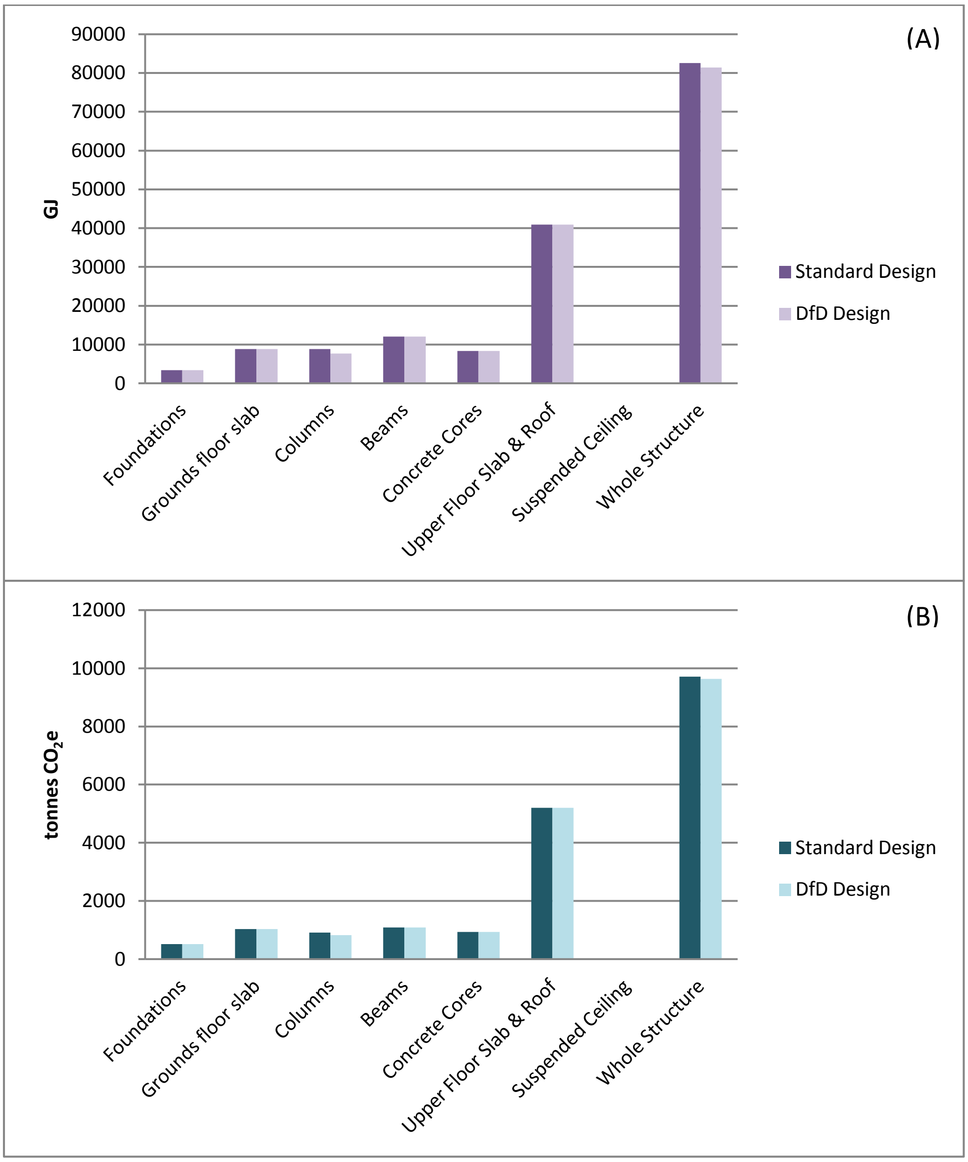


Figure 7.31: Office Option 2, distribution of embodied energy (A) and embodied carbon (B) for the structural elements

The impacts of the different materials are shown in Figure 7.32, concrete has the largest contribution to both embodied energy and carbon. The steel sections benefit slightly from design from deconstruction but this is small. The predominantly reinforced concrete structure makes the project unsuitable for design for deconstruction and future reuse.

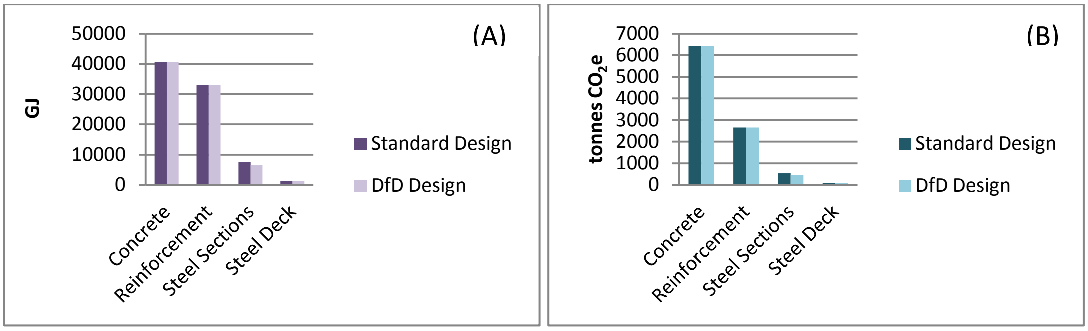


Figure 7.32: Office Option 2, distribution of embodied energy (A) and embodied carbon (B) for different materials

This case study demonstrates that there is little benefit to a concrete frame by designing for deconstruction, the only benefit shown is to the small number of steel sections utilised.

7.7 Supermarket Case Studies

Both supermarket case studies are based on the same building design. The building is split into retail space and back of house accommodation, with a total floor area of 9393m^2. The retail space has a 1910m^2 mezzanine level and is 5731m^2 in total, making up the majority of the whole building area. The rest of the structure houses offices, cold storage, a bakery, staff cafeteria and warehousing (Target Zero, August 2011). The two case studies incorporate different structural designs within this building layout. Supermarkets will often have a shorter life span than other buildings; therefore a twenty year life span is taken for both of these case studies.

7.7.1 Supermarket 1, a steel portal frame

The structure in this design is a steel portal frame supported on concrete piles. A standardised 12m x 12m grid is adopted in the main retail space; the mezzanine floor in this area is constructed from cold rolled steel joists, with plywood boarding on top. A composite deck is used to form the upper floor of the back of house area (Target Zero, August 2011). The columns and roof structure throughout will be suitable for design for deconstruction and future reuse. The beams used with the composite deck could not be reused. It is possible that those beams with plywood boarding on top could be reused but the separate masses for the different floor beams are not known and so it is assumed that none of the beams can be reused.

7.7.2 Supermarket 2, glue laminated timber frame

This incorporates glue laminated timber columns, beams and roof rafters as the main frame. Softwood timber joists are used to construct the mezzanine floor, with plywood boarding on top. There is still some steel framing in the back of house area and a composite deck is used for the upper floor as in option 1. The foundation and ground floor slab design is the same as in option 1 (Target Zero, August 2011). The timber frame throughout can be designed for deconstruction and subsequently reused. The embodied factors for timber assume that all timber is sourced from a sustainably managed forest and do not take into account carbon sequestration. In addition, the direction that the industry is moving in (see section 4.3.7.7) means that timber is unlikely to be landfilled in the future so emissions from decomposition are not factored into results.

7.7.3 Results

7.7.3.1 Comparison of Options

The two different structural options are compared side by side in Table 7.15. Option 2, the timber frame, overall has both lower embodied energy and carbon, as can be seen in Figure

7.35. A breakdown of the elements, comparing the two options both for the standard designs and the DfD designs is shown in Figure 7.33 and Figure 7.34.

		Supermarket 1 Steel frame		**Supermarket 2 timber frame**	
Element	**Material**	**EE (MJ)**	**EC (kg CO_2e)**	**EE (MJ)**	**EC (kg CO_2e)**
Foundations	**Concrete**	4126766	634887	467525	73987
	Reinforcement	1374130	110562	1374130	110562
	Total	5500896	745449	1841655	184549
GFS	**Concrete**	4720741	747069	4720741	747069
	Reinforcement	1680596	135220	1680596	135220
	Total	6401338	882289	6401338	882289
Columns	**Steel**	3348303	238275	177891	12659
	Gluam			560892	19631
	Total	3348303	238275	738783	32290
Beams	**Steel**	3348303	238275	177891	12659
	Gluam			2087640	73067
	Concrete	132869	21027	132869	21027
	Total	3481171	259301	2398400	106753
UFS	**Concrete**	255158	40379	255158	40379
	Steel Deck	215333	14673	215333	14673
	Reinforcement	35148	2828	35148	2828
	Plywood	759135	22774	807585	24228
	Timber Joists			275983	7459
	Total	1264774	80655	1589207	89567
Roof	**Steel**	512228	36452		
	Gluam			1928927	67512
	Total	512228	36452	1928927	67512
Total for the Structure		20508710	2242421	14898310	1362962
Standard Design	**per m^2**	2183	239	1586	145
Total if structure DfD		17420285	2022640	11094030	1224665
DfD Design	**per m^2**	1855	215	1181	130
Total saving if structure DfD		3088424	219781	3804280	138296

Table 7.15: Embodied energy and carbon results for Supermarket case studies

The massive impact of the concrete in the foundations and ground floor for both designs is evident (Figure 7.33) this reaffirms the need to explore alternatives for these elements as discussed earlier in the chapter, forming Recommendations 10 and 12 The steel frame option shows significant impact from the columns and beams, which is reduced in the DfD design (Figure 7.34). The timber design, as expected, shows larger impact for the timber, in particular the roof beams, the impact of these also reduces in the DfD design.

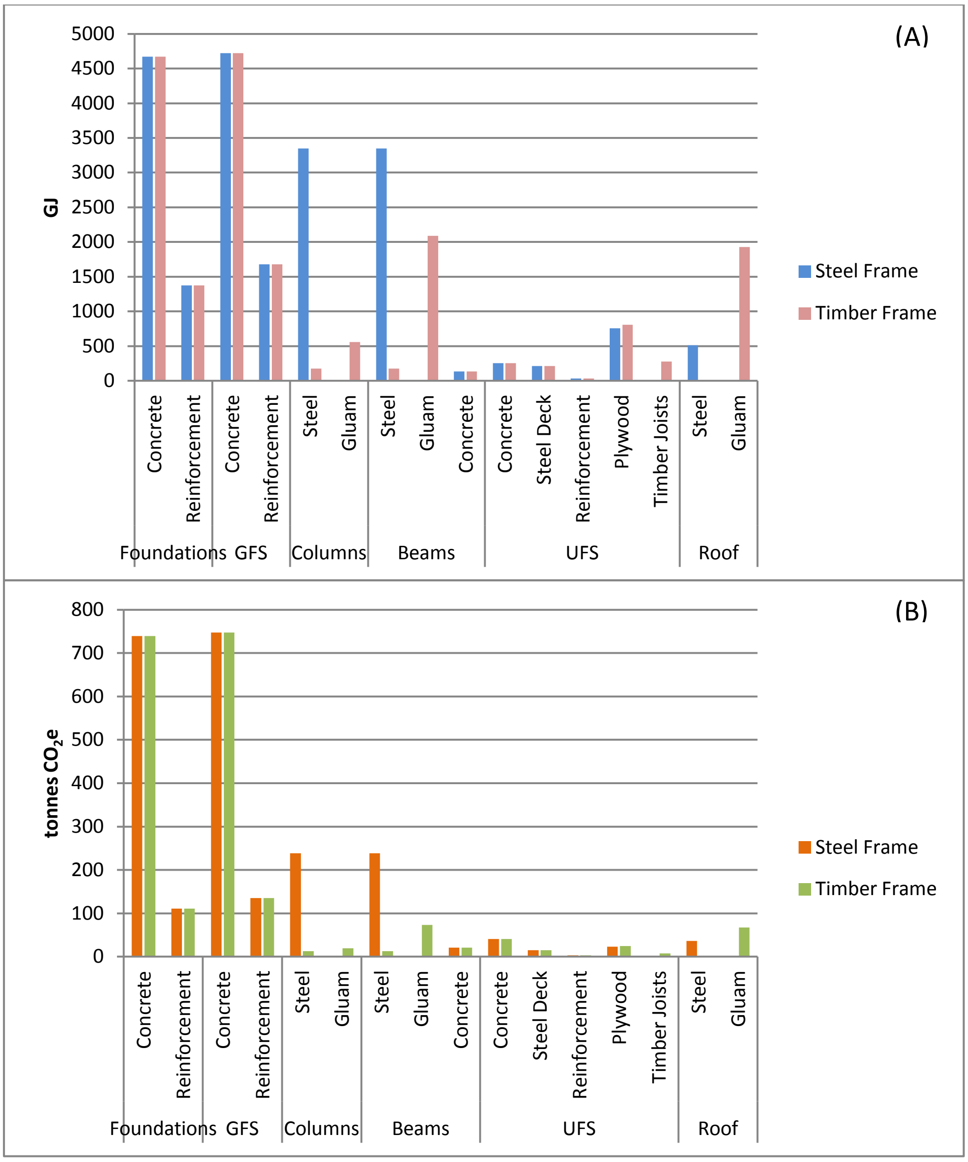


Figure 7.33: Comparison of the 2 standard Supermarket design options, (A) shows embodied energy, (B) embodied carbon

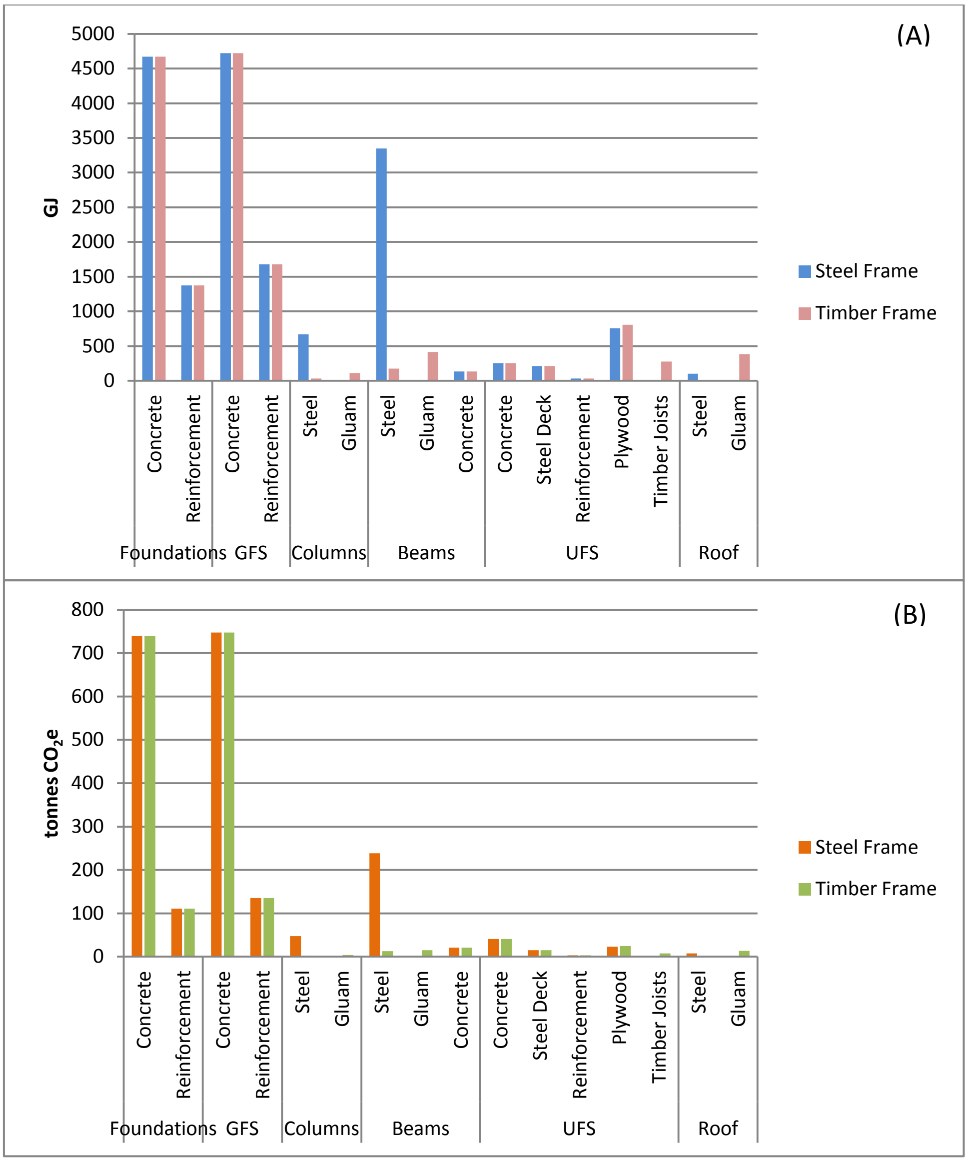


Figure 7.34: Comparison of the 2 Supermarket DfD design options, (A) shows embodied energy, (B) embodied carbon

The timber frame has the lowest embodied energy and carbon for both the standard design and the DfD design (Figure 7.35). The embodied carbon for the two designs ranges from 201 kg CO_2e/m^2 for the timber DfD design up to 250 kg CO_2e/m^2 for the steel standard design. There is no data to compare these to, emphasising the need to develop embodied carbon benchmarks for a range of building types, detailed in Recommendation 3.

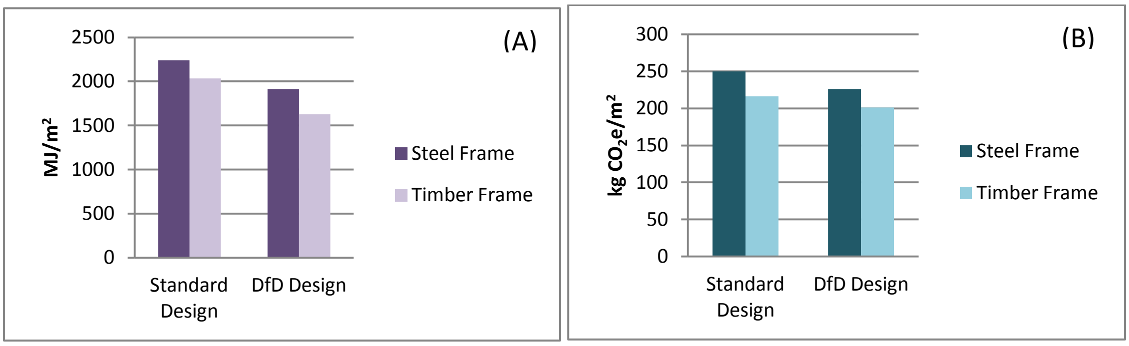


Figure 7.35: Comparison of the Supermarket options, (A) shows embodied energy/m^2 and (B) embodied carbon/m^2

Figure 7.36 demonstrates that both designs show significant benefits from design for deconstruction, with the greatest savings for the timber frame for the embodied energy, this reverses for the embodied carbon with the steel frame accruing the greatest savings. This swap is due to timber from sustainable forests having a lower embodied carbon factor than embodied energy factor as much of the energy is produced using biomass so there is a lower carbon intensity than if solely fossil fuels were used (Hammond & Jones, Inventory of Carbon & Energy (ICE), 2011).

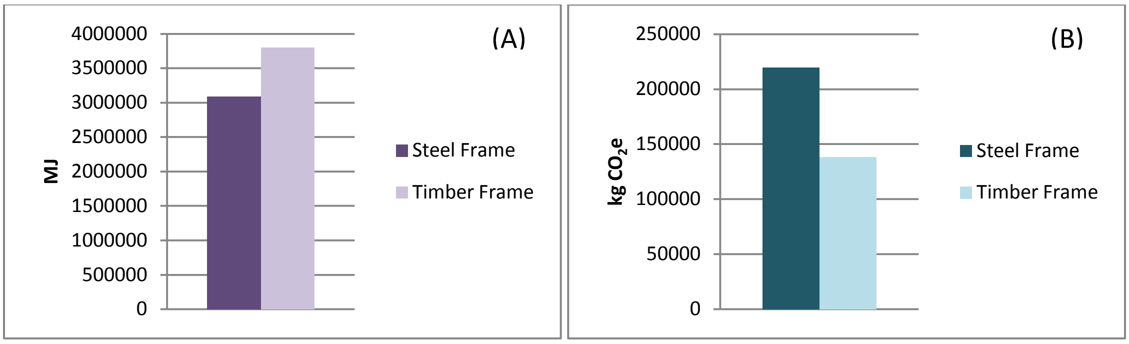


Figure 7.36: Potential savings from DfD of each of the Supermarket options, (A) shows embodied energy, (B) embodied carbon

7.7.3.2 Standard versus DfD design

This section debates where the potential benefit for design for deconstruction can be found within the structural elements and material types.

7.7.3.2.1 Option 1, the Steel Frame

The breakdown of the different structural elements shows (Figure 7.37) that the ground floor slab makes the largest contribution to both the embodied energy and carbon. The foundations also have significant impact. The columns and beams both make an impact as well, although the columns benefit from a substantial saving in the DfD design. The roof structure also shows a reduction for the DfD design. Exploring the benefit to the different materials, Figure 7.38, the steel sections gain most in the DfD design. The impact of the concrete for both embodied energy and carbon is high, which ties in with the large impact of the foundations and ground floor, as these are mainly concrete.

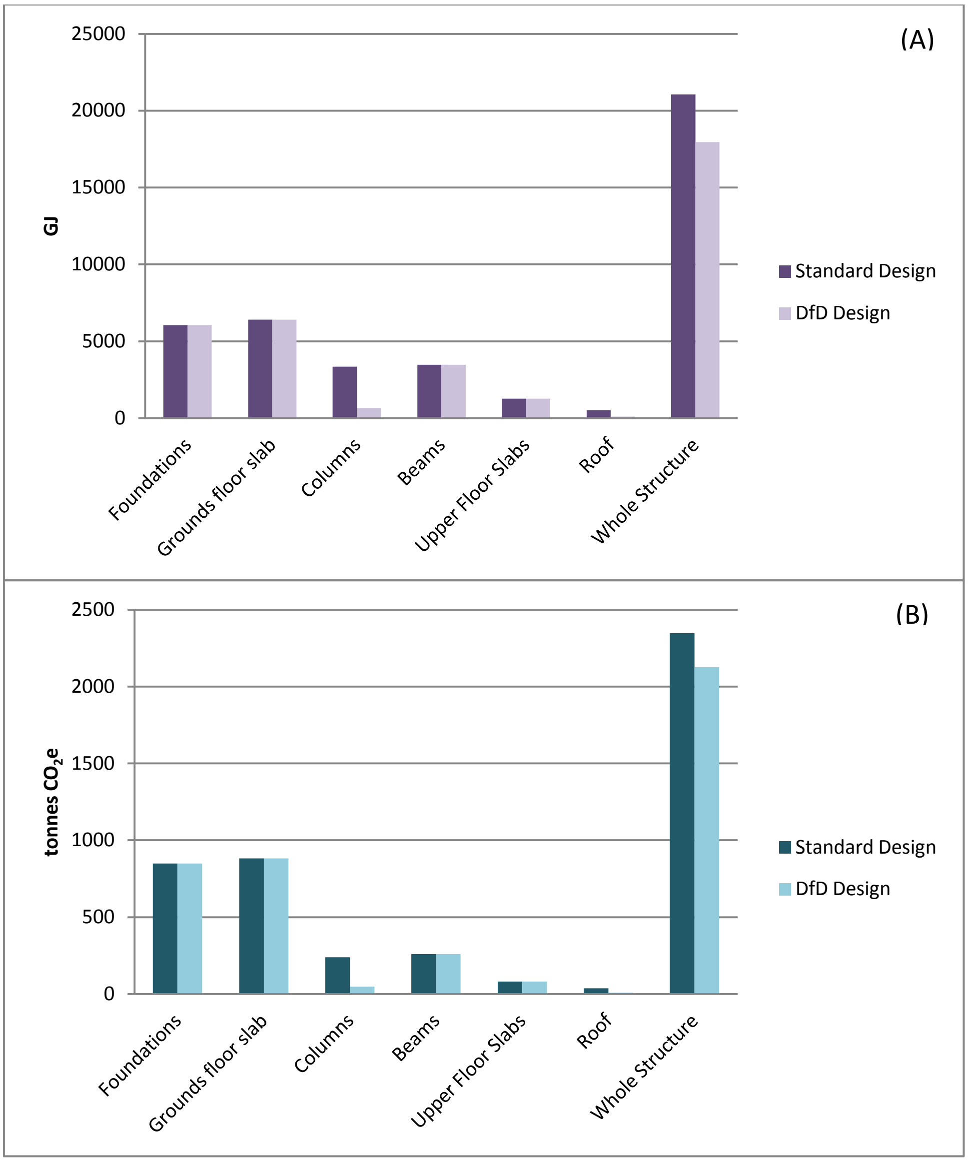


Figure 7.37: Supermarket 1, steel frame, distribution of embodied energy (A) and embodied carbon (B) for the structural elements

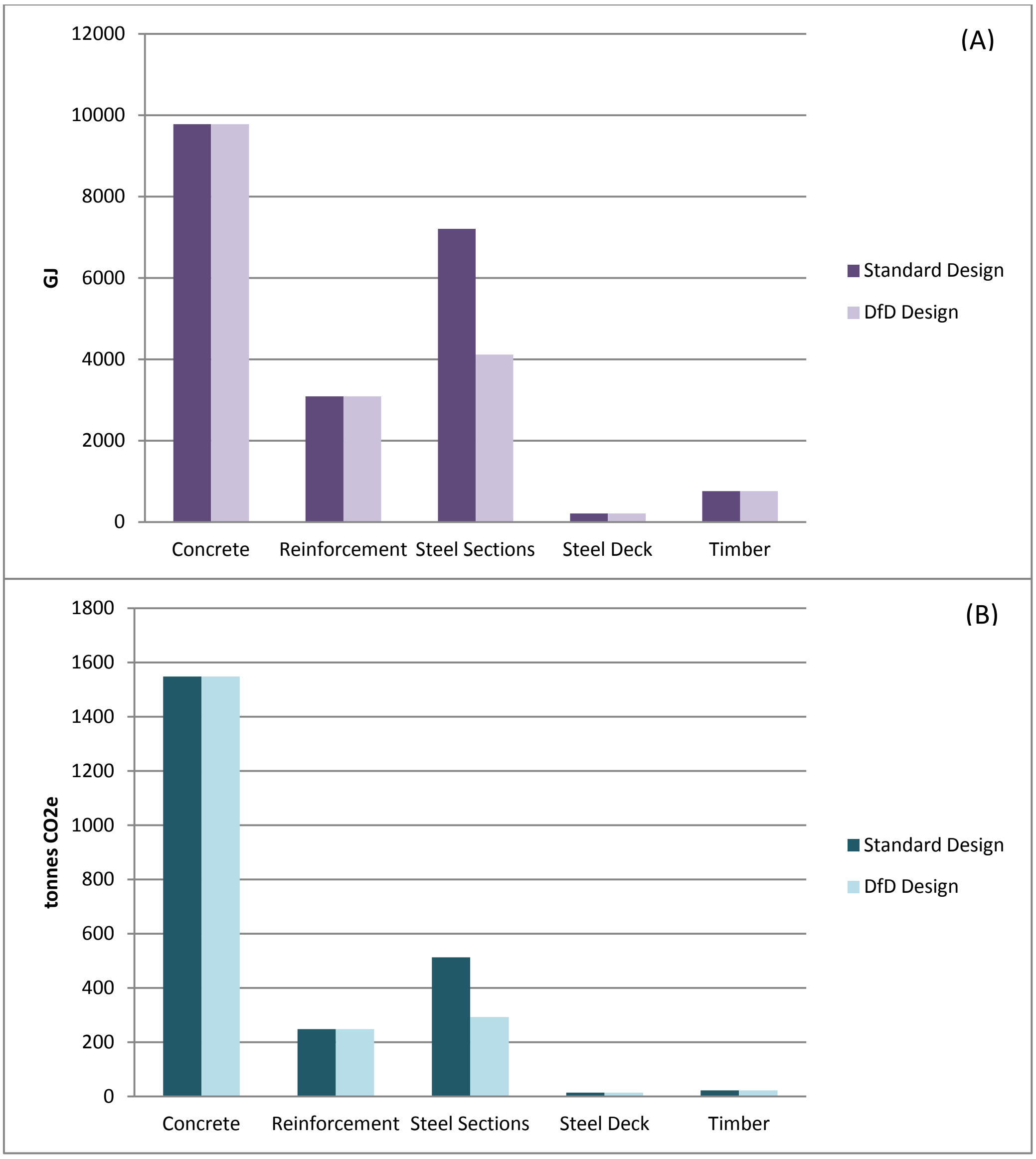


Figure 7.38: Supermarket 1, steel frame, distribution of embodied energy (A) and embodied carbon (B) for different material types

This case study shows that steel framed supermarkets can achieve large savings for the embodied energy and carbon of the superstructure if they are designed for deconstruction.

7.7.3.2.2 Option 2, the timber frame

The foundations and ground floor slab make the largest contribution to the embodied energy and carbon (Figure 7.39). The other elements all have a similar, much lower impact. The columns, beams and roof elements all see reductions in both the embodied energy and carbon resulting from design for deconstruction. When the material breakdown is explored (Figure 7.40), concrete dominates the impact on the embodied carbon and contributes the most to the embodied energy, although timber does also have a significant impact on the latter. Both timber and steel sections see savings in the DfD design. For this case study the superstructure makes up only 15% of the embodied carbon, reaffirming the importance of exploring alternatives for foundation and ground floor slab design, see Recommendations 10 and 12. However, for a supermarket with a twenty year life span, design for deconstruction reduces the embodied carbon of the superstructure by 47%.

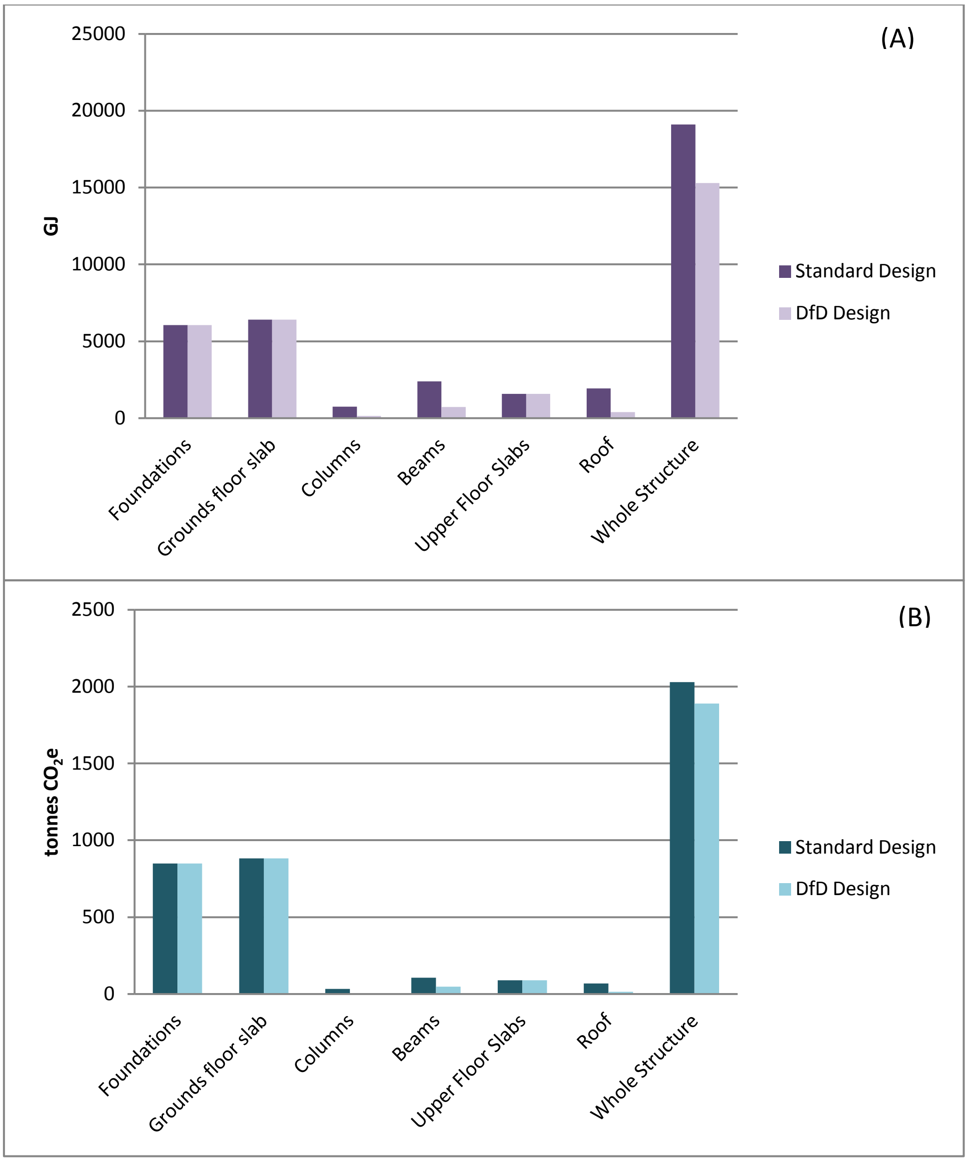


Figure 7.39: Supermarket 2, timber frame, distribution of embodied energy (A) and embodied carbon (B) for the structural elements

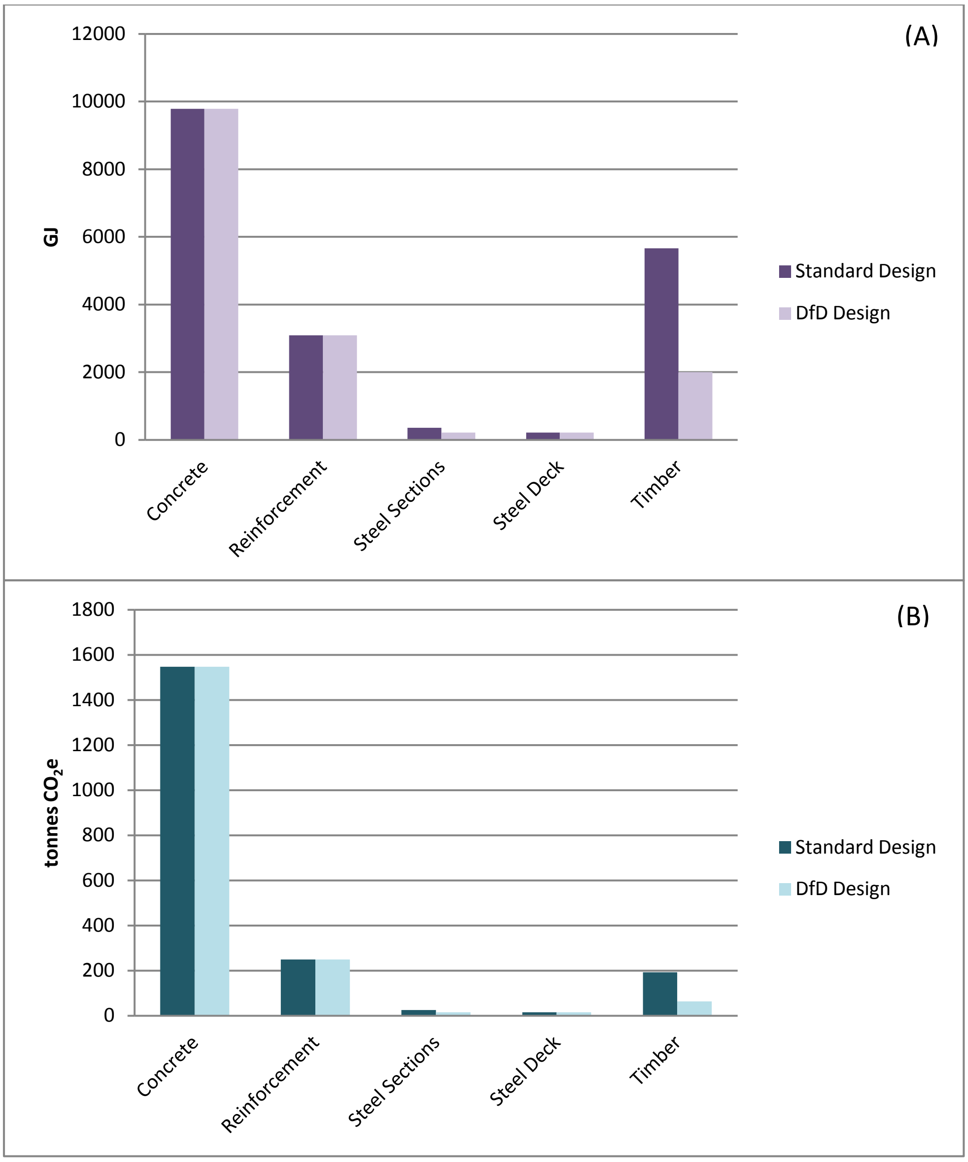


Figure 7.40: Supermarket 2, timber frame, distribution of embodied energy (A) and embodied carbon (B) for different materials

This case study demonstrates that timber designs can significantly benefit from design for deconstruction.

7.8 Conclusions

Through the examination of a range of case studies two main structural types, steel frames and timber frames, have been identified as providing the most potential for benefits arising from design for deconstruction. The benefits are quantified for embodied energy and carbon. Composite steel structures result in lower savings as the beams cannot be reused. As expected, concrete frame structures show no gains from design for deconstruction.

All building types showed some benefit from design for deconstruction, although this was minimal for the office buildings. The greatest saving in embodied carbon was by the stadium case study at over 1000 tonnes CO_2e, however, this was largely due to the scale and amount of structure rather than the appropriateness of it for design for deconstruction. A warehouse case study showed a saving of nearly 700 tonnes CO_2e and one of the school designs 500 tonnes CO_2e. Whilst the supermarket case studies displayed lower savings, the DfD timber design reduced the embodied carbon of the superstructure by 47%; demonstrating that it is the scale of this structure that gives lower savings rather than unsuitability for deconstruction.

There is an emerging argument to explore alternative designs for foundations and ground floor slabs due to the impact these have on the total embodied energy and carbon, particularly for low rise structures. This forms Recommendation 10 and 12, in Chapter 9.

Finally, the potential of Sakura is displayed here; it gives clear results and should be an effective aid for designers in assessing the potential of design for deconstruction within their own projects.

8 Discussion

8.1 Introduction

With efforts across the UK to reduce carbon emissions and create a more sustainable built environment, momentum in this area is gathering. A greater awareness of resource depletion is developing and the need to reduce dependence on natural resources may move to the forefront of the sustainable agenda over the next few years. Carbon emission reductions and minimised resource extraction, combined with targets to reduce land filled waste, suggest that now might be the ideal time to encourage people to incorporate design for deconstruction within projects as it addresses these three areas.

Even though measures are being implemented to curb carbon emissions and reduce the scale of climate change, future impacts should be considered. Changing climates will impact upon building stock, potentially affecting the amount of temperature control required within buildings. One study comments that ‘as the effects of climate change begin to take hold, many buildings will face the risk of climatic obsolescence’ (Roberts, Dwyer, & Taylor, 2011, p. 9). This may suggest a need for buildings that are adaptable so that they can be significantly altered in the future. Alternatively, the uncertainty of life spans alluded to provides the opportunity to utilise strategies which safeguard the components within new buildings. By enabling the individual elements to be reused, even if the building becomes obsolete, the waste of valuable resources is avoided. This backdrop could form the perfect stage for the roll out of design for deconstruction across the construction sector.

Design for deconstruction has gained recognition on an international stage with its inclusion within the main stadium of the 2012 Olympics. Whilst perhaps not shown to its greatest potential within this project, it has enabled a wide audience to grasp the potential of the concept. This might be the catalyst required to persuade more designers to investigate the possibilities of design for deconstruction within their own projects. Using Sakura the environmental benefits of the strategy can be quantified, highlighting those schemes which will profit from significant energy and carbon savings.

This chapter explores the sustainability of design for deconstruction; investigates and discusses potential barriers which may cause designers to have concerns, as well as identifying those construction types and buildings which may benefit most from the strategy. Finally, areas that could be altered to further facilitate design for deconstruction are identified and examined. This chapter aims to tie the body of work within the thesis together and highlight the potential of this strategy, demonstrating that it could be included within a range of buildings, adding to the sustainability of the built environment. This is the optimum time for a subtle shift in attitude across the industry to viewing buildings as warehouses of valuable materials that can be accessed by designing for deconstruction.

8.2 Is Design for Deconstruction truly sustainable?

To answer the question of whether design for deconstruction is sustainable then the case should be examined from the three facets of sustainability.

8.2.1 The Environmental Perspective

Through the assessment of feasibility studies, the development of Sakura and the exploration of case studies, the benefits of design for deconstruction in terms of embodied energy and carbon savings have been quantified for a range of materials and different building types. Embodied energy and carbon savings result in reduced energy use and carbon emissions, the benefit of this to the environment is self evident. It is this role that Sakura emphasises.

However, this is not the only area in which design for deconstruction has an impact. By including a deconstruction plan for a structure at the design stage, elements can be easily separated, ideally for reuse. In addition to this, those elements that are not suitable for reuse can be easily separated into different material types and then recycled. Increased reuse and recycling rates will significantly reduce the quantity of demolition waste that is sent to landfill. As outlined in the literature review in Chapter 2, there are EU targets in place to reduce construction and demolition waste sent to landfill due to the large negative impact this has on the environment. Reuse and preparing for reuse are mentioned in point 18 of this directive (European Parliament, 2008). Design for deconstruction specifically targets the demolition part of this waste. Nonetheless, there may also be some reduction in construction waste by carefully considering material choices. Furthermore, by assessing how elements fit together during the design process, there may be a cutback in excess materials ordered to site and in waste cut offs.

The third way in which design for deconstruction contributes to the environment is in reducing resource depletion. By increasing reuse rates of materials there is a diminished need to extract natural resources from the earth. This is becoming increasingly important as awareness of limited resources grows. As discussed in Chapter 2, there is a reliance on natural resources for structural materials. Aiming to close the material loop by dramatically increasing reuse rates in conjunction with current recycling practices will lessen this dependence on the extraction of natural resources. Design for deconstruction is the most effective way of increasing the amount of materials available for reuse in the future.

8.2.2 The Economic Perspective

Design for deconstruction, facilitating reuse of materials, provides the potential for new business models. Rather than selling new materials, they could be leased for the life time of the building. At end of life the building would be deconstructed and the materials returned to the company that leased them. If required they would be re-fabricated and leased again. Alternatively, in the future, material reuse markets will be significantly increased, expanding this area and assisting growth of the economy.

At a time when it is suggested that the business community is largely responsible for building green growth into the economy (Shankleman, 2012) new business models with a sustainable agenda embedded within them will become crucial. The Innovation and Growth Team (IGT) suggest that ‘the transition to low carbon can almost be read as a business plan for construction, bringing opportunities for growth’ (Innovation and Growth Team, 2010), creating effective material reuse markets could be one of these opportunities.

The idea of using the construction sector to stimulate economic growth has been built on by the UK Green Building Council. Their ‘Plan for Growth’ report highlights ‘opportunities for growth and commercial exploitation in [a] future resource constrained world’ (UK Green Building Council, 2012c). The mention of ‘resource constrained’ in the title of the report alone demonstrates the importance of this. There is significant potential for material reuse as a way to help close the material loop, lessen dependence on natural resources and grow the green business agenda. Those buildings that are designed to exploit future reuse of the components may be seen to be very forward thinking in a decade or two. With suggestions that business as usual won’t work for future growth and that now is the time to revolutionise the construction industry (UK Green Building Council, 2012c), it is the ideal moment to recognise the economic potential of design for deconstruction and material reuse.

Carbon taxes[3] may also impact upon buildings that have been designed for deconstruction. If carbon intensive processes become heavily taxed, the resulting products will increase in price. Steel structural elements would fall into this category, meaning that elements within buildings that have been designed for deconstruction become more valuable. Design for deconstruction could therefore be seen as a strategy to invest in carbon. The payback would be at the building end of life when the recovered elements could be sold or utilised in a different building by the current owner.

8.2.3 The Social Perspective

This area is varied and in many ways links strongly with the economic perspective. Job creation is a key area of the social gains from design for deconstruction and future material reuse. Increasing reuse markets, either for existing companies who expand into this area or for new business developed for this purpose, will create more jobs, providing benefits to some local communities. In addition, design for deconstruction is potentially more labour intensive and less reliant on demolition equipment, this could also create more jobs. Workers may also be encouraged to develop new skills as those required for deconstruction will be different to those needed for demolition.

Another important area that design for deconstruction and material reuse may impact upon is the social responsibility of businesses. Bortolozzo (2012) outlines the potential of embedding sustainability within a company. For some businesses this involves creating products that have a lower environmental impact, for others reshaping supply chains, as a result more socially responsible companies can emerge. The provision of lower impact materials for construction, like reused materials, may become the niche of some companies. Others may intentionally source reused materials for new buildings. Forward thinking business may integrate design for deconstruction into their buildings, enabling the future supply chain of reused materials to grow. Encouraging this behaviour change may fall to others and could include consumers who expect socially responsible corporations.

The importance of public image as a driver cannot be underestimated. Most large corporations have a section on their website outlining corporate responsibility which often includes sustainability. Tesco, for example, has a section on ‘Caring for the environment’ which includes emissions targets and the aim to become a zero-carbon business by 2050 (Tesco PLC, 2012). Marks and Spencer have named their green agenda ‘Plan A’, reporting in June that they are the first big UK retailer to become ‘carbon neutral’ (Smithers, 2012). Reuse of materials is also on their agenda, with 100% of construction waste from their shops being reused or recycled in 2012 (Marks and Spencer plc, 2012). As more companies compete to be recognised in this area, construction methods may come to the forefront, presenting further opportunities for design for deconstruction and material reuse to gain recognition and contribute to the sustainability of the built environment.

8.2.4 Whole Picture

The above sections outline the contribution design for deconstruction and material reuse make to the different elements of sustainability, demonstrating the many areas which benefit. Design for deconstruction creates buildings which are in effect an accessible store of valuable materials. Whilst reducing the embodied energy and carbon of projects is the focus of Sakura, the other sustainable aspects of design for deconstruction are equally important and hence

---

[3] This is a tax on the amount of carbon dioxide produced when burning a fuel; it would therefore focus on fossil fuel use. Theoretically the more CO_2 emitted the higher the tax would be on that fuel, therefore coal would incur a higher tax than natural gas as it produces more CO_2 when it is burnt. It is suggested that high carbon taxes would be an effective way to reduce CO_2 emissions (Carbon Tax Center, 2012).

discussed within this chapter. The implementation of this design strategy across the building sector would be a positive step towards a more sustainable built environment.

Whilst it is very difficult to predict the impact of design for deconstruction across the construction sector, if 70% of the UK's steelwork in a single year was designed for deconstruction, and 70% of this was reused then 600,000 tonnes of CO_2e could be saved, equating to the emissions produced by over 100,000 houses in a year (Densley Tingley & Davison, 2012). This is a substantial saving which may only provide a glimpse of the potential across the sector once other materials and many years of design are considered.

8.3 Overcoming the barriers

Whilst the use of Sakura quantifies the potential savings of designing for deconstruction, there are a number of barriers that could lead designers to have concerns. Table 2.2 in Chapter 2 outlines these. During the course of developing Sakura and in exploring case studies, additional knowledge has been gained allowing a number of the barriers to be readdressed, as discussed within this section.

Several of the barriers related to material reuse and deconstruction can be combated through design for deconstruction. Currently, specifying reused materials can be a problem due to a fragmented reuse market: the availability of reused materials is limited. This would change if large numbers of buildings were designed for deconstruction, giving a large pool of future resources that could stimulate reused material markets. In addition, problems associated with the safety of deconstructing buildings, or contaminated materials will not be an issue for buildings that have been designed for deconstruction. Contamination of materials that aim to be reused would be designed out; for example, alternative fire protection such as fire resistant boarding could be used around steel structure rather than use of intumescent paint. A deconstruction plan will be developed as part of the course of designing the building, this will involve a risk assessment, ensuring operatives are placed in minimal danger. This addresses concerns that materials be salvaged in a safe manner.

8.3.1 Additional fabrication

Elements may need some re-fabrication after they have been salvaged to make them suitable for reuse. This might be to cut them to the appropriate length required for a project, or to trim ends off which have a large number of bolt holes. However, any potential fabrication will utilise small amounts of energy. When this energy use is compared to the energy saved by reusing, which can be quantified in Sakura, it is minimal. By quantifying potential savings from reuse, this barrier of additional fabrication is removed.

8.3.2 Existing perception towards reused materials

Quantifying the significant embodied energy and carbon savings that can occur from reusing materials is an important step to overcoming the perception of reused materials. This could be an important driver for designers to incorporate reused materials into a design. Furthermore, reuse is increasingly seen to be sustainable and the image of this, as outlined in section 8.2.3, could be the incentive required by clients to include reused materials within projects. There are also an increasing number of precedent studies (Natural Resources Canada, Unknown; Lazarus, 2002) that include reused materials which will help to further remove this barrier.

8.3.3 Economic Considerations

Designing for deconstruction will potentially be more expensive for some building types. Perhaps for initial design costs if more time is spent at the design stage and in construction costs. Quantifying the cost of design for deconstruction forms Recommendation 13 of further work as there is little hard evidence of what the costs might be. There may even be no additional cost, Barrett Steel Buildings designed a warehouse at ProLogis Park, Heathrow for deconstruction with no extra cost to the client (NSC, 2008).

There is an argument to be made that an additional cost may be warranted for those projects that experience significant embodied energy/carbon savings by designing for deconstruction. Sakura can help to identify those projects. The cost increase will likely be minimal and may be lower than alternative methods of reducing the embodied energy/carbon of the project. Any additional costs will likely be reduced if design for deconstruction becomes a more common practice.

In addition, if carbon taxes are introduced and the cost of carbon intensive materials increases, designing in a way which allows reuse will become more economical. If carbon taxes are predicted to increase as time passes, investors may see the benefits of designing buildings so that valuable materials can be salvaged and resold at the end of life.

8.3.4 Composite Construction

As has been discussed throughout the thesis, composite construction is a major barrier for the reuse of elements. Whilst composite construction reduces the scope of the deconstruction, case studies in Chapter 7 demonstrate that designing the steel columns for deconstruction in a composite structure can result in savings, 250 tonnes of CO_2e for the school building studied. This implies that it would be worth applying this design principle to those projects that feel there is no alternative other than a composite slab. Further research is being conducted to explore alternatives to the traditional composite slab. Work at Northwestern University (Herring, 2012) is commencing to demonstrate the potential of a substitute concrete and steel system. Whilst research at the University of Sheffield (Okutu, 2012) is starting to investigate the possibility of cross-laminated timber as a floor alternative.

8.3.5 Performance Guarantees for Reused Materials

With the development of Building Information Modelling (BIM) and CE marking, the properties of structural elements within new buildings will be clear in the future. This will largely remove the barrier of requiring performance guarantees for reused materials as their properties will be known.

The government has made BIM compulsory for all public projects from 2016 (Ballantyne, 2011). This means that all the design data for a building will be stored, with the suggestion that it can be used by the owner to reduce construction and maintenance costs. It will also be very valuable as a record of the materials and elements that are stored within the building. For projects designed for deconstruction, as discussed in chapter 2, it is suggested a record should be made of materials and elements within the building and a full set of drawings should be retained. The advent of BIM should fulfil both of these criteria, providing all the information required to enable reuse of the building elements. A deconstruction plan could even be included so all the information is stored in one place and kept by the owner of the building.

CE marking should also assist with the provision of structural properties for steel elements. It would be most useful if the mark was placed on the product, rather than packaging or manuals as there is a possibility that these could be lost. The mark should provide structural characteristics for the element (BCSA, 2008). The provision of structural characteristics removes the barrier of performance guarantees for reused materials.

8.3.6 Lack of Legislation/incentives for design for deconstruction

Whilst there is no legislation to require design for deconstruction, there are a number of different mechanisms which may provide sufficient incentive to encourage this strategy, these could however be improved to increase effectiveness, as discussed below.

Often designers and clients will be more likely to consider new design options if there is an incentive to do so. For example, credit within environmental assessment methods. Currently, Green Star in Australia is the only major assessment method to reward design for deconstruction, although it may be possible to obtain innovation points for it within LEED and BREEAM (Densley Tingley & Davison, 2011; Charlson & Kaethner, 2012). More projects would be aware of the possibility and encouraged to incorporate the strategy if it was a specific credit.

An indirect incentive for companies might be the importance of a sustainable image as discussed in section 8.2.3. However, with the range of options available to present this image it might not result in a large quantity of buildings designed for deconstruction.

Another potential incentive is that incorporating design for deconstruction might help to obtain planning permission. A case could be put forward that by designing the entire structure, including foundations, using this strategy would enable the site to be completely cleared at end of life. This would give greater scope for the site in the future, giving no limitations to designs, whereas if the foundations were left in the ground, as is the norm, the next building on the site has to design around these or remove them, which can be challenging for concrete foundations. Local planning authorities are being encouraged by the UK Green Building Council to consider the opportunities available for reusing demolition waste. The report suggests exploring the potential of 'centralising the recovery, distribution and re-use of demolition materials' (UK-GBC Green Building Guidance Task Group, 2012, p. 16) in addition to using collaborative approaches between developers, local planning authorities and neighbourhood forums to maximise the recovery and reuse of materials.

8.4 What could be done?

This section outlines the potential scope of design for deconstruction across the construction industry. It identifies areas of opportunity and those materials and building types which have the greatest potential for energy and carbon savings.

8.4.1 Construction types

The feasibility studies identify a non-composite steel frame as accruing the greatest carbon savings by incorporating design for deconstruction. Case study projects which utilised this construction type also incurred significant savings (52 kg CO_2e/m^2 for steel framed school). In all cases the non-composite designs yielded the highest quantity of material for future reuse. Whilst composite steel frame designs did show savings (38 kg CO_2e/m^2 for a composite steel framed school), these could have been significantly increased by removing the composite nature of the designs as none of the components of a composite floor slab can be reused. It is important for designers to be aware that initially, before reuse is considered, a non-composite design will likely have a higher embodied carbon than the composite design due to the use of larger section sizes. Once a cradle to cradle approach is adopted and reuse incorporated, the embodied carbon will be significantly reduced. The potential savings should be compared to the increase in embodied carbon for the non-composite design to ensure that there is a significant net gain. Sakura could be used to assess both schemes and the data output compared.

There is also support from literature to suggest that steel frames are well suited to design for deconstruction and future reuse. Gorgolewski suggests that for 'structural steel sections, the expected performance of reclaimed components can be predicted more easily' (1999, p. 26) when compared to many other materials. The majority of precedent studies in industry that have been designed for deconstruction are also steel frame structures; these include Vulcan House and the London 2012 Olympic Stadium as discussed in Chapter 2.

The case studies suggest that timber frames are also suitable for design for deconstruction and that significant embodied energy/carbon savings can occur (405 KJ/m^2 and 15 kg CO_2e/m^2 for a supermarket building). Reusing timber is of significant benefit as an end of life scenario as it has received criticism for the greenhouse gases it emits at end of life if sent to landfill (TATA Steel & BCSA, 2012). Reusing timber and extending its life span also means that carbon is sequestered within it for longer. DEFRA are currently gathering evidence regarding the restriction of the landfill of wood waste (DEFRA, 2012). If legislation is introduced to support this, then alternative end of life options for timber will be even more important. Timber panel solutions may also provide excellent opportunities for design for deconstruction and future reuse (Green, 2012).

Steel and timber frames are therefore identified as having the best potential to produce schemes with reduced embodied energy and carbon through the inclusion of design for deconstruction.

8.4.2 Building types

Current approaches of design for deconstruction may be best suited to lower rise buildings where ensuring adequate robustness with reversible connection details may be less problematic. For higher rise or large occupancy buildings, meeting the robustness requirements may present a greater challenge. However, when the market share of multi-storey, steel buildings is considered, the majority are lower rise, 36.1% are two storey buildings and 27.3% are three storey buildings (Dowling, Steel Information, 2012). These would be well suited to design for deconstruction, suggesting that 63.4% of steel multi-storey buildings could be designed for future reuse. This would dramatically increase future supply chains of reused steel.

In Chapter 2, three building types, warehouses, supermarkets and schools, were suggested as being particularly suited for design for deconstruction. Several different structural designs for each of these building types were examined in the case studies in Chapter 6.

Two warehouse structures were examined in the case studies, a steel frame and a concrete frame with timber roof beams. Both of these showed savings from designing for deconstruction, 20 kg CO_2e/m^2 and 10 kg CO_2e/m^2. As identified in the previous section, steel frames reap high savings when designed for deconstruction, as evidenced further here; the steel saving is twice that of the concrete/timber option. These savings are substantial once the size of the warehouse (34,000 m^2) is considered. The savings will also likely have a high impact on the whole life cycle carbon. As discussed in Chapter 2, the embodied energy could make up 60% of the whole life energy of a warehouse. The high embodied energy contribution is relatively unique to warehouses and in this respect enables design for deconstruction to be a very effective method of reducing the whole life carbon of a warehouse.

There were three different school designs analysed in the case studies, a non-composite steel frame, a composite steel frame and a concrete frame. As identified in section 8.4.1, the steel frame has the largest savings at 52 kg CO_2e/m^2. This really emphasises the potential scope to reduce embodied carbon within schools if a steel frame is utilised. Savings will likely also occur if a timber frame was used but no timber frame schools have been analysed to quantify this. These savings occurred if a 50 year life span is assumed. Life spans might be shorter as schools have changing requirements and varying demographics so may need to be rebuilt or significantly altered every 20 years for example. Design for deconstruction facilitates significant alterations. If the school needed to be rebuilt, it could be deconstructed and the elements reused in different configuration for the new design. Furthermore, the embodied carbon savings would be even more substantial for short life spans as elements could be reused more times.

Two different supermarket designs were explored in the case studies, a steel frame and a timber frame. Both showed substantial savings by designing for deconstruction, 24 kg CO_2e/m^2 and 15 kg CO_2e/m^2. Whilst the timber savings are less when compared in this way, if considered as a percentage saving, both material types achieve a 10% saving. The large spans of supermarkets potentially mean that the structural components have more scope for reuse in the future due to the length and section size. The shorter life span of supermarkets, as evidenced in town centres up and down the country, gives a good reuse potential. Twenty years was assumed to be the life span in the case studies, although this might be even less in practice.

The final case study that showed significant savings is the stadium. By designing this for deconstruction over 1000 tonnes CO_2e would be saved. However, the large scale of the building should be taken into account as it is partially due to this that such large savings occur. If the saving is considered per m^2, a 9.8% saving is achieved. The composite nature of this stadium makes it less than ideal for deconstruction, therefore leading to questions of the potential savings that could be achieved with a non-composite stadium design. The large amount of structure in a stadium gives a high yield of material, which if designed appropriately can be reused. However, the life span of stadia may be less suited to design for deconstruction since in most cases stadia will be designed for longevity, to be iconic structures which will endure. Long life spans reduce the potential for future reuse of materials.

There are some cases where stadia may be downscaled if designed for a specific event but the initial capacity will not be needed in the future. This is the case for the London 2012 Olympic stadium which was designed for deconstruction so the capacity could be reduced after the games (LOCOG, 2012). Other deconstructable venues include the basketball arena and Horse Guards arena (Brown J. , 2012). Both of these were designed to be temporary and therefore designed for deconstruction.

A summary of the savings achieved for the different building and construction types is shown in Table 8.1. From this it can be seen that the steel frame school benefits most from design for deconstruction with nearly a 25% saving on the embodied carbon of the structure. Suggesting that a steel frame and a school might be the optimum combination for design for deconstruction.

Building	**Construction Type**	**Embodied Carbon Saving per m^2**
Warehouse	Steel Frame	16.0%
	Concrete/timber Frame	9.3%
School	Steel Frame	24.8%
	Concrete Frame	9.4%
	Composite Steel Frame	16.3%
Supermarket	Steel Frame	10.0%
	Timber Frame	10.3%
Stadium	Composite Steel Frame	9.8%

Table 8.1: Summary of savings for different building and construction types

8.5 What needs to change?

Throughout this chapter the sustainability and potential of design for deconstruction have been discussed and the scope and benefit across the construction industry have been demonstrated. The quantification of the energy and carbon savings will overcome a number of barriers and should help to encourage designers to incorporate this strategy. However, there are a number of aspects which could be altered or developed to further improve the uptake of this strategy.

A major change that would assist with future reuse is to develop a recertification procedure for reused elements. This suggestion forms Recommendation 8 Chapter 9. It would help to address any concerns over the quality of reused materials and would remove suggestions that the materials might not be suitable for structural reuse. In addition, if reused materials were certified for use then potential insurance problems should be combated and firms prevented from raising premiums up when reused materials are incorporated.

Others areas that it would be beneficial to develop are requirements and incentives for design for deconstruction. The potential role of legislation to require a detailed end of life consideration, for example, could significantly alter peoples' attitudes. By requiring thought and planning for end of life at the design stage many more projects might include design for deconstruction within them, facilitating future reuse, preserving resources and reducing waste. The advantages of this approach are clear and these steps would help form a more sustainable built environment, perhaps suggesting that it would not be an unreasonable area to legislate.

There is potentially a debate of the level of government that should be responsible for end of life legislation. Work by Theaker and Cole (2001) implies that local governments can be the best place to develop and implement legislation that directs the industry to more sustainable buildings. Local governments already deal with planning applications and building regulations, expanding this to requiring end of life planning of buildings would be a natural extension of their role.

An alternative to legislative requirements is to incentivise design for deconstruction and material reuse. This, as discussed in Chapter 2, and section 8.3.6, could include incorporating additional credits within environmental assessment methods as these can be effective catalysts for change. Other less explicit incentives might be that it could be easier to get projects through planning if they have been designed for deconstruction, as discussed in section 8.3.6. Moving forward in a combination of these ways could spark a greater uptake of design for deconstruction.

8.6 Conclusion

As advances are made towards a sustainable future it is important that the whole life cycle of the built environment is considered so that its potential can be maximised. By designing for deconstruction significant amounts of resources are conserved, reusing rather than recycling saves energy and carbon emissions and the amount of unusable waste produced is significantly reduced. This chapter outlines the sustainability of the strategy, demonstrating how it contributes to each of the three cores that together form a better future. The quantification of the energy and carbon savings possible from design for deconstruction and subsequent reuse should enable designers to realise the potential of the strategy and encourage its inclusion within designs. As discussed in the introduction, now is the ideal time to be setting in motion this concept. By exploiting the opportunities within buildings and the valuable resources that they house, a more sustainable future can be constructed.

9 Conclusions and Recommendations

9.1 Conclusions

In a world where many natural resources are becoming scarce and environmentally damaging quarrying must take place to excavate reserves, it is important to consider alternatives and aim to close the material loop. This involves increasing reuse and recycling rates, so reliance is shifted towards materials that have already been extracted to fulfil demand. The other benefit of reusing and recycling more materials is the resulting reduction in waste sent to landfill. Furthermore, there is an advantage of reusing over recycling because it uses significantly less energy. With reduction targets for carbon emissions across the world, reducing energy use is vital, further demonstrating the importance of reuse. However, fragmented supply chains are currently preventing wide scale reuse. Design for deconstruction is suggested as a strategy to increase future supply chains; the more buildings built for deconstruction, the greater the amount of reused materials available in the future.

However, in spite of the arguments in favour of design for deconstruction and material reuse it is not common practice. From an extensive literature review two alternatives were identified to increase the uptake of design for deconstruction, viz., inclusion within environmental assessment methods and a quantification of the environmental benefits that occur from the designed-in reuse.

In a detailed examination of the LEED environmental assessment method it was found that few projects achieved material reuse credits; further implying procurement problems. *It was recommended that design for deconstruction be included as a specific credit to encourage use of this strategy* (Densley Tingley & Davison, 2011). If methods were altered to consider embodied carbon this would also potentially increase reused material specification. Environmental assessment methods are seen as an effective incentive to encourage design concepts and could be a strong catalyst for the design for deconstruction of new buildings.

The second alternative to increase uptake was quantifying the environmental benefits of design for deconstruction. A critical review of existing sustainability tools was undertaken, demonstrating that no tools currently calculate the benefits of design for deconstruction. It was therefore established that a new tool needed to be created. *A new methodology was developed to share the environmental impacts of an element between the number of predicted lives of the element* (Densley Tingley & Davison, Developing an LCA methodology to account for the environmental benefits of design for deconstruction, 2012). The examples considered are set within a hundred year life span and the majority of buildings are assumed to have a fifty-year life, meaning that elements have two potential uses. These assumptions may give conservative results for durable materials such as steel, which may have the potential to reused beyond the 100 year time frame of the study. The environmental impact is calculated in energy and carbon terms and it is in this form that potential savings are given. Estimations were also made for the contribution of each of the life cycle stages to the whole life cycle carbon in order that the benefit of design for deconstruction could be explored over the whole life cycle. However, the level of the approximation means that whole life cycle estimations will not be included within the tool, only in studies contained in this thesis.

Initial feasibility studies were conducted to test the idea of quantifying the environmental benefits of design for deconstruction. A structural bay for three steel frame types was explored (composite, partially composite and non-composite) revealing that the non-composite bay incurred the best savings, 49% reduction in embodied carbon from design for deconstruction and subsequent material reuse. The other two bay types also displayed some savings but these were less significant. When savings were considered over the whole life cycle, a 5.4% reduction in whole life carbon was achieved if the structure was designed for deconstruction. *A sensitivity study was conducted to examine the effect of dataset choice revealing a 45% increase between the lowest and highest set of results*. It is important to bear this variation in mind when comparing the results of studies which may have used different datasets. The feasibility studies demonstrated the significant savings that could be achieved through design for deconstruction, reinforcing the idea of creating a tool that would allow designers to investigate the benefits for their specific projects. The importance of creating a tool that can be used at a conceptual design stage before too many decisions have been made was also highlighted. For example, if a composite slab was already a firm design decision then the potential material yield from design for deconstruction would be significantly less.

Sakura, a web-based tool has been developed to calculate the embodied energy and carbon and the saving arising from design for deconstruction (Densley Tingley & Davison, In-press 2013). Students have piloted the tool in coursework designs and it is has been used for the assessment of a number of case studies within this thesis. Sakura should assist designers in the decision making process, enabling them to establish the savings to their project if it was designed for deconstruction.

From the analysis of case studies two material types, timber and steel, consistently showed good savings from design for deconstruction. These were initially identified in the literature review as likely to be suited to this strategy and this was confirmed in the case studies. *Warehouses, schools and supermarkets offer the most potential for reducing environmental impact when designed for deconstruction.* A steel structure within a school was found to have the greatest saving, 25% of the embodied carbon per m^2. The identification of materials and building types that may be best fitted with this strategy is potentially very useful for designers as a starting point. Sakura can then be used to explore the particular project in more detail. The quantification of potential savings is an effective way to persuade designers to consider this strategy and include it when the reduction in embodied values is significant.

The body of work within this thesis demonstrates the significant contribution that design for deconstruction can make to the sustainability of structures (Densley Tingley & Davison, 2011). The validity of the strategy is demonstrated by case studies run through Sakura and in feasibility studies. Sakura in itself should enable designers to explore the advantages of design for deconstruction in their projects, highlighting where significant savings can be made and assisting in the design process. This work and Sakura aspire to make a small step towards constructing a truly sustainable built environment.

9.2 Recommendations for further work

The recommendations fall into two main categories, general recommendations that have evolved or come to light during the course of the thesis and those related to the development of Sakura. The former are addressed first, and then the latter which includes studies to be carried out using Sakura, development of the datasets within Sakura and advances in the scope of Sakura.

9.2.1 General Recommendations

These recommendations cover a range of topics for further study which have been identified during the course of this PhD. For each, an explanation of why it is important is outlined and start points for the study are identified.

1. *Additional studies of environmental assessment methods*

Chapter 3 identified a number of patterns in the credits obtained in LEED. Further studies into this should be conducted in order to gain a better understanding of credits obtained and those that are harder to achieve. Exploring projects from all levels of certification would enhance understanding. Assessment of projects which have used LEED version 3 could also reveal more about credit uptake. It would also be very useful to conduct this type of study for other environmental assessment methods, for example, BREEAM and Green Star. This could also lead to analysis of different procedures in different countries and a more thorough comparison of these different methods.

2. *Determine estimates for the contribution of different life cycle stages to whole life carbon for buildings with low operation energy use*

In Chapter 4, in order to make whole life estimates, precedents from literature were averaged to estimate the contribution of each life cycle stage. However, these estimations were carried out for projects already built, which for the most part have a standard operation energy use. New buildings within the UK should have lower regulated energy use due to stricter building regulations. This means the estimates used in Chapter 4 may not be accurate for these new, low carbon buildings. It would also be useful to have these estimations for a range of building types as the contribution from each life cycle stage will likely differ from a warehouse to an office for example. It is therefore suggested that a study be conducted predicting the impact of each life cycle stage for low operational energy buildings. A range of building types should be explored and different construction types could also be investigated. Recommendation 21 requires this work to be undertaken.

3. *Estimate average benchmarks for the embodied carbon of different structural types and building types*

As embodied carbon calculations become more common and integrated within the design process, it will be important to have a reference point for what a good embodied carbon figure is for a low operational energy building. A large number of case studies would need to be studied and the embodied carbon of them calculated in order to gather this information. Different building types and different structural types would need to be assessed so a series of benchmarks could be derived. It would be very useful for designers to have a frame of reference for high embodied carbon, average embodied carbon and low embodied carbon. This would enable them to shape their designs into low embodied carbon buildings. The course of this work would also likely yield various design tactics which result in reductions in embodied carbon. This in time could form guidance for the construction industry. Recommendation 20 relies on this work being fulfilled.

4. *Calculate the embodied water of different materials*

In the same way that there are embodied energy and carbon values for a range of materials, it would be useful to develop this for embodied water, meaning that the amount of water used to produce a material would be estimated. Water scarcity is already an increasing problem and material production can utilise large amounts of water. For example, 14 tons of water are required to produce a single ton of steel (Brown L. , 2011, p. 30). As a valuable commodity used to construct buildings, this is a factor which should be considered that it is not currently assessed. There is limited data currently available but this is information that manufacturers will have, and it is likely a case of collating and averaging large amounts of data. Putting together a dataset of embodied water factors would enable designers to have a discussion and consider this resource in the design process, in the same way as embodied carbon is entering these debates. Recommendation 16 is dependent on this work first being conducted.

5. Quantify and compare the environmental impacts of refurbishment against deconstruction then rebuilding

As identified in Chapter 4 it would be useful to conduct a study exploring the environmental impacts of refurbishing existing buildings and comparing this to the impacts that occur by deconstructing the existing building and then rebuilding a new energy efficient version, utilising materials from the existing building. This should also explore the embodied impacts of both designs as well as the potential energy savings in use. This type of study could help to identify if refurbishing the existing building stock is better for the environment than deconstructing it and rebuilding.

6. The effect of transport on embodied carbon

A study that explores the effect of transport on the embodied carbon of different materials would enable a great understanding of the impact of this area. Transport should be included within embodied carbon values but there can be a difficulty in assessing this. An exploration of the procurement of the main structural materials within the UK could quantify the average impact of transport on the embodied carbon of these materials. This study could also explore whether it is better to specify a local material with a high initial embodied impact or a material from further away that has a low initial embodied impact. A better understanding of this issue would help designers with material choices. In addition, if average data was developed it could be included within Sakura to give an indication of the effect of transport on embodied carbon.

7. Explore the potential impact of carbon taxes on the future reuse of steel

As discussed in Chapter 8, carbon taxes could have an impact on the future value of steel and thus may make a strong argument to design it for reuse now, maximising the potential of what could in the future be a very valuable resource. A study to explore this is suggested, considering different scenarios for carbon taxes and exploring how these might affect the price of steel and thus impact on design for deconstruction and future reuse.

8. Develop a structural recertification procedure for reused materials

If a recertification procedure was developed for structural reused materials it would eliminate a major barrier to specifying them. This would assess if the materials were safe to use again as structural components. It would potentially encourage more designers to specify reused materials and might eliminate insurance concerns that sometimes arise from the reuse of structural materials. Ways to minimise the cost of the recertification procedure should be explored. It suggested that an emphasis be placed on recertifying timber and steel elements as these materials lend themselves to design for deconstruction and future reuse.

9. Calculate the embodied energy and carbon of a pre-tensioned strand

When calculating the embodied carbon of pre-cast planks during feasibility studies, the lack of reliable embodied data for pre-tensioned strands was identified. The closest match within the ICE data is for wire and the values are stated to be uncertain and an initial study modelling the strand in SimaPro (LCA software) was conducted but insufficient information was easily available for a thorough analysis. More detailed modelling of all the processes is suggested to ascertain a more reliable figure. Discussions with industry might result in a better understanding of the processes and the impacts involved and thus to a more accurate model. This information could then be used for more representative embodied calculations of pre-cast elements. Once embodied energy and carbon estimates are derived they could be integrated within the datasets of Sakura for more representative calculations.

10. *Conduct an investigation into methods to reduce the embodied energy & carbon of foundations*

A number of the case studies in Chapter 7 highlighted the large impact foundations can have on the total embodied energy and carbon of a structure, this is particularly the case for low rise buildings. It is therefore suggested that an investigation is conducted exploring ways of reducing the embodied energy and carbon of traditional foundation types and developing alternative foundations types with lower embodied carbon than traditional sorts. The use of cement replacements, fly ash and ground granulated blast furnace slag might be good starting points for concrete based foundations. Reuse of H piles and steel sheet piles is suggested as a way to reduce the embodied values of these foundation methods, investigations into the practicality of this is suggested.

11. *Developing pile caps that require less materials or non-cementitious materials resulting in lower embodied energy/carbon pile caps*

Several of the case studies demonstrated the large quantity of material that can be required to construct pile caps, this amounts to significant quantities of embodied energy and carbon. It is therefore suggested that a study is undertaken to investigate if less material can be used within pile caps or the cement content sufficiently reduced to produce low embodied energy/carbon pile caps.

12. *Explore alternatives for ground floor slab design in order to reduce the embodied energy & carbon*

In Chapter 7 it could be seen that the ground floor slab had a large impact on the embodied energy and carbon, particularly for low rise buildings. It would therefore be beneficial to explore alternative designs to the traditional in-situ concrete that forms ground floor slabs. Ways to reduce the impact of the current design could be explored as well as innovative construction forms to replace the traditional designs. An investigation could be conducted for a range of options, identifying the option with the lowest embodied energy/carbon.

13. *Estimating the additional cost of Design for Deconstruction*

As discussed in Chapter 8, whilst there are suggestions that Design for Deconstruction may cost more, this has not been quantified. A study is proposed to explore the potential costs of design for deconstruction, both in terms of design and for construction. This would further assist designers in the decision making process.

9.2.2 Recommendations Related to Sakura

This set of recommendations relate to the development of Sakura or outline studies to be conducted using Sakura. Some of the recommendations are dependent on the output from earlier recommendations. Others will be more useful updates if Sakura is widely used throughout the construction industry.

14. *Conduct a sensitivity study for the input options within Sakura*

There are two input options for material quantities, kg or kg/m^2 for each of the input options. The latter is designed for projects at a conceptual stage, the former for more detailed designs. More detailed information will give a better estimate for the embodied energy and carbon; it is not known how close results from kg/m^2 input are to results for kg input. It would be useful to know the level of accuracy that can be achieved using the kg/m^2 input. The study suggested would attempt to quantify this. Building information would need to be obtained for a number of case studies where there were few major design changes between the scheme design stage and construction. The calculations done throughout the design process would be needed. Using scheme design information, Sakura would be used to estimate the embodied carbon and energy. A second run through would be conducted using detailed construction information. The results would then be compared and the level of accuracy for the first estimation could be calculated. Guidance could then be given to users of Sakura as to the expected accuracy of results at a scheme design stage.

15. Addition of new datasets to Sakura

Currently Sakura runs off one dataset, the Inventory of Carbon and Energy (Hammond & Jones, Inventory of Carbon & Energy version 2.0, 2011). Additional datasets could be added to give users more options when carrying out calculations. CESMM3 data (Franklin + Andrews Ltd., 2011) and the UK Building Blackbook data (Franklin + Andrews Ltd., 2010) could be used as datasets. However, the format the data is presented in does not suit Sakura, for example, for steel sections embodied carbon is given for different section sizes. This would either need to be converted to a averaged value for steel sections so that it could be used with current kg or kg/m^2 input options or an additional input option would need to be added to Sakura, which allows specific section sizes to be entered and the embodied carbon assessed from these. At present these datasets only contain embodied carbon information so studies selecting these datasets would be limited to this output.

16. Inclusion of embodied water estimates within Sakura

The importance of considering the water embodied within construction projects is discussed in Recommendation 4. It is for these reasons that embodied water would ideally be included within Sakura, as a way to encourage designers to think about this in addition to energy/carbon. However, the lack of current information means that Recommendation 4 must be carried out before this recommendation could be implemented. Embodied water could be presented in much the same way as embodied energy and carbon are on the results page within Sakura.

17. Inclusion of Structural Walls/Shear Cores within Sakura

When the office case studies were being conducted, the need to include input options for structural walls was identified. It was only in this 10 storey building that concrete cores were present. As an inherent part of the structure it was felt they should be included in the study, they were modelled as in-situ floors as the input options are very similar. However, once others are using Sakura it would be more useful if there was a specific input option with the potential materials for structural walls. This would make Sakura easier to use and ensure that all major structural elements are included and analysed in the study.

18. Expansion of Sakura to include non-structural elements

The scope for design for deconstruction is not limited to structural elements. Sakura could be expanded to include all major building elements and demonstrate the potential for deconstruction within these as well. Alternatively this could form a different version of Sakura that users could select depending on their requirements. Providing a full embodied carbon assessment would be useful for designers and designing the entire building for deconstruction could produce addition embodied energy/carbon savings, as alluded to in Chapter 5.

19. Perform further studies exploring the impact of DfD on different bay sizes and construction types

An expansion of the feasibility studies conducted in Chapter 5 would give a more in depth understanding of the implication of design for deconstruction on a wide variety of structure bay designs. Sakura could be used to analyse the different structural designs and assess the potential energy and carbon savings. Mammen (2012) utilised Sakura to do just this for certain concrete and steel bay types. However, this work can still be further extended, in particular it would be useful to explore the impact of different bay sizes and to quantify the benefits for different types of timber construction.

20. Include embodied energy and carbon benchmarks for different buildings and construction types

This relies on Recommendation 3 being carried out. It would be useful for designers to compare their schemes that they have run through Sakura with industry benchmarks so that they know if the embodied carbon for their project is low, average or high compared to the benchmarks. This would help designers decided if they should revise designs to lower the embodied energy/carbon value. This would be included on the results page of Sakura and would be refined to the building type selected at the initial information stage.

21. Develop Sakura to include a whole life cycle study

In Chapter 4 a methodology was developed to assess whole life carbon. However, this was not included within Sakura due to the uncertainty of the estimated impact of each life cycle stage. If the work in Recommendation 2 is completed then there should be sufficient and reliable data to estimate the impact of the different life cycle stages and this could then be incorporated within Sakura, allowing it to estimate the environmental impacts over a full life cycle of a building.

22. Develop output options for results in Sakura

One potential expansion of Sakura is to include graphical results to assist users in visualising the impact of design decisions. This may be more useful to compare options or for when Sakura is developed to include the impacts of the whole life cycle (Recommendation 21). A second development is to include a print function for the output as this might be useful for some users. The final suggestion is to relate energy and carbon savings to a visual metric. A MJ of energy and kg CO_2 can be abstract metrics and people may not have a good understanding of what they mean or the implications of the savings. If the savings were equated to the average amount of energy used in a house over a year for example then they would perhaps mean more. By translating energy and carbon savings it could help non-specialists using Sakura understand the impact that designing for deconstruction can make.

10 References

Addis, B., & Schouten, J. (2004). *Design for deconstruction - principles of design to facilitate reuse and recycling.* London: CIRIA.

Athena Institute. (2008). *Athena Impact Estimator for Buildings V3.03 Software and Database Overview*. Retrieved August 16, 2010, from http://www.athenasmi.org/tools/impactEstimator/innerWorkings.html

Athena Institute. (2010). *The Impact Estimator for Buildings*. Retrieved August 16, 2010, from Athena: http://www.athenasmi.org/tools/impactEstimator/index.html

Australian Steel Insitute (ASI). (2010). *Recycle, reuse, and reduce*. Retrieved May 9, 2010, from http://www.steel.org.au/inside_group.asp?ID=614&pnav=612

Ballantyne, B. (2011, July). Sharing the vision. *New Civil Engineer* , 16-17.

BBC. (2009). *Climate Change - Sea Level Rises*. Retrieved May 8, 2010, from http://www.bbc.co.uk/climate/impact/sea_level.shtml

BCSA. (2008). *Guide to the CE Marking of Structural Steelwork.* London: British Constructional Steelwork Association.

BIS - Department for Business Innovation & Skills. (2010). *Estimating the amount of CO2 emissions that the construction industry can influence - supporting material for the Low Carbon Construction IGT report.* Retrieved August 11, 2011, from http://www.bis.gov.uk/assets/biscore/business-sectors/docs/e/10-1316-estimating-co2-emissions-supporting-low-carbon-igt-report

Blengini, G. A., & Carlo, T. D. (2010b). Energy-saving polices and low-energy residential buildings: an LCA case study to support decision makers in Piedmont, Italy. *International Journal of Life Cycle Assessment , 15*, 652-665.

Blengini, G. A., & Carlo, T. D. (2010a). The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. *Energy and Buildings , 42* (6), 869-880.

BLP Insurance. (2011). *Butterfly*. Retrieved June 6, 2012, from http://www.blpinsurance.com/news-events/events-exhibitions/article/7-feb-2012-event-full-free-presentation-butterfly-low-carbon-design-decision-tool-3681/

Bordigoni, M., Hita, A., & Le Blanc, G. (2012). Role of embodied energy in the European manufacturing industry: application to short term impacts of carbon tax. *Energy Policy* , 335-350.

Bortolozzo, B. (2012). *The Secret of Sustainable Branding*. Retrieved September 26, 2012, from PRe: http://www.pre-sustainability.com/the-secret-of-sustainable-branding

Bramley, R., Ciotti, L., Parnaby, R., & White, C. (2010). Carbon profiling of a school building at an architectural practice. In A. Akintoye, J. Goulding, F. Rahiman, D. Brindley, & S. Emmitt (Ed.), *9th International Detail Design in Architecture Conference*, (pp. 157-168). Preston, England.

Braungart, M., & McDonough, W. (2009). *Cradle to Cradle: Re-making the way we make things.* London: Vintage.

Bridges Carbon Calculator. (2012). Retrieved June 7, 2012, from SteelConstruction.org: http://www.steelconstruction.org/resources/sustainability/bridges-carbon-calculator.html

British Standards Institution. (2010). *BS EN 1990:2002+A1:2005. Eurocode - basis of structural design.*

British Standards Institution. (2006a). *BS EN ISO 14040:2006, Environmental management - life cycle assessment - principles and framework.*

British Standards Institution. (2006b). *BS EN ISO 14044:2006 - Environmental management - life cycle assessment - requirements and guidelines.*

Brocklesby, M. (1998). *The Environmental Impact of frame materials, an assessment of the embodied impacts for building frames in the UK construction industry.* Ph.D Thesis, The University of Sheffield.

Brown, J. (2012). *What's next for the London 2012 Olympic venues?* Retrieved October 03, 2012, from The Independent: http://www.independent.co.uk/sport/olympics/news/whats-next-for-the-london-2012-olympic-venues-8037297.html

Brown, L. (2011). *World on the edge, how to prevent environmental and economic collapse.* New York: W.W. Norton & Company.

BSCA & Corus. (Unknown date). *Sustainable Steel Construction - building a sustainable future - guidance booklet.* Retrieved May 9, 2010, from http://www.corusconstruction.com/file_source/StaticFiles/Construction/Responsibility/sustainable_steel_construction_final.pdf

Buchanan, A. H., & Honey, B. G. (1994). Energy and carbon dioxide implications of building construction. *Energy and Buildings , 20*, 205-217.

Building Codes Assistance Project (BCAP). (2010a). *Code Status: Arizona.* Retrieved March 23, 2010, from http://bcap-energy.org/node/54#current

Building Codes Assistance Project (BCAP). (2010b). *Code Status: Missouri.* Retrieved March 23, 2010, from http://bcap-energy.org/node/78

Building Codes Assistance Project (BCAP). (2010c). *Code Status: New York.* Retrieved March 25, 2010, from http://bcap-energy.org/node/86

Building Research Establishment (BRE). (2010c). *BREEAM International*. Retrieved May 5, 2010, from http://www.breeam.org/page.jsp?id=96

Building Research Establishment (BRE). (2010d). *Code for Sustainable Homes*. Retrieved May 5, 2010, from http://www.breeam.org/page.jsp?id=86

Building Research Establishment (BRE). (2012). *envest 2 - about*. Retrieved May 30, 2012, from envest 2: http://envest2.bre.co.uk/account.jsp

Building Research Establishment (BRE). (2007). *Methodology for environmental profiles of construction products.* Retrieved May 5, 2010, from http://www.bre.co.uk/filelibrary/greenguide/PDF/Environmental_Profiles_Methodology_2007_-_Draft.pdf

Building Research Establishment (BRE). (2010a). *Scheme document SD 5051 - BREEAM Education 2008.* Retrieved May 5, 2010, from http://www.breeam.org/filelibrary/SD5051_4_0_BREEAM_Education_2008.pdf

Building Research Establishment (BRE). (2010b). *Schemes from starter homes to opera houses.* Retrieved May 5, 2010, from http://www.breeam.org/page_1col.jsp?id=54

Building Research Establishment (BRE). (2010). *SMARTWaste*. Retrieved August 17, 2010, from http://www.smartwaste.co.uk/index.jsp

Building Research Establishment (BRE). (2008). *The True Cost of Waste*. Retrieved May 31, 2012, from http://www.wastecalculator.co.uk/page.jsp?id=48

Burgan, B. A., & Sansom, M. R. (2006). Sustainable Steel Construction. *Journal of Constructional Steel Research , 62* (11), 1178-1183.

CALGreen Code. (2010). *California Green Building Standards Code.* Retrieved March 2, 2010, from CALGreen: California Green Building Standards Code

Canada Green Building Council (CaGBC). (2010). *LEED Canada Green Building Rating Systems*. Retrieved March 10, 2010, from http://www.cagbc.org/leed/systems/index.htm

Carbon Tax Center. (2012, June 29). *Introduction, What's a Carbon Tax?* Retrieved October 12, 2012, from Carbon Tax Center - Pricing carbon efficiently and equitably: http://www.carbontax.org/introduction/#what

Carr, J., & Reynolds, P. (2007, April 17). Design and Construction of the Kingston Communications Stadium, Hull. *The Structural Engineer* , 28-32.

Charlson, A., & Kaethner, S. (2012). *The Value of Structural Engineering to Sustainable Construction.* London: The Instiution of Structural Engineers.

Chini, A. R., & Balachandram, S. (2002). Anticipating and responding to deconstruction through building design. *Design for deconstruction and material reuse, proceedings of the CIB Task Group 39, deconstruction meeting, Karlsruhe, Germany, April 2002.* CIB Publication 272, Paper 14.

Chini, A. R., & Bruening, S. F. (2003). *Deconstruction and materials reuse in the United States.* Retrieved October 14, 2009, from http://web.dcp.ufl.edu/ckibert/DeconstructionBook

Chini, A. R., & Nguyen, H. T. (2003). Optimising deconstruction of lightwood framed construction. *Proccedings of the 11th Rinker International Conference, Gainesville, Florida, USA, May, 2003.* CIB Publication 287, paper 26.

Choppin, S. (2009). *Emissions by transport type.* Retrieved July 6, 2012, from Guardian Datablog: http://www.guardian.co.uk/environment/datablog/2009/sep/02/carbon-emissions-per-transport-type

CIBSE. (2008). *Energy Benchmarks, TM46.* London: CIBSE.

Cole, R. J., & Kernan, P. C. (1996). Life-cycle energy use in office buildings. *Building and Environment , 31* (4), 307-317.

Communities and Local Government. (2008d). *Code for Sustainable Homes - techincal guide.* Retrieved May 5, 2010, from http://www.planningportal.gov.uk/uploads/code_for_sustainable_homes_techguide_oct08.pdf

Communities and Local Government. (2008c). *Definition of zero carbon homes and non-domestic buildings, consultation.* Retrieved April 26, 2010, from http://www.zerocarbonhub.org/resourcefiles/1101177.pdf

Communities and Local Government. (2008a). *Improving the energy efficiency of our buildings - A guide to Display Energy Certificates and advisory reports for public buildings.* London: Crown Copyright.

Communities and Local Government. (2008b). *The Government's methodology for the production of Operational Ratings, Display Energy Certificates and Advisory Reports.* London: Crown Copyright.

Cooper, M. (2009). Stadium Sprints to finishing line. *New Steel Construction , 17* (9), 16-17.

Corus. (2008). *Vulcan House, Sheffield, Framed in Steel - sustainable development in the city.* Retrieved Feburary 11, 2010, from http://www.corusconstruction.com/file_source/StaticFiles/Construction/Library/Sections/FIS_Vulcan_House.pdf

Crowther, P. (2001). Developing an inclusive model for design for deconstruction. *Deconstruction and material reuse: technology, economic and policy, Proceedings of the CIB Task Group 39, Deconstruction Meeting, Wellington, New Zealand, 6 April 2001* (pp. 1-26). CIB publication 266, paper 1.

Crowther, P. (2003). *The State of Building Deconstruction in Australia.* Retrieved October 12, 2009, from http://web.dcp.ufl.edu/ckibert/DeconstructionBook

Cyberphysics. (2008). *Sankey Diagrams*. Retrieved October 22, 2012, from http://www.cyberphysics.co.uk/general_pages/sankey/sankey.htm

Davis Langdon & Urban Green Council. (2009). *Cost of Green in NYC.* Retrieved Feburary 18, 2010, from http://www.davislangdon.com/upload/images/publications/USA/Cost_Study_NYC_10.02.09.pdf

Defra. (2012). *Waste Review*. Retrieved July 17, 2012, from Waste and Recycling: http://www.defra.gov.uk/environment/waste/review/

DEFRA. (2012, July). *Wood Waste Landfill Restrictions in England, Call for Evidence*. Retrieved October 02, 2012, from http://www.defra.gov.uk/consult/files/consult-wood-waste-document-20120808.pdf

Densley Tingley, D., & Davison, B. (In-press 2013). Desigin-in reuse and quantifying the benefits. *Reclaim and Remake International Symposium, Washington DC, 11-13 April 2013.*

Densley Tingley, D., & Davison, B. (2011). Design for deconstruction and material reuse. *Proceedings of the ICE, Energy , 164*, 195-204.

Densley Tingley, D., & Davison, B. (2012). Developing an LCA methodology to account for the environmental benefits of design for deconstruction. *Building and Environment , 57*, 387-395.

Densley Tingley, D., & Davison, B. (2012). Making the case for design for deconstruction. *IStructE Young Researchers Conference 2012*, (p. Poster Presentation). London.

Densley Tingley, D., & Davison, B. (2011, June). Supporting Design for Deconstruction through Environmental Assessment Methods. *Architectural Science* , 1-18.

Dixit, M. K., Fernandez-Solis, J. L., Lavy, S., & Culp, C. H. (2010). Identification of parameters for embodied energy measurement: a literature review. *Energy & Buildings , 42*, 1238-1247.

Dolan, P. J., Lampo, R. G., & Dearborn, J. C. (1999). *Concepts for reuse and recycling of construction and demolition waste, US Army Document.* Retrieved August 19, 2010, from http://www.cecer.army.mil/TechReports/lam_rere/lam_rere.flm.post.pdf

Dong, B., Kennedy, C., & Pressnail, K. (2005). Comparing life cycle implications of building retrofit and replacement options. *Canadian Journal of Civil Engineering , 32*, 1051-1061.

Dorsthorst, B., & Kowalczk, T. (2002). Design for recycling. *Design for deconstruction and material reuse, Proceedings of the CIB Task Group 39 – deconstruction meeting, Karlsruhe, Germany, April 2002.* CIB Publication 272, paper 8.

Dorsthorst, B., & Kowalczyk, T. (2003). *State of Deconstruction in the Netherlands.* Retrieved October 12, 2009, from http://web.dcp.ufl.edu/ckibert/DeconstructionBook/

Dowling, J. (2010). Steel – the never ending process. *New Steel Construction , 18*, 26-27.

Dowling, J. (2012). *Steel Information.* Email to: d.densleytingley@sheffield.ac.uk.

Duffy, A. (2009). Land use planning in Ireland - a life cycle analysis of recent residential development in the Greater Dublin Area. *International Journal of Life Cycle Assessment , 14*, 268-277.

Edmonds, J., & Gorgolewski, M. (Unknown Date). *Steel Component Design for Deconstruction.* Retrieved July 21, 2010, from http://johnjing.co.nz/green_web/papers/2.pdf

Emmanual, R. (2004). Estimating the environmental suitability of wall materials: preliminary results from Sri Lanka. *Building & Environment , 39*, 1253-1261.

Environment Agency. (2012). *Sustainable Construction*. Retrieved June 8, 2012, from Environment Agency: http://www.environment-agency.gov.uk/business/sectors/136252.aspx

Estevez, B., Aguado, A., & Josa, A. (2003). Environmental impact of concrete recycling, coming from construction and demolition waste (CDW). *Deconstruction and material reuse, Proceedings of the 11th Rinker International Conference, Gainesville, Florida, USA, May 2003.* CIB Publication 287, paper 14.

Europa. (2009). *Environmental compliance assistance programme for SMEs, Waste*. Retrieved April 28, 2010, from http://ec.europa.eu/environment/sme/legislation/waste_en.htm

Europa. (2008). *Summaries of EU Legislation - waste electrical and electronic equipment*. Retrieved April 28, 2010, from http://europa.eu/legislation_summaries/environment/waste_management/l21210_en.htm

European Parliament. (2008, November 19). *Directive 2008/98/EC of the European Parliament and of the council of 19 November 2008 on waste and repealing certain Directives.* Retrieved September 25, 2012, from Europa, EUR - Lex, Access to European Union law: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32008L0098:EN:NOT

European Parliament. (2008, November 19). *Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives.* Retrieved Septemeber 25, 2012, from Europa, EUR-Lex, Access to European Union law: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32008L0098:EN:NOT

Fachinger, B. (2012). *Ten sources of Greenhouse Gases*. Retrieved Febuary 10, 2012, from http://knowledge.allianz.com/climate/agenda/?651/greenhouse-gas-sources

Faithful + Gould. (2012). *Construction Carbon Calculator - Estimated carbon emissions*. Retrieved September 20, 2012, from http://www.fgould.com/carbon-calculator/

Fletcher, S. (2001). *Developing Disassembly Strategies for building to reduce the lifetime impacts by applying a systems approach. .* Ph.D, The University of Sheffield.

Florides, G., & Christodoulides, P. (2008). Global Warming and Carbon Dioxide through science. *Environment International , 35* (2), 390-401.

Forest Stewardship Council (FSC). (2007). *Standard for sourcing reclaimed materials for use in FSC product groups or FSC certified products.* Retrieved May 9, 2010, from http://www.fsc.org/fileadmin/web-data/public/document_center/international_FSC_policies/standards/FSC_STD_40_007_V1_0_EN_Sourcing_reclaimed_materials.pdf

Franklin + Andrews Ltd. (2011). *CESMM3 - carbon & price book 2011.* London: Thomas Telford.

Franklin + Andrews Ltd. (2010). *UK Building Blackbook - the captial cost and embodied CO2 guide, volume 2: major works.* Wiltshire: Antony Rowe.

Futaki, M. (2003). *Deconstruction in Japan.* Retrieved October 12, 2009, from http://web.dcp.ufl.edu/ckibert/DeconstructionBook/

GaBi. (2012). *Building Life Cycle Assessment*. Retrieved May 31, 2012, from GaBi: http://www.gabi-software.com/uk-ireland/solutions/building-lca/

Garrod, E. (2002). Deconstruction of Masonry Components. *Design for deconstruction and material reuse, Proceedings of the CIB Task Group 39 – deconstruction meeting, Karlsruhe, Germany, April 2002.* CIB Publication 272.

Gjerde, M., Storey, J., & Pederson, M. (2003). A deconstructable car-parking building in an active seismic zone. *Deconstruction and material reuse, Proceedings of the 11th Rinker International Conference, Gainesville, Florida, USA, May 2003.* CIB Publication 287, paper 27.

Goedkoop, M., De Schryver, A., Oele, M., Durksz, S., & De Roest, D. (2010). *Introduction to LCA with SimaPro 7.* Retrieved May 31, 2011, from Pre Consultants - Product Ecology Consultants: http://www.pre.nl/content/manuals

Goodier, C. (2002). Deconstruction of concrete components. *Design for deconstruction and material reuse, Proceedings of the CIB Task Group 39 – deconstruction meeting, Karlsruhe, Germany, April 2002.* CIB Publication, paper 13.

Gorgolewski, M. (2006). The Implications of reuse and recycling for the design of steel buildings. *Journal of Civil Engineering , 33* (4), 489-496.

Gorgolewski, M. (1999). *The role of steel in environmentally responsible buildings, SCI publication 174.* Ascot: Steel Construction Institute.

Grantham, R. (2002). Deconstruction of Timber Components. *Design for deconstruction and material reuse, Proceedings of the CIB Task Group 39 – deconstruction meeting, Karlsruhe, Germany, April 2002.* CIB Publication 272, paper 13.

Green Building Council Australia (GBCA). (2009a). *Green Star Overview - background*. Retrieved May 7, 2010, from http://www.gbca.org.au/green-star/what-is-green-star/background/2140.html

Green Building Council Australia (GBCA). (2010). *Green Star, office version 3*. Retrieved May 7, 2010, from http://www.gbca.org.au/green-star/rating-tools/

Green Building Council Australia (GBCA). (2009b). *What is Green Star?* Retrieved May 7, 2010, from http://www.gbca.org.au/green-star/green-star-overview/

Green Building Council Australia (GBCA). (2009c). *World Green Building Council*. Retrieved May 9, 2010, from http://www.gbca.org.au/about/world-green-building-council/

Green Building Council Australia. (2008). *The 2020 Challenge - Carbon Neutral Buildings*. Retrieved April 13, 2010, from http://www.gbca.org.au/resources/the-2020-challenge-carbon-neutral-buildings/1690.htm

Green, M. (2012). *The Case for Tall Wood Buildings.* Email to: d.densleytingley@sheffield.ac.uk.

Guy, B. (2001). Building Deconstruction Assessment Tool. *Deconstruction and material reuse: Technology, Economic and Policy, Proceedings of the CIB Task Group 39: Deconstruction Meeting, Wellington, New Zealand, 6 April 2001* (pp. 125-137). CIB Publication 266, paper 9.

Guy, B. (2003). *Green Demolition Certificate.* Retrieved January 28, 2010, from http://www.deconstructioninstitute.com/files/learn_center/74145578_GreenDemoCert09-16.pdf

Guy, B., & Ciarimboli, N. (Unknown date). *Seattle Guide: Design for disassembly in the built environment*. Retrieved August 18, 2010, from http://your.kingcounty.gov/solidwaste/greenbuilding/documents/Design_for_Disassembly-guide.pdf

Guy, B., & Ohlsen, M. (2003). Creating business opportunities through the use of deconstruction feasibility tool. *Deconstruction and material reuse, Proceedings of the 11th Rinker International Conference, Gainesville, Florida, USA, May 2003.* CIB Publication 287, paper 3.

Guy, B., & Shell, S. (2002). Design for deconstruction and material reuse. *Design for deconstruction and material reuse, proceedings of the CIB Task Group 39: deconstruction meeting, Karlsruhe, Germany, April, 2002.* CIB Publication 287, paper 3.

Guy, B., Hood, T., Priselac, A., Gendt, S., Shell, S., Gutierrez, O., et al. (Unknown date). *Design for Deconstruction.* Retrieved May 7, 2010, from http://www.chartwell.org/UserFiles/File/Design_for_Deconstruction.pdf

Haapio, A., & Viitaniemi, P. (2008). Environmental effect of structural solutions and building materials to a building. *Environmental Impact Assessment Review , 28*, 587-600.

Hammond, G., & Jones, C. (2011). *Inventory of Carbon & Energy version 2.0*. Retrieved Feburary 17, 2011, from http://www.bath.ac.uk/mech-eng/sert/embodied/

Hammond, G., & Jones, C. (2008). *Inventory of Carbon and Energy (ICE) version 1.6a.* Retrieved July 11, 2012, from http://perigordvacance.typepad.com/files/inventoryofcarbonandenergy.pdf

Hernandez, P., & Kenny, P. (2010). From net energy to zero energy buildings: defining life cycle zero energy buildings (LC-ZEB). *Energy and Buildings , 42* (6), 815-821.

Herring, A. (2012). *Design for deconstruction: building with sustainability in mind*. Retrieved September 29, 2012, from news@Northeastern: http://www.northeastern.edu/news/2012/05/design-for-deconstruction-building-sustainability-into-our-buildings/

Hinze, J. (2002). Design for deconstruction safety. . *Design for deconstruction and material reuse, Proceedings of the CIB Task Group 39 – deconstruction meeting, Karlsruhe, Germany, April 2002.* CIB Publication 272, paper 16.

Hobbs, G. (2012). *The 2010 Assessment for CD&E waste to landfill in England, prepared for the Strategic Forum for construction.* Retrieved August 2012, 31, from http://www.strategicforum.org.uk/pdf/CD&E-waste-to-landfill-figures2010.pdf

Hobbs, G., & Hurley, J. (2001). Deconstruction and the reuse of construction materials. *Deconstruction and material reuse: Technology, Economic and Policy, Proceedings of the CIB Task Group 39: Deconstruction Meeting, Wellington, New Zealand, 6 April 2001* (pp. 98-124). CIB Publication 266, paper 8.

Huberman, N., & Pearlmutter, D. (2008). A life-cycle analysis of building materials in the Negev Desert. *Energy and Buildings , 40*, 837-848.

Hurley, J. (2003). Valuing the pre-demolition audit process. *Deconstruction and material reuse, Proceedings of the 11th Rinker International Conference, Gainesville, Florida, USA, May 2003.* CIB Publication 287, paper 13.

Hurley, J., Goodier, C., Garrod, E., Grantham, R., Lennon, T., & Waterman, A. (2002). Design for deconstruction and material reuse, BRE technical opinions. *Design for deconstruction and material reuse, Proceedings of the CIB Task Group 39 – deconstruction meeting, Karlsruhe, Germany, April 2002.* CIB publication 272, paper 13.

Innovation and Growth Team. (2010). *Low Carbon Construction, final report.* London: Department of Business, Innovation and Skills.

Intergovernmental Panel on Climate Change (IPCC). (2001). *Climate Change 2001, Working Group 1, the scientific basis, chapter 6, radiative forcing of climate change.* Retrieved August 30, 2012, from http://www.grida.no/publications/other/ipcc_tar/

Johnson, P., Everard, M., Santillo, D., & Robert, K. (2007). Reclaiming the Definition of Sustainability. *Environmental Science and Pollution Research , 14* (1), 60-66.

Julien. (2008). Assessing the assessor BREEAM vs LEED. *Sustain , 9* (6), 30-33.

Kaethner, S. C., & Burridge, J. A. (2012). *Embodied CO2 of Structural Frames.* Retrieved 9 20, 2012, from The Concrete Centre:

http://www.concretecentre.com/sustainability/energy_efficiency/embodied_co2/embodied_co2_of_frames.aspx

Kaethner, S. C., & Yang, F. (2011). Environmental impacts of structural materials - finding a rational approach to default values for software. *The Structural Engineer , 89* (13), 24-30.

Katz, A. (2003). *The State of Deconstruction in Israel.* Retrieved October 12, 2009, from http://web.dcp.ufl.edu/ckibert/DeconstructionBook

Kennett, S. (2009). *BREEAM and LEED work together on a new global standard*. Retrieved March 24, 2010, from http://www.building.co.uk/sustain_story.asp?sectioncode=284&storycode=3135155&channel=747&c=3

Kestner, D., & Webster, M. (2010). *Achieving Sustainability through durability, adaptability, and deconstruction.* Retrieved July 30, 2010, from Structure: http://www.structuremag.org/article.aspx?articleID=1040

Khan, A. (2011). *Application of Design for Deconstruction Principles to Contemporary Buildings: Assessment of Feasibility and Environmental Impact.* PhD Thesis, The University of Sheffield.

Khasreen, M. M., & Banfill, P. F. (2010). Carbon dioxide emissions of a typical office building in Scotland. In A. Akintoye, J. Goulding, F. Rahiman, D. Brindley, & S. Emmitt (Ed.), *International Detail Design in Architecture Conference*, (pp. 43-54). Preston, England.

Khoo, H. H., & Tan, R. B. (2010). Environmental impacts of conventional plastic and bio-based carrier bags, part 2: end of life options. *International Journal of Life Cycle Assessment , 15*, 338-345.

Kibert, C. (2000). *Deconstruction as an essential component of sustainable construction.* Retrieved May 9, 2010, from http://www.sustainablesettlement.co.za/event/SSBE/Proceedings/kibert.pdf

Kingspan. (Unknown date#). *Delivering low energy and low carbon buildings*. Retrieved April 27, 2010, from http://www.kingspan.com/kingspangroup/sustainableconstruction/low_energy_carbon/

Knight, D., & Addis, B. (2011). Embodied carbon as a design tool - a case study. *Proceedings of ICE, Civil Engineering , 164*, 171-176.

Kofoworola, O. F., & Gheewala, S. H. (2009). Life cycle energy assessment of a typical office building in Thailand. *Energy and Buildings , 41*, 1076-1083.

Lane, T. (2010). *Embodied energy: the next big carbon challenge*. Retrieved August 16, 2010, from building.co.uk: http://www.building.co.uk/technical/embodied-energy-your-next-crisis-is-on-its-way/5000487.article

Lasvaux, S., Peuportier, B., & Chevalier, J. (2009). *Modelling the recycling processes in the LCA of Buildings.* Retrieved July 13, 2012, from http://www.insavalor.fr/wascon2009/fichiers_envoyes/Sebastien%20Lasvauxet%20full%20paper.pdf

Lausten, J. (2008). *Energy Efficiency Requirements in Building Codes, Energy Effciency Policies for New Buildings, International Energy Agency Information Paper.* Retrieved Febuary 8, 2012, from https://www.iea.org/g8/2008/Building_Codes.pdf

Lazarus, N. (2002). *BedZED: Toolkit Part 1 - a guide to construction materials for carbon neutral developments*. Retrieved October 9, 2012, from http://www.oneplanetcommunities.org/wp-content/uploads/2010/03/BedZED-Toolkit-Part-1-Materials-Report-screen.pdf

Lee, B., Traka, M., & Hensen, J. (2011). Embodied energy of building materials and green building rating systems - a case study for industrial halls. *Sustainable Cities and Society , 1*, 67-71.

Lennon, T. (2002). Deconstruction of steel components. *Design for deconstruction and material reuse, Proceedings of the CIB Task Group 39 – deconstruction meeting, Karlsruhe, Germany, April 2002.* CIB Publication 272, paper 13.

Linb, E., & Mueller, A. (2003). The Electro-hydraulic comminution for the separation of old concrete. *Deconstruction and material reuse, Proceedings of the 11th Rinker International Conference, Gainesville, Florida, USA, May 2003.* CIB publication 287, paper 2.

LISA. (2003). *LISA - LCA In Sustainable Architecture.* Retrieved December 8, 2011, from http://www.lisa.au.com

LOCOG. (2012, April 27). *Delivering Change - London 2012 Pre-games sustainability report*. Retrieved October 03, 2012, from http://www.london2012.com/mm%5CDocument%5CPublications%5CSustainability%5C01%5C25%5C43%5C65%5Cpre-games-sustainability-report_Neutral.pdf

Lui, C., Pun, S., & Itoh, Y. (2003). Techincal development for deconstruction management. *Deconstruction and material reuse, Proceedings of the 11th Rinker International Conference, Gainesville, Florida, USA, May 2003.* CIB Publication 287, paper 16.

MacKay, D. (2008). *Sustainable Energy - without the hot air.* Retrieved October 10, 2009, from http://www.withouthotair.com/

Malmqvist, T., Glaumann, M., Scarpellini, S., Zabalza, I., Aranda, A., Llera, E., et al. (2011). Life cycle assessment in buildings: the ENSLIC simplified method and guidlines. *Energy , 36*, 1900-1907.

Mammen, V. A. (2012). *Flexibility in the design of new buildings - how much do we really need, and how sustainable is it?* Dissertation for MSc in Architectural Engineering Design, The University of Sheffield.

Marks and Spencer plc. (2012). *Zero waste to landfill*. Retrieved September 26, 2012, from http://plana.marksandspencer.com/we-are-doing/waste/stories/97

Mattila, T. J., Pakarinen, S., & Sokka, L. (2010). Quantifying the total environmental impacts of an industrial symbiosis - a comparison of process, hybrid and input-output life cycle assessment. *Environmental Science & Technology , 44* (11), 4309-4314.

Mercante, I. T., Bovea, M. D., Ibanez-Fores, V., & Arena, A. P. (2012). Life cycle assessment of construction and demolition waste management systems: a Spanish case study. *International Journal of Life Cycle Assessment , 17*, 232-241.

mgb Architecture + Design. (2012). *The case for tall wood buildings - how mass timber offers a safe, economic, and environmentally friendly alternatives for tall building structures.* Retrieved August 31, 2012, from http://wecbc.smallboxcms.com/database/rte/files/Tall%20Wood.pdf

Mithraratne, N., & Vale, B. (2004). Life cycle analysis model for New Zealand houses. *Building and Environment , 39*, 483-492.

Monahan, J., & Powell, J. C. (2011). An embodied carbon and energy analysis of modern methods of construction in housing: a case study using lifecycle assessment framework. *Energy and Buildings , 43* (1), 179-188.

Moore, D. (2010). *Re-using metal without melting.* Presentation in London, 28th April 2010.

Myhre, L. (2003). *The State of Deconstruction in Norway.* Retrieved October 14, 2012, from http://web.dcp.ufl.edu/ckibert/DeconstructionBook/

Nassen, J., Holmberg, J., Wadeskog, A., & Nyman, M. (2007). Direct and indirect energy use and carbon emissions in the production phase of buildings: an input-output analysis. *Energy , 32*, 1593-1602.

National Defence Centre for Environmental Excellence (NDCEE). (2005). *NDCEE develops comprehensive planning tools for deconstruction and building material recovery.* Retrieved August 19, 2010, from NDCEE Newsletter, fall 2005: http://www.ndcee.ctc.com/newsletters/fall2005.html

Natural Resources Canada. (Unknown). *Projects*. Retrieved October 09, 2012, from Reuse Steel: http://www.reuse-steel.org/projects.aspx

Neun, D., & Grothe, M. (2001). *Report of the feasibility of deconstruction: an investigation of deconstruction activity in four cities.* Retrieved September 14, 2010, from NAHN Research Centre for the US department of housing and development: http://www.toolbase.org/PDF/CaseStudies/FeasibilityofDeconstruction.pdf

Newnhouse, S., Fuller, A., & Kunde, J. (2003). Overture deconstruction project in Madison. *Deconstruction and material reuse, Proceedings of the 11th Rinker International Conference, Gainesville, Florida, USA, May 2003.* CIB publication 287, paper 8.

Nichols, W. (2012). *M&S goes 'carbon neutral' as sustainability savings stack up*. Retrieved September 1, 2012, from http://www.businessgreen.com/bg/news/2182619/-goes-carbon-neutral-sustainability-savings-stack

NIST (National Institute of Standards and Technology - an agency of the US Department of Commerce. (2007). *BEES 4.0*. Retrieved August 17, 2010, from http://www.bfrl.nist.gov/oae/software/bees/bees.html

NSC. (2008). Sustainable steel aims at Olympic gold. *New Steel Construction* , 22-23.

Odom, B. (2003). Start up and development of a full scale used building materials store and salvage & deconstruction business in a small town. *Deconstruction and material reuse, Proceedings of the 11th Rinker International Conference, Gainesville, Florida, USA, May 2003.* CIB publication 287, paper 15.

Office of Government Commerce (OGC). (2009). *OGC case study, high performing property, Vulcan House, Developing a sustainable workplace.* Retrieved Febuary 16, 2010, from http://www.ogc.gov.uk/documents/OGC_Vulcan_House.pdf

Okutu, K. (2012). *Structural implications of replacing concrete floor slabs with timber in composite construction.* Dissertation for MSc in Structural Engineering, The University of Sheffield.

Ortiz, O., Pasqualino, J. C., & Castells, F. (2010). Environmental performance of construction waste: comparing three scenarios from a case study in Catalonia, Spain. *Waste Management , 30*, 646-654.

Ortiz-Rodriguez, O., Castells, F., & Sonnemann, G. (2010). Life cycle assessment of two dwellings: one in Spain, a developed country, and one in Colombia, a country under development. *Science of the Total Environment , 408*, 2435-2443.

Owens, B. (2008). LEED Evolution, not revolution. *HPAC , 80* (10), 7-10.

Oxford English Dictionary (Compact). (2008). Retrieved May 8, 2010, from http://www.askoxford.com/concise_oed/sustainable?view=uk

Parker, J. (2009). *BREEAM or LEED - strengths and weakness of the two main environmental assessment methods*. Retrieved March 24, 2010, from http://www.bsria.co.uk/news/breeam-or-leed/>,

PAS 2050. (2008). *Guide to PAS 2050 - How to assess the carbon footprint of goods and services.* British Standards Institution, Carbon Trust & DEFRA Document.

Penn, G., Knudsen, S., & Bensch, I. (2003). A deconstruction business model. *Deconstruction and material reuse, Proceedings of the 11th Rinker International Conference, Gainesville, Florida, USA, May 2003.* CIB Publication 287, paper 17.

Peuportier, B. (2001). Life cycle assessment applied to the comparative evaluation of single family houses in the French context. *Energy and Buildings , 33*, 443-450.

Pons, O. (2010). Evolution of Spanish industrialised steel technologies for school buildings. *Proceedings of the first international conference on structures and architecture, Guimaraes, Portugal, 21-23 July 2010.* CRC Press.

PRe Consultants. (2010). *SimaPro Features*. Retrieved June 7, 2012, from SimaPro: http://www.pre.nl/content/the-features-of-simapro

Rabl, A., Spadaro, J. V., & Zoughaib, A. (2008). Environmental impacts and costs of solid waste: a comparison of landfill and incineration. *Waste Management and Research , 26*, 147-162.

Ramesh, T., Prakashm, R., & Shukkla, K. K. (2010). Life cycle energy analysis of buildings: an overview. *Energy and Buildings , 42*, 1592-1600.

Roberts, G., Dwyer, P., & Taylor, J. (2011). Non-domestic Real Estate Climate Change Model - Quantifying the sensitivity of carbon emissions and operating costs to regional climatic impacts. *RICS Research* .

Rose, C., Ishil, K., & Stevels, A. (2001). ELDA and EVCA: Tools for building product End-of-Life strategy. *The Journal of Sustainable Product Design , 1* (3), 181-195.

Saghafi, M., & Hosseini Teshnizi, Z. (2011). Recycling value of building materials in building assessment systems. *Energy and Buildings , 43*, 3181-3188.

Saleh, T. (2009). *Building green via design for deconstruction and adaptive reuse.* Retrieved July 13, 2010, from Thesis for Master of Science in Building Construction, University of Florida: http://etd.fcla.edu/UF/UFE0024439/saleh_t.pdf

Scheuer, C., Keoleian, G. A., & Reppe, P. (2003). Life cycle energy and environmental performance of a new university building: modelling challenges and design implications. *Energy and Buildings , 35*, 1049-1064.

Schwarzenegger, A. (2004). *State of California, Executive Order S-20-40*. Retrieved March 1, 2010, from http://www.energy.ca.gov/greenbuilding/documents/executive_order_s-20-04.html

Scottish Ecological Design Association (SEDA). (2005). *Design and Detailing for Deconstruction.* Retrieved May 7, 2010, from http://www.seda.uk.net/dfd/dfd.pdf

Shankleman, J. (2012, June 25). *Green businesses set to lead creation of Rio's+20 "Future We Want"*. Retrieved September 25, 2012, from businessGreen, Sustainable thinking: http://www.businessgreen.com/bg/news/2186805/green-businesses-set-lead-creation-rios-future-want

Shapps, G. (2011, May 17). *Buildings and the Environment.* Retrieved July 16, 2012, from Communities and Local Government: http://www.communities.gov.uk/statements/newsroom/1905627

Silverstein, S. (2009). *Applying 'Design for disassembly' to connection design in steel structures.* Retrieved July 13, 2010, from Paper submitted as part pf Master of Engineering in Civil and Environmental Engineering at MIT: http://dspace.mit.edu/handle/1721.1/53071

Smithers, R. (2012, June 7). *M&S becomes 'carbon neutral'*. Retrieved Septemeber 26, 2012, from theguardian, environment, sustainable development: http://www.guardian.co.uk/environment/2012/jun/07/marks-spencer-carbon-neutral-sustainability

Steel Construction Institute (SCI). (2009). *Sustainable Construction in Steel, Information sheet 3 – Management of Construction and Demolition Waste.*

Storey, J. (2002). Reconstructing Deconstruction. *Design for deconstruction and material reuse, Proceedings of the CIB Task Group 39 – deconstruction meeting, Karlsruhe, Germany, April 2002.* CIB Publication 272, paper 10.

Storey, J., & Pedersen, M. (2003). Overcoming the barriers to deconstruction and material reuse in New Zealand. *Deconstruction and material reuse, Proceedings of the 11th Rinker International Conference, Gainesville, Florida, USA, May 2003.* CIB publication 287, paper 23.

Sturgis, S., & Roberts, G. (2010). *Redefining zero: carbon profiling as a solution to whole life carbon emission measurement in buildings. RCIS Research Report.* Retrieved August 16, 2010, from http://www.isurv.com/site/download_feed.aspx?fileID=2493&fileExtension=PDF

Suh, S., Lenzen, M., Treloar, G., Hondo, H., Horvath, A., Huppes, G., et al. (2004). System boundary selection in life-cycle inventories using hybrid approaches. *Environmental Science and Technology , 38* (3), 657-664.

Suzuki, M., & Oka, T. (1998). Estimation of life cycle energy consumption and CO2 emission of office buildings in Japan. *Energy and Buildings , 28*, 33-41.

Target Zero. (2012). *Guidance on the design and construction of sustainable, low carbon office buildings.* TATA Steel, BSCA, AECOM, cyril sweet, SCI, Development Securities PLC.

Target Zero. (2010). *Guidance on the design and construction of sustainable, low carbon school buildings.* Corus, BCSA, AECOM, cyril sweet, SCI & Balfour Beatty.

Target Zero. (August 2011). *Guidance on the design and construction of sustainable, low carbon supermaket buildings.* TATA Steel, BCSA, AECOM, cyril sweett, SCI, ASDA.

Target Zero. (2011). *Guidance on the design and construction of sustainable, low carbon warehouse buildings.* TATA Steel, BCSA, AECOM, cyril sweet, SCI & ProLogis.

Target Zero. (2012). *Target Zero, collaboration between BCSA, TATA Steel, AECOM, Sweet Group, SCI*. Retrieved July 5, 2012, from http://www.targetzero.info/

TATA Steel & BCSA. (2012). *The Whole Storey - from cradle to grave.* beclientsolutions.

TATA Steel, BCSA. (2012, June). Cradle to grave. *The Surest way is steel - supplement to NSC* , pp. 14-15.

Tesco PLC. (2012). *Caring for the environment*. Retrieved September 26, 2012, from http://www.tescoplc.com/index.asp?pageid=103

The Stern Review. (2006). *The Economics of Climate Change, the Executive Summary.* Retrieved October 6, 2009, from http://www.hm-treasury.gov.uk/sternreview_summary.htm

Theaker, I., & Cole, R. (2001). The role of local governments in fostering 'green' buildings: a case study. *Building Research and Information , 29* (5), 394-408.

Tolis, A., & Rentizelas, A. (2011). An impact assessment of electricity and emission allowances pricing in optimised expansion planning of power sector portfolios. *Applied Energy , 88*, 3791-3806.

UK Green Building Council. (2012c). *A Plan for Growth in a Resource-Constrained World.* London: UK Green Building Council.

UK Green Building Council. (2012a). *A Rio+20 round-up*. Retrieved August 30, 2012, from http://www.ukgbc.org/news/rio20-round

UK Green Building Council. (2012b). *Delivering a Sustainable Stadium, slides from London 2012 Sustainability Lessons Learned Series*. Retrieved August 30, 2012, from http://www.ukgbc.org/events/delivering-sustainable-stadium

UK-GBC Green Building Guidance Task Group. (2012). *Advice for planners and developers*. Retrieved October 01, 2012, from http://www.ukgbc.org/content/advice-planners-and-developers

Umberto. (2012). *Umberto - functions and features*. Retrieved June 7, 2012, from Umberto: http://www.umberto.de/en/functions/

United Nations Environment Program. (2010). *Common Carbon Metric - Draft for Pilot Testing.* Retrieved December 16, 2010, from Sustainable Buildings & Climate Initiative: http://www.unep.org/sbci/pdfs/Common-Carbon-Metric-for_Pilot_Testing_220410.pdf

United Nations Environment Programme (UNEP). (2007). *Global Environment Outlook (GEO-4) - environment for development.* Retrieved November 2, 2009, from http://news.bbc.co.uk/1/hi/sci/tech/7060072.stm

United Nations Population Fund (UNFPA). (2011). *People and Possibilities in a World of 7 Billion.* Retrieved August 30, 2012, from http://www.unfpa.org/swp/index.html

United Nations. (2012). *The future we want, Outcomes of RIO+20 Conference. Rio de Janerio, Brazil.* Retrieved August 30, 2012, from https://rio20.un.org/sites/rio20.un.org/files/a-conf.216l-1_english.pdf.pdf

US Department of Energy. (2012). *Commercial Buildings Energy Consumption Survey (CBECS)*. Retrieved July 16, 2012, from US Energy Information Administration: http://205.254.135.7/consumption/commercial/

US Green Building Council (USGBC). (2009). *Foundations of LEED*. Retrieved Feburary 12, 2010, from http://www.usgbc.org/ShowFile.aspx?DocumentID=6103

US Green Building Council (USGBC). (2009). *LEED 2009 Weighting Background*. Retrieved March 25, 2010, from http://www.usgbc.org/DisplayPage.aspx?CMSPageID=1971

US Green Building Council (USGBC). (2005). *LEED for New Construction and Major Renovations, version 2.2*. Retrieved Febuary 18, 2010, from http://www.usgbc.org/ShowFile.aspx?DocumentID=1095

US Green Building Council (USGBC). (2009). *LEED for New Construction and Major Renovations, version 3*. Retrieved Febuary 18, 2010, from http://www.usgbc.org/ShowFile.aspx?DocumentID=5546

US Green Building Council (USGBC). (2010). *Project Certification*. Retrieved Feburary 12, 2010, from http://www.usgbc.org/DisplayPage.aspx?CMSPageID=64

US Green Building Council (USGBC). (Unknown date). *Regional Priority Credits - frequently asked questions*. Retrieved March 25, 2010, from http://www.usgbc.org/ShowFile.aspx?DocumentID=5732

Utama, A., & Gheewala, S. H. (2009). Indonesian residential high rise buildings: a life cycle energy assessment. *Energy and Buildings , 41*, 1263-1268.

Van Ooteghem, K., & Xu, L. (2012). The life cycle assessment of a single-storey retail building in Canada. *Building and Environment , 49*, 212-226.

Venkatarama Reddy, B. V., & Jagadish, K. S. (2003). Embodied energy of common and alternative building materials and technologies. *Energy and Buildings , 35*, 129-137.

Wallhagen, M., Glaumann, M., & Malmquist, T. (2011). Basic building life cycle calculations to decrease contribution to climate change - case study on an office building in Sweden. *Building and Environment , 46*, 1863-1871.

Webster, M., & Costello, D. (2005). *Designing structural systems for deconstruction: how to extend a new building's useful life and prevent it going to waste when the end finally comes.* Retrieved July 13, 2010, from http://www.lifecyclebuilding.org/files/Designing%20Structural%20Systems%20for%20Deconstruction.pdf

World Commision on Environment and Development (WCED). (1987). *Our common future (the Brundtland Report).* Retrieved May 9, 2010, from http://www.un-documents.net/wced-ocf.htm

WRAP. (2010). *Designing out Waste Tool for Buildings*. Retrieved August 17, 2010, from http://www.wrap.org.uk/construction/tools_and_guidance/designing_out_waste/dowtb.html

WRAP. (2009). *Legislation & Planning Developments in demolition in selected European Countries.* Retrieved October 29, 2009, from http://www.aggregain.org.uk/demolition/the_supply_chain/drivers/legislation_.html

WRAP. (2011). *Market Situation Report - Realising the value of recovered wood.* WRAP.

WRAP. (2009). *Practical solutions for sustainable construction - reclaimed building products guide.* Retrieved November 3, 2009, from http://www.wrap.org.uk/construction/tools_and_guidance/reclaimed_building.html

Yohanis, Y. G., & Norton, B. (2002). Life-cycle operational and embodied energy for a generic single-storey office building in the UK. *Energy , 27*, 77-92.

Zero Carbon Hub. (2011). *'Energy' in the definition*. Retrieved August 31, 2012, from http://www.zerocarbonhub.org/definition.aspx?page=2

Zimmerman, A., & Kibert, C. (2007). Informing LEED’s next generation with the Natural Step. *Building Research and Information , 35* (6), 681-689.

Supporting Appendices

Appendices can be found in pdf format on the attached disc, an outline of the contents can be found in the subsequent pages.

Appendix A
Supporting information for Chapter 5, Feasibility Studies

Appendix B
Supporting information for Chapter 6, Development of Sakura

Appendix C
Supporting Information for Chapter 7, Case Studies

Table of Contents - Appendices

List of Figures in Appendices:

Appendix A2:

Appendix C1:

Appendix C2:

Appendix C3:

Appendix C4:

Appendix C5:

List of Tables in Appendices:

Appendix B1:

Appendix B3:

Appendix C1:

Appendix C2:

Appendix C3:

Appendix C4:

Appendix C5: