Sir Ian Dixon Scholarship

Designing for the Deconstruction Process

Final Report

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Executive Summary

The construction and demolition industry is responsible for about a third of the waste generated in the UK. Reusing building elements in new construction, after the initial development has become obsolete can assist in diverting waste from landfill and can result in lower overall CO_2 emissions associated with the new construction, thus helping to meet the government's CO_2 reduction commitments.

In this research the current barriers to the reuse of more structural materials are explored. It finds that there are barriers associated with the building design process, the demolition process, the logistics associated with reclaimed materials and the lack of demand for reclaimed materials.

It then proposes how the quantity of structural materials that are recoverable in a reusable condition could be increased. This is through encouraging design practices which facilitate careful deconstruction, thereby removing some of the barriers associated with the building design and demolition processes.

Design for deconstruction principles are identified through both a literature review and a survey of demolition contractors. It is also identified that there needs to be some additional incentive for these principles to be applied, as those benefiting from the increased recoverability of the materials are different from those paying for the design in the first place.

Recognition in green building rating schemes is one way that those involved in the initial procurement of buildings can be encouraged to consider design choices that will have benefits for others in the future. Based on this, the research develops the detail of a design for deconstruction credit.

The credit includes the definition of a structure recoverability index (SRI) and a deconstruction plan. The SRI aims to measure how much of a structure is likely to be recoverable at end of life, with a higher weighting given to material recovered for reuse than recycling.

The deconstruction plan aims to both give enough information to allow the demolition contractors to be able to plan the deconstruction process and help promote the business case for deconstruction over demolition.

The credit proposed should hopefully be deemed to meet the requirements for an 'approved innovation' in the current BREEAM scheme and potentially form the basis for a full credit in future revisions of the scheme. In addition the work should provide guidance to those aiming to achieve credits on this subject in other schemes.

Designing for the construction process is only one aspect that needs to be tackled in order to maximise material recovery in the construction industry. This research does not address other aspects which are also important to increasing the amount of structural materials that are recoverable, in particular challenges associated with the logistics of stocking reclaimed materials. It is important that systems are established to facilitate the exchange of materials in the construction industry so that when the buildings we are currently constructing reach the end of their life they can be recovered effectively.

Reusability at end of life is only one aspect of the sustainability of a structure and may not always be the most appropriate strategy for a building. The client and

design team should assess early on in the design process whether premature end of life is a risk for the building being commissioned, or if other issues such as optimisation for materials efficiency or future adaptability are more important.

Acknowledgments

I would like to thank everyone who has helped me during the course of this research.

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1 Introduction

The construction and demolition industry is responsible for about a third of the waste generated in the UK. Reusing building elements in new construction, after the initial development has become obsolete can assist in diverting waste from landfill and can result in lower overall CO_2 emissions associated with the new construction, thus helping to meet the government's CO_2 reduction commitments.

This research aims to explore the current barriers to reuse within the construction industry and identify ways in which architects and engineers can assist in increasing the quantity of structural materials that are reused as opposed to recycled.

Sections 1 and 0 establish the challenges around reuse in the construction industry and section 3 looks at how some of these can be overcome. Following this in sections 4 to 7, an approach to promoting the increased consideration of this topic during the design process is developed.

1 Waste in the construction industry

The construction and demolition industry is responsible for about a third of the waste generated in the UK; in 2008 this was approximately 100,000 thousand tonnes (1). There are incentives in place to reduce the amount of waste that is land-filled; in 1996 the UK Government introduced the Landfill tax, imposing an additional penalty per tonne of waste land filled. When the tax was first introduced, the standard rate of tax was £7 (2), currently is £64/tonne (2012) (3) and it continues to be raised. In addition, Wrap's 'Halving Waste to Landfill' campaign, is a construction sector commitment to encourage the reduction of waste (4).

Data from the demolition industry, Figure 1, shows the composition and fate of the demolition portion of UK waste. This shows that the UK demolition industry has succeeded in diverting a very large proportion of their waste away from landfill, only 4% of the waste arisings are sent to landfill, which includes hazardous waste.

However, it can also be seen that the data collected does not differentiate between materials that are reused or recycled. Within the waste hierarchy, as defined by The Waste (England and Wales) Regulations 2011 (5), Figure 1, these terms are separated, with reuse being preferable to recycling.

Recycling is also often segregated into two terms, recycling and down-cycling. Recycling referring to the material being re-processed to deliver the same function, as is common with many metals. Down-cycling refers to a material being re-processed but delivering a lower function, for example structural concrete being crushed to form fill or aggregate.

Other recovery includes generating energy from the burning of waste.

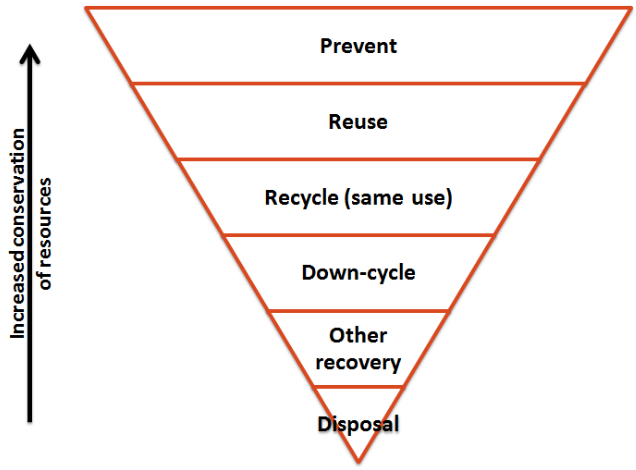

Figure 1: The waste hierarchy (5)

The next step for the construction industry is to look to moving the waste management up the waste hierarchy, and aiming to recover more material to be reused rather than recycled.

The ideal scenario would be for the concept of waste to be eliminated, as every component of a building would be a valuable resource upon recovery. This concept is often called ‘cradle-to-cradle’ based on the work of McDonough and Braungart (6). The demolition industry already recognises this;

‘Part of the challenge is knowing where the materials will end up and how they will be used, maximising potential for using demolition materials.’ (7)

However, despite this awareness, there is currently no over–arching incentive for the industry to shift the focus from recycling to reuse. As highlighted in a report by WRAP in 2008 (8), although the net value of dismantling is greater than demolition, the process takes longer and there are more commercial risks involved. Therefore some additional incentive or a change in this balance is required.

1.1 Importance of structure

Structural materials account for a large proportion of both material use and environmental impact associated with buildings. Research conducted on behalf of the Institution of Structural Engineers (9) found that structure was typically responsible for 12% of the initial cost, 90% of the mass and around 50% of the embodied CO_2 and energy of a building.

This research aims to explore what the current barriers to reuse are and identify ways in which building designers (architects and engineers) can assist in increasing the quantity of structural materials that are reused as opposed to recycled.

2 Barriers to reuse

A literature review of the current barriers to reuse found they can be grouped into barriers associated with:

1. The building design; current construction methods and materials are not conducive to recovery.
2. The demolition process; current demolition schedules and practices are not conducive to recovering materials in a reusable state.
3. Logistics associated with reclaimed materials; lack of space to store reclaimed materials.
4. Market; lack of demand for reclaimed materials.

Each of these areas is explored in more detail below.

2.1 Building design

In buildings that are currently being demolished there can be issues due to contamination with hazardous materials, examples include lead and asbestos (10). These were not seen as hazardous when they were incorporated into buildings, however, now it is considered unsafe to be part of a building's fabric and this results in issues when demolition arises and the elements not able to be reused.

Entanglement of components of the building that are not performing the same function, such as the running of services through structural beam makes maintenance, replacement, deconstruction and separation more difficult, as well as leaving the beams less desirable for future reuse (11).

Many commercial buildings are constructed using composite steel and concrete floor systems which bonds the steel beams to the concrete floor plate via shear studs. This connection makes it difficult if not impossible to recover the steel beams in a reusable condition (12).

2.2 Demolition practices

Current construction and demolition practices hinder steel section recovery as mechanical shears are often used to cut the sections, which leaves them badly deformed and unable to be reused (13). These shears are used either because the connections have been welded or because sufficient time is not available to un-bolt connections.

Current demolition practices very rarely take place in such a way which allows the steel work to be reclaimed in a reusable state. Even when there is a market for the steel, factors such as constrained time on site and health & safety implications for the workers often outweigh the small commercial gain provided by the price of the reclaimed steel (13).

2.3 Logistics

A key barrier to reusing steel can be the logistics and costs involved with storage of reclaimed sections before they are required in new construction (14).

Where elements are currently recovered in a manner that leaves them fit for reuse, problems often arise at the fabrication stage either from elements requiring modification in terms of the addition or removal of bolt holes and stiffeners or through problems with removal of fire protection (14).

Elements that require modification and reprocessing once reclaimed, such as stiffeners and fin plate removal, new bolt holes, removal or addition of coatings will be less desirable as there will be more cost and time implications (10).

2.4 Market

It is currently difficult to construct from reclaimed sections where they exist due to limited supply and variability of sizes, it is speculated that one of the reasons reclamation has declined in the past 30 years is due to the greater variation of UBs and UCs, compared to RSJs, which were more commonly recovered for reuse (12)

One of the issues in reusing current steel sections is uncertainty about the material properties and its use history (15).

The extent of the market for reclaimed, refurbished and recycled materials has been seen to be a factor in influencing the likelihood of reuse and/or recycling of building components. (16)

It has also been noted that although reuse makes logical carbon sense, its practical implementation is constrained by a business as usual approach and economic disincentives. (17)

2.5 Relevance to designers

From these barriers, engineers and architects are most able to influence the building's design and modify it the make the deconstruction process easier, allowing the materials to be recoverable at end of life. This is often termed 'design for deconstruction' (15).

'Designing for deconstruction is one valuable approach that can be used to embed material reuse in new building... while the project remains on the design table.' (18)

The following chapter discusses what designing for deconstruction means in practice.

3 Designing for materials reuse

The literature review found there is currently guidance available for designers on how to design buildings to facilitate easier deconstruction at end of life.

The published literature on designing for deconstruction was reviewed to establish the most frequently cited actions, as summarised in Table 1.

Table 1: Frequently cited actions from literature review

Actions cited as contributing to design for deconstruction	Number of sources that cited action
Use reversible mechanical/non-chemical connections	15
Ensure elements of the building are independent and separable (structure, envelope, services, fit out)	12
Use standardised elements	10
Use non-composite floor systems	10
Permanently mark materials with properties	10
Ensure as-built drawings are available	9
Develop a deconstruction plan during design phase	8
Avoid use of resins, adhesives and coatings	8
Ensure post-construction ease of access to fixings	8
Do not use in-situ concrete	7
Avoid use of hazardous materials	7
Use modular elements	6
Use prefabricated elements	6
Use lime-based mortar with masonry	6
Minimal number of materials and components	6
Think about early in design process (scheme & design development)	6
Use components of singular materials	5
Train all team members on DfD	5
Establish feasibility of element reuse	5
Design in tie offs for deconstruction	4
Provide construction plan	4
Use durable materials	4
Size components for manual handling	4
Include information on deconstruction techniques	3
Do not use structural grout with precast elements	3

Appendix A contains the full review of the literature sources.

The majority of this guidance is published by the design community; however it is demolition professionals who will be impacted by these actions. Prior to promoting any design actions that are intending to assist the deconstruction process it is sensible to check that these actions will achieve their aim.

The suitability of these actions was validated with the demolition industry. This was conducted through an online survey process. Demolition contractors were presented with a selected list from those actions identified in Table 1 above and asked to consider whether each of these would make it easier or harder to deconstruct buildings in a manner that left the structural elements in a reusable (as opposed to recyclable) condition.

Input was gained from 26 demolition industry professionals, with global representation, as shown in Figure 2.

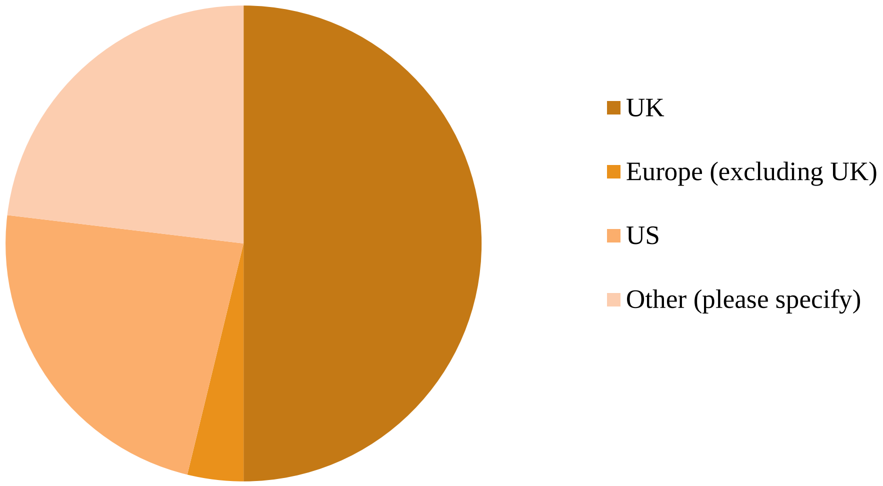

Figure 2: Locations of contributors to demolition industry survey

Table 2 summarises the results of the survey of demolition contractors.

Table 2: Results from survey of demolition contractors. 'Consider whether each of these would make it easier or harder to deconstruct buildings in a manner that left the structural elements in a reusable (as opposed to recyclable) condition.'

Action intended to assist the deconstruction process	**Much harder**	**A bit harder**	**No difference**	**A bit easier**	**Much easier**
Structural elements are standardised sizes and lengths	1	1	11	9	4
The connections are mechanical and reversible (not chemical)	0	0	8	6	12
The elements of the building e.g. structure, envelope, services & internal finishes, being independent and easily separable	0	0	4	7	15
The floors in the building being non-composite	0	2	10	10	4
The main structure not being in-situ concrete	0	1	10	7	8
Full as-built drawings being available	0	0	3	8	15
A deconstruction plan being available	1	2	2	10	11
The construction sequence being available	0	1	8	8	8
No resins, adhesives or coatings on the elements	0	0	3	10	13
Ease of access to connections	0	0	5	8	13
Elements being made of singular materials	0	3	5	7	11
Elements being sized for manual handling	1	2	10	2	11

Table 3 below compares the popularity of the suggested actions between the literature review and the survey of demolition contractors.

Table 3: Rank of results from the literature review and survey of demolition contractors of actions intended to aid the deconstruction process and recoverability of materials.

Action intended to assist the deconstruction process	Rank from Demolition Contractors	Rank from Literature Review
Full as-built drawings being available	1	6
A deconstruction plan being available	2	7
The elements of the building e.g. structure, envelope, services & internal finishes, being independent and easily separable	2	2
Ease of access to connections	4	7
The connections are mechanical and reversible (not chemical)	5	1
Elements being made of singular materials	6	12
No resins, adhesives or coatings on the elements	6	7
The main structure not being in-situ concrete	8	10
The floors in the building being non-composite	9	3
The construction sequence being available	10	20
Structural elements are standardised sizes and lengths	11	3
Elements being sized for manual handling	12	20
Permanently mark materials with properties	N/A	3

This research found that two types of actions need to be encouraged:

1. The passing on of information about the building, including full as-built drawings and a deconstruction plan.
2. Specific design actions to ease the separation of materials and elements.

The design actions that should be encouraged are:

- Independent and easily separable elements of the building e.g. structure, envelope, services & internal finishes
- Easy to access to connections
- Mechanical and reversible (not chemical) connections
- No resins, adhesives or coatings on the elements
- The main structure not being in-situ concrete
- The floors in the building not being of composite construction
- Prefabricated elements are permanently marked with properties

One of the challenges with the concept of designing for deconstruction is that the benefits of the process are realised at the end of life of the building but the effort is required during the initial design process. This often means that it is also different parties who would benefit from the ease of recovery and reusability of materials that would be paying for the building in the first place. Therefore some incentive is required to encourage clients of buildings to have design for deconstruction as a brief requirement and accept the additional design time or material use required. Section 4 explores how to encourage these actions.

3.1 Additional findings

In the survey demolition contractors were also asked if they had any other comments in relation to designing for the deconstruction process and material reuse. The over-arching theme from this question was the importance of the supply chain for reclaimed materials, as identified in section 2.4, highlighted by these comments:

'Designing in the demolition/deconstruction process will certainly help but it will only work if the components are then specified again for reuse in new builds. A ready market for these components needs to be developed to mitigate these costs.'

'The most import requirement is that there is a market for the entire building or the individual elements for re-use. No matter how simple it is to deconstruct a building if there is no demand for the dismantled structure or elements for re-use, you will end up re-cycling or disposing of them in the most economic manner available.'

'If the materials that are used do not have a strong salvage market no amount of design or change will help. Just because you can disassemble or salvage a material does not mean someone else wants to buy it.'

These comments confirm that designing for the construction process is only one aspect that needs to be tackled in order to maximise material recovery in the construction industry. It is important that systems are established to facilitate the exchange of materials in the construction industry so that when the buildings we are currently constructing reach the end of their life they can be recovered effectively.

4 Incentivising sustainable actions in the UK construction industry

In the UK, the status quo for assessing the sustainability of buildings is a rating scheme called the BRE Environmental Assessment Method (BREEAM). The scheme, first established in 1990, but most recently updated in 2011, covers a wide variety of environmental and sustainability issues associated with buildings (19). Buildings are scored against the system and given a rating of either Pass, Good, Excellent or Outstanding.

Clients are increasingly recognising the value that a BREEAM certificate can bring to their buildings (20) and councils are using it as part of the planning process. Therefore a good method for incentivising sustainable actions, such as designing for the deconstruction process, is to reward them in rating schemes such as BREEAM.

Research by Arup on behalf of the Institution of Structural Engineers (IStructE) (9) investigated how materials and the work of structural engineers is represented in rating schemes from around the world. This research found that designing for deconstruction (DfD) was recognised in a number of the schemes, DGNB from Germany, the Estidama Pearls scheme from Abu Dhabi and Green Star in Australia, as illustrated in Figure 3.s

Greenstar Mat-9 *Design for Disassembly*	**DGNB Technical SB 42** *Demolition, dismantling and recycling*	**Estidama Pearls SM-4** *Design for Disassembly*
Design 50% (by area) of the structural framing, roof and facade systems for disassembly.	Assess the easiness in dismantling and separating the elements of the building.	Develop a building disassembly plan and demonstrate amounts designed for dissembly.

Figure 3: Details of existing DfD credits in rating schemes from around the world (9)

Noticeably DfD is not covered in the two leading schemes globally; LEED, originating from the US, and BREEAM. The research also found that the DfD credits in existing schemes were not very effective as the schemes did not provide an effective framework for assessing DfD and therefore designers were not clear on what was expected to prove compliance. However, the report recommends that considering the end of life of buildings is something that should be promoted by rating schemes.

It was felt it was important to reward this action through the rating schemes as there are no other incentives for clients to consider the sustainability implications of the end of life of their buildings, as oppose to the in-use aspects which may have direct financial reward for the building occupier through reduced energy use and therefore operational costs. This view is echoed by others who have considered this topic:

'One important driver could be the inclusion of deconstruction criteria into green building assessment methods.' (18)

Although changes to the rating schemes themselves can only be made by the operators of the schemes, for BREEAM that is BRE, there is currently a mechanism within BREEAM for rewarding sustainable actions which are not covered in other credits through the ‘approved innovations’ method of achieving innovation credits.

BREEAM approved innovations are defined as ‘any technology, method or process that can be shown to improve the sustainability performance of a building’s design, construction, operation, maintenance or demolition, and which is approved as innovative by BRE Global.’ (21)

Therefore this research proposes to formalise how a design team can effectively implement design for deconstruction principles in a manner that could be used to apply for an innovation credit in BREEAM. Ideally this work could also form the basis for a fully established credit within the BREEAM scheme in the future.

It was identified in the IStructE research, that the success of a credit promoting a sustainable section also depends on the reward being proportional to the effort required to achieve the credit and that effective credits provide:

- incentives for sustainable actions;
- a comparable measure of the sustainability of buildings;
- a framework to define sustainable design practices for professionals;
- a practical tool which can cost effectively be deployed during the procurement of buildings.

Sections 1 and 0 validated the sustainability of DfD. These sections identified that the aim of the credit should be to:

Increase the quantity of structural materials that is recoverable in a reusable condition, through encouraging design practice which facilitates careful deconstruction.

As identified in section 3, this requires the encouragement of two key actions:

1. The passing on of information about the building, including full as-built drawings and a deconstruction plan.
2. Specific design actions to ease the separation of materials and elements.

In addition, the literature review also identified that DfD needs to implemented from early on in the design process, Table 1.

Therefore to ensure that the credit is effective a method needs to be defined which can be used to compare the implementation of DfD principles between designs, which can be practically applied early on in the design process, along with finding a practical way to provide the information requested by the demolition contractors.

The first of these aspects has been termed a ‘structure recoverability index’, defined in section 5 and the second a deconstruction plan, defined in section 6. How these would be combined to form a credit within the BREEAM scheme is described in section 7.

This work is intended to be considered alongside other incentives for end of life planning, such as those discussed in section 8. The detail of the credit developed in the following sections assumes that designing for deconstruction is appropriate for the building being assessed.

5 Structure recoverability index

In order to be able to demonstrate an improvement in the recoverability of the structure at end of life, a system for measuring this needs to be established. This is also important as for some materials there are very few end of life options and following the DfD guidelines may not always result in an improvement. As discussed in section 3, this measure needs to be able to be practically applied in the early stages of the design process to be effective.

Therefore it is proposed that the main focus of the credit is a simple calculator which looks at the masses of the materials in the building design at concept design stage (RIBA stage C) to assess the recoverability of the structural materials in options being considered.

It is proposed that the recoverability of the structure should be assessed in the form of a 'structure recoverability index' (SRI). This would be expressed as a percentage defined by the following formula:

$$SRI = \frac{\sum \text{mass of each structural element} \times \text{recoverability factor}}{\text{total mass of structure}}$$

Based on this definition of the SRI, two items are required;

1. The quantity and type of materials being used in the structure;
2. The recoverability factor for each structural material, being established from the likely end of life fate of the materials, and the desirability of the end of life fates, in relation to the waste hierarchy.

The quantity and type of materials being used will be defined by the design team as a normal part of the design process, the other aspects of the calculation are discussed in detail here.

5.1 End of life fate of construction materials

In order to develop the measurement of recoverability of materials, it is necessary to establish what is 'business as usual' (BAU) for the end of life of structural materials and what the best case scenario would be if they were able to be recovered.

Table 4 shows the likely 'business as usual' (BAU) end of life fates for the three key structural materials, steel, timber and concrete. From this it can be seen that while steel and concrete are commonly recovered for recycling or down-cycling and timber rates are increasing year on year (22), reuse is not currently common for any of these materials.

Table 4: 'Business as usual' end of life fates for key structural materials

Material	Reused	Recycled	Down-cycled	Incineration	Landfill	Ref.
Steel	5%	94%	0%	0%	1%	(23)
Concrete	0%	20%	75%	0%	5%	(23)
Timber	0%	32%	14%	25%	29%	(22)

For the best case scenario, it has been assumed that the end of life fates of in-situ concrete, steel decking and reinforcing steel remain the same, but precast concrete, structural timber elements, including glue laminated beams and cross laminated timber, and structural steel could be 100% reused, as summarised in Table 5.

Table 5: 'Best case' end of life fates for key structural elements

Material	Reused	Recycled	Down-cycled	Incineration	Landfill
Structural steel sections	100%	0%	0%	0%	0%
Profiled metal decking and reinforcing steel	5%	94%	0%	0%	1%
In-situ concrete and composite precast	0%	20%	75%	0%	5%
Precast concrete (non-composite)	100%	0%	0%	0%	0%
Structural timber	100%	0%	0%	0%	0%

5.2 Desirability of end of life fates

In order to assess the improvement in the structure from a recycling fate to a reuse fate it is necessary to define how much ‘better’ reuse is than recycling. Indeed to calculate percentage recoverability a weighting for each fate in the waste hierarchy, Figure 4, is required.

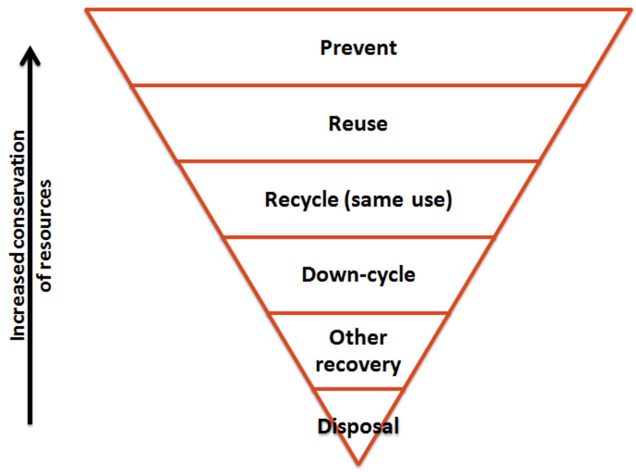

Figure 4: The waste hierarchy

There are scientific methods for quantifying the environmental impacts of reusing, recycling, landfill, etc. using methods such as life cycle assessment.

Life cycle assessment is defined in ISO 14040 as the ‘compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle’ (24). LCA can provide a structured way of looking at a whole system from the impacts associated with the extraction of the raw materials through all the processes these materials go through to make a product or provide a service, until they are finally disposed of or otherwise dealt with at the end of their usefulness (25).

The results would differ for each material being considered and for each environmental impact (global warming, eutrophication, land use, toxicity etc.). When conducting life cycle assessments, the results of the individual environmental impact categories are sometimes combined to create an overall impact. This is called weighting and is based on the relative importance of each issue to the interested parties. This helps provide guidance to non-experts on the issue (26).

This approach is used by the BRE (operators of the BREEAM scheme) to create the environmental profiles used in the Green Guide to Specification, the ‘Green Guide’, (27). The weightings were established by an international panel of ten experts (26).

To eliminate the complex life cycle assessment process, it was chosen to assess the relative importance of the end of life fates through a weighting process. This was achieved by conducting a poll of 36 engineers with an interest in sustainability. Participants were asked to rank each fate on the waste hierarchy (excluding prevention/reduction as that is out of the scope of the credit) on a scale of zero to ten.

From the results of this poll, Table 6, a weighting to each fate was assigned. This weighting was chosen considering the mean and mode of the results.

Table 6: Results from poll on waste hierarchy

	Mean	**Mean normalised for landfill = 0**	**Mode**	**Chosen weighting**
Reuse	10	10	10	10
Recycle	7	8	8	8
Downcycle	5	6	5	5
Energy Recovery	4	4	1	4
Landfill	1	0	0	0

A detailed look at the results of the poll (Table 7) shows how variable opinion on this subject is. While there was general consensus on the extremes of reuse and landfill, there was much more disagreement on the options in between, particularly with respect to energy recovery.

Table 7: Detailed results of poll on desirability of end of life fates

Weighting	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Reuse	0	0	0	0	0	1	0	0	4	3	28
Recycle	0	0	0	0	2	5	6	5	7	7	4
Downcycle	0	0	2	4	4	10	6	6	2	1	0
Energy Recovery	0	8	5	4	6	4	2	3	2	1	0
Landfill	27	4	3	0	0	1	1	0	0	0	0

This method of applying a weighting to results is fit for purpose in the appraisal of various design options. However, if this method was developed into a full credit for inclusion in BREEAM or other rating schemes, a more rigorous assessment of the relative benefits of the different options for different materials may be required.

5.3 Recoverability factors

Combining the likely end of life fates from Table 4 and Table 5 and the desirability of the end of life fates from Table 6 gives the following factors which can be applied to structural quantities to calculate the structure recoverability index.

Table 8: Recoverability factors for key structural elements

Material	Business as Usual (BAU)	Designed for Deconstruction (DfD)
Structural steel sections	0.80	1.00
Profiled metal decking and reinforcing steel	0.80	0.80
In-situ concrete and composite precast	0.54	0.54
Precast concrete (non-composite)	0.54	1.00
Structural timber	0.43	1.00

5.4 Worked example

This example illustrates how the structure recoverability index can be applied as part of the design process.

A typical layout and design specification has been assumed. The design is for a high end office building, in compliance with the guidelines produced by the British Council for Offices (28). The building is 6 storeys high and the floor plate is based on a 9.0m x 9.0m grid, Figure 5 and Figure 6.

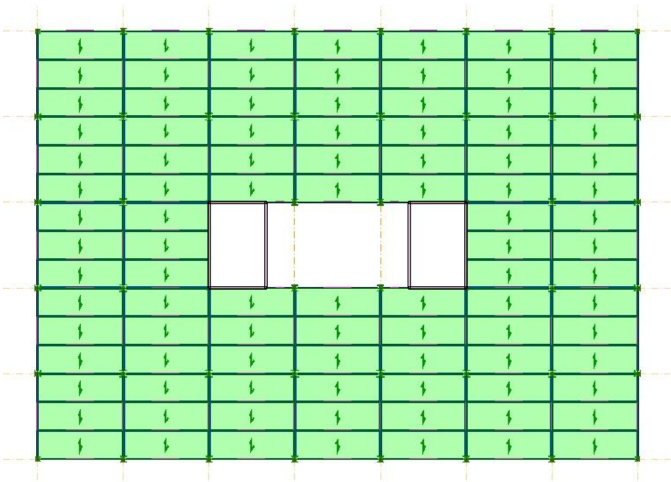

Figure 5: Floor plan of typical office building design

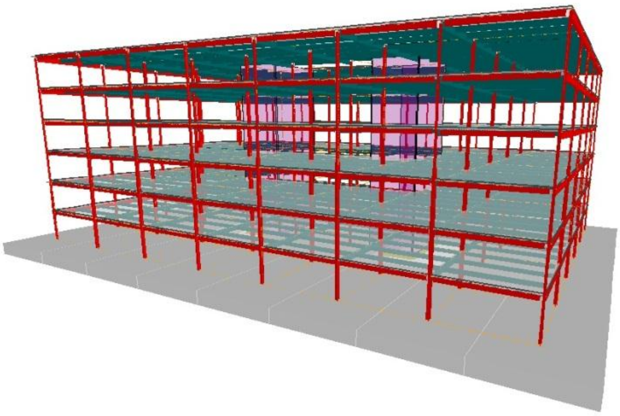

Figure 6: 3D view of typical office building design

Two structural solutions were considered for this building;

1. A structural steel frame with composite profile metal decking and concrete floors

2. A structural steel frame with non-composite profile metal decking and concrete floors, following the DfD principles

Typical build ups for these systems are illustrated in Figure 7.

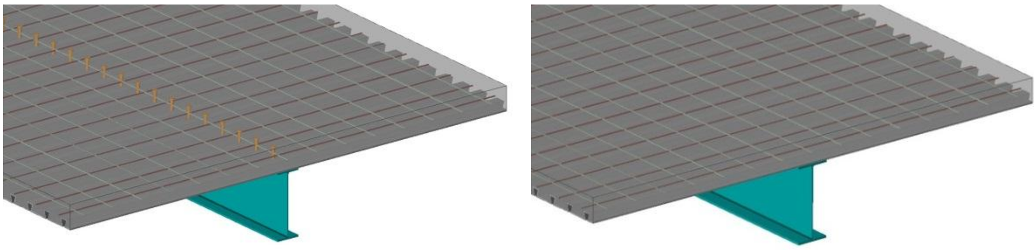

Figure 7: Build-up of floors for 'business as usual' (left) and 'designed for deconstruction' (right) options

Masses of the main structural materials in each of the design options were calculated using CSC Fastrak, an industry standard software package, and are summarised in Table 9. In each case the optimum weight frame was designed, i.e. no depth restrictions were enforced. Full details of the material quantities in each design option are included in Appendix B.

Table 9: Material quantities in design options (tonnes)

	Structural Steel	**Profile metal decking**	**In-situ concrete**	**Reinforcement**	**Total**
Option 1	542	217	4641	52	5452
Option 2	710	217	4641	47	5614

These material quantities can then be multiplied by the factors defined in Table 8 and divided by the total material quantities in the designs to calculate the structure recoverability index for each design. This calculation is shown for option 1 in Table 10 below.

Table 10: Calculation of structure recoverability index for option 1 (business as usual)

	Structural Steel	Profile metal decking	In-situ concrete	Reinforcement	Total
Mass (tonnes)	542	217	4641	52	**5452**
Recoverability Factor	0.80	0.80	0.54	0.80	
Recoverable material (tonnes)	435	174	2483	42	**3133**
Structure Recoverability Index					**57%**

The same calculation can be carried out for the ‘designed for deconstruction’ option and the results compared, as shown in Table 11.

Table 11: Comparison of structure recoverability index for ‘business as usual’ and ‘designed for deconstruction’ options

	Structure Recoverability Index
Option 1 (BAU)	57%
Option 2 (DfD)	61%

The design team could decide to go one step further and try to recover the floors as well as the frame by considering a third option:

3. A structural steel frame with non-composite precast concrete floors, following the DfD principles

The revised floor layout and build up is shown in Figure 8 and Figure 9.

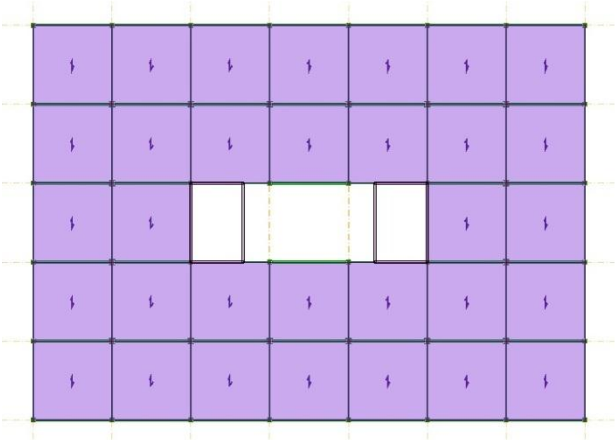

Figure 8: Floor plan for option 3

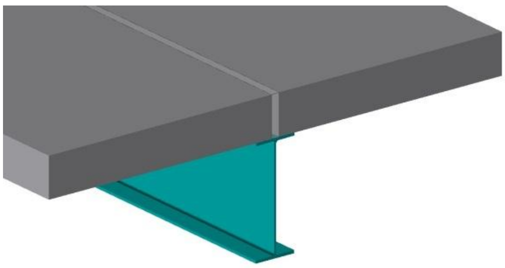

Figure 9: Build-up of floor for option 3

This would have additional impacts on the overall design of the building for example; the robustness of the floor without a structural topping would need to be achieved. However, this would increase the SRI to 100% as shown in Table 12.

Table 12: Calculation of structure recoverability index for option 3

	Structural Steel	Precast concrete (non-composite)	Total
Mass (tonnes)	399	5417	**5816**
Recoverability Factor	1.00	1.00	
Recoverable material (tonnes)	399	5417	**5816**
Structure Recoverability Index			**100%**

5.5 Further considerations

As with all actions that have the aim of improving one aspect of a building's sustainability, there are risks that the actions may lead to unintended consequences in other aspects. Some potential risks associated with the structure recoverability index (SRI) are discussed below.

5.5.1 Materials efficiency

One of the most obvious challenges for the SRI and promoting design for deconstruction (DfD) is that it is likely that this will result in more materials being used in the design. This was illustrated in the example in section 5.4 which shows that 7% more material is used in the maximum recovery option than the business as usual, summarised in Table 13. This increase will be highly variable, depending of the form of construction and performance requirements.

Table 13: Comparison of mass in different options

	Total mass (kg)	Percentage increase
Option 1 (business as usual)	5452	
Option 2 (designed for deconstruction)	5614	103%
Option 3 (maximum recovery)	5816	107%

This will have impacts on both the cost and embodied carbon of the original building design. If the original building is deconstructed and the materials reused, then in the long term this can be justified, however this relies on future actions over which the original designers have no control.

This will limit the appropriateness of designing for deconstruction and is discussed further in section 8.

5.5.2 In-situ concrete

It is evident from section 5.1 that currently there is no advantage to be gained from designing in-situ concrete structures for deconstruction as the end of life fate remains the same. This does not necessarily present a disadvantage for concrete as its strengths lie in other areas.

If the preferred structural system for a building, that is susceptible to an early end of life, is based on in-situ concrete the designer needs to take measures to improve the adaptability of the building thereby minimising the risk of early end of life.

6 Defining a deconstruction plan

Both the literature review and the survey of demolition contractors found that the availability of a deconstruction plan was considered very important. The IStructE research (9) also showed that lack of guidance on what a deconstruction plan should contain was felt to be a weakness of some of the existing credits in other rating schemes. Therefore defining this is an important part of the credit detail.

In this context, a deconstruction plan is be something that is created during the original design process and available to the building owners at its end of life. The purpose of the plan should be two-fold, it should give enough information to allow the demolition contractors to be able to plan the deconstruction process and additionally it should help promote the business case for deconstruction over demolition.

6.1 Information to aid planning of deconstruction process

As identified in the survey of demolition contractors, the most important thing to help plan a deconstruction is the provision of full as-built drawings. The lack of provision of full building drawings is hopefully now a legacy issue in the UK, as these are now required to be kept with the building as part of the Health and Safety file required by the Construction (Design and Management) Regulations 2007 (29). For countries where this is not a legal requirement, as-built drawings should be incorporated into the deconstruction plan.

Other key aspects that should aid the planning of the deconstruction process are now also mandated to be incorporated in the health and safety file in the UK are:

- Information about the key structural principles
- Information about any known hazardous materials used

Again if a deconstruction plan is being developed outside the UK, these aspects should be included.

6.2 Information to help promote deconstruction and materials recovery

The type of information that can help determine the feasibility of deconstruction over demolition is similar to that which may be gathered in a pre-demolition survey currently. The advantage of this information being easily available means that the feasibility of the deconstruction can be established earlier on in the process without any additional expense from the client.

The Institution of Civil Engineers Demolition Protocol 2008 (30) sets out a method for maximising the amount of material recovered from existing buildings. It highlights a number of considerations for the principle contractor to do this including the type, quality, measurability and quantity of items with reclamation potential. Similarly, guidelines on deconstruction from New Zealand also suggest that the quantities of materials to be salvaged for reuse, recycled and sent for disposal should be included in a deconstruction plan (31).

The amount of material in the structure is used as an input in the calculation of the structure recoverability index, as defined in section 5. Combined with schedules of any prefabricated elements used in the structure, this would provide a high level of information about the potential quantity of materials that can be recovered. These prefabricated elements include structural steel sections.

6.3 Deconstruction plan

It is recommended that deconstruction plans include:

- Full as-built drawings
- Information about the key structural principles
- Information about any known hazardous materials used
- Identification of the amount of materials able to be salvaged for reuse
- Schedules of any prefabricated elements in a format to facilitate reselling

7 A design for deconstruction innovation credit

This section summarises the details of the proposed innovation credit for designing for deconstruction.

7.1 Aim

Increase the quantity of structural materials that are recoverable in a reusable condition, through encouraging design practice which facilitates careful deconstruction.

7.2 Assessment criteria

Where the building is suitable appropriate for designing for deconstruction, the following is required to demonstrate compliance:

1. The Structure Recoverability Index (SRI) for the building should be assessed for the structural options at or prior to RIBA stage C. This should be based on the following calculation:

$$SRI = \frac{\sum \text{mass of each structural element} \times \text{recoverability factor}}{\text{total mass of structure}}$$

The recoverability factor for each structural element should be determined from the table below:

Material	BAU	DfD
Structural steel sections	0.80	1.00
Profiled metal decking and reinforcing steel	0.80	0.80
In-situ concrete and composite precast	0.54	0.54
Precast concrete (non-composite)	0.54	1.00
Structural timber	0.43	1.00

The designed for deconstruction (DfD) factors can be assumed to apply if the following conditions have been met:

- The elements of the building e.g. structure, envelope, services & internal finishes are independent and easily separable
- The connection are easy to access
- The connections are mechanical and reversible (not chemical)
- No resins, adhesives or coatings have been used on the elements
- The main structure is not in-situ concrete
- The floors in the building are not of composite construction
- Prefabricated elements, including steel sections, are permanently marked with properties

Otherwise the business as usual (BAU) factors must be used.

2. A deconstruction plan for the building is created. This should include as a minimum:
    - Full as-built drawings*
    - Information about the key structural principles*
    - Information about any known hazardous materials used*
    - Identification of the amount of materials able to be salvaged for reuse
    - Schedules of any prefabricated elements

    *In the UK these will form part of the Health and Safety file required under the Construction (Design and Management) Regulations 2007.

8 Limitations and further work

Designing for the construction process is only one aspect that needs to be tackled in order to maximise material recovery in the construction industry.

As discussed in section 2, a particular challenge is associated with the logistics of stocking reclaimed materials. It is important that systems are established to facilitate the exchange of materials in the construction industry so that when the buildings we are currently constructing reach the end of their life they can be recovered effectively.

Reusability at end of life is only one aspect of the sustainability of a structure and may not always be the most appropriate strategy for a building.

It will be important for designers to understand whether the building is likely to become obsolete within its design life. For example, new offices and commercial developments in city centres are likely to be demolished for aesthetic reasons or due to changing needs long before the materials have deteriorated. Social infrastructure, such as hospitals and schools, and arts buildings, such as theatres and museums, are more likely to be utilised for their whole design life.

If the designers expect the building will fulfil its design life it might not be appropriate to include more materials to allow for DfD. It would be more appropriate to ensure that the design if fully optimised to use minimum materials or has been designed to be adaptable throughout its life. These aspects were also identified in the IStructE report as actions that should be rewarded in rating schemes (9).

The client and design team should assess early on in the design process whether premature end of life is a risk for the building being commissioned.

9 Conclusion

In this research the current barriers to the reuse of more structural material have been explored. It was found that there are barriers associated with building design, the demolition process, logistics associated with reclaimed materials and the lack of demand for reclaimed materials.

It is then proposed how the quantity of structural materials that are recoverable in a reusable condition could be increased through encouraging design practice which facilitates careful deconstruction, thereby removing some of the barriers associated with building design and the demolition process.

Design for deconstruction principles are identified through both a literature review and a survey of demolition contractors. However it is identified that there needs to be some additional incentive for these principles to be applied as those benefiting from the increased recoverability of materials are different from those paying for the design in the first place.

Recognition in green building rating schemes is one way that those involved in the initial procurement of buildings can be encouraged to consider design choices that will have benefits for others in the future. Based on this, the detail of a design for deconstruction credit has been developed.

The credit detail includes the definition of a structure recoverability index (SRI) and a deconstruction plan. The SRI aims to measure how much of a structure is likely to be recoverable at end of life, with a higher weighting given to recoverable for reuse than recycling. It has been designed to be applied using materials quantities that are available early in the design process, therefore allowing different design options to be appraised.

The definition of a deconstruction plan has been developed to both give enough information to allow the demolition contractors to be able to plan the deconstruction process and help promote the business case for deconstruction over demolition.

The credit proposed should hopefully be deemed to meet the requirements for an 'approved innovation' in the current BREEAM scheme and potentially form the basis for a full credit in future revisions of the scheme. In addition the work should provide guidance to those aiming to achieve credits on this subject in other schemes.

Designing for the construction process is only one aspect that needs to be tackled in order to maximise material recovery in the construction industry. This research has not addressed other aspects which are also important to increasing the amount of structural materials that are recoverable, in particular challenges associated with the logistics of stocking reclaimed materials. It is important that systems are established to facilitate the exchange of materials in the construction industry so that when the buildings we are currently constructing reach the end of their life they can be recovered effectively.

Reusability at end of life is only one aspect of the sustainability of a structure and may not always be the most appropriate strategy for a building. The client and design team should assess early on in the design process whether premature end of life is a risk for the building being commissioned, or if other issues such as optimisation for materials efficiency or future adaptability are more important.

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Appendix A

Results from survey of literature

Action				Reference in which action mentioned																			
	Aid process	Aid deconstruction	Aid reuse	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	**Total**
Use reversible mechanical/non-chemical connections		✓			✓	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓	✓	✓	✓			15
Ensure elements of the building are independent and separable (structure,		✓			✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓							12
Use standardised elements		✓	✓			✓	✓			✓		✓		✓	✓	✓			✓				10
Use non-composite floor systems		✓			✓		✓				✓	✓		✓		✓		✓			✓	✓	10
Permanently mark materials with properties			✓		✓			✓		✓	✓	✓			✓	✓			✓	✓			10
Ensure as-built drawings are available		✓				✓				✓			✓	✓		✓	✓	✓	✓				9
Develop Deconstruction plan during design phase		✓				✓					✓	✓	✓	✓			✓		✓				8
Avoid use of resins, adhesives and coatings		✓				✓	✓	✓			✓						✓		✓			✓	8
Ensure post-construction ease of access to fixings		✓				✓	✓	✓		✓				✓					✓	✓			8
Do not use in-situ concrete		✓			✓	✓	✓	✓			✓						✓						7
Avoid use of hazardous materials		✓				✓	✓	✓		✓	✓							✓					7
Use modular elements		✓	✓			✓						✓			✓				✓				6
Use prefabricated elements		✓	✓			✓								✓	✓				✓				6
Use lime-based mortar with masonry		✓		✓		✓				✓									✓	✓			6
Minimal number of materials and components		✓					✓			✓				✓		✓			✓				6
Think about early in design process (scheme & design development)	✓				✓	✓	✓													✓	✓		6
Use components of singular materials		✓				✓	✓			✓		✓											5
Train all team members on DfD	✓					✓							✓	✓					✓				5
Establish feasibility of element reuse	✓			✓		✓					✓								✓				5
Design in tie offs for deconstruction		✓					✓	✓		✓													4
Provide construction plan		✓						✓		✓									✓				4
Use durable materials													✓	✓	✓	✓							4
Size components for manual handling														✓	✓	✓		✓					4
Include information on deconstruction techniques		✓				✓		✓															3
Do not use structural grout with precast elements		✓				✓	✓																3
Physically mark deconstruction points		✓								✓													2
Allow extra design time	✓					✓																	2
Demonstrate best practice examples of DfD to client	✓					✓																	2
Include DfD clauses in contracts	✓					✓																	2
Include in specifications	✓					✓																	2

	Aid process	Aid deconstruction	Aid reuse	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	**Total**
Have no fire-proofing on steel elements			✓								✓												2
Have fixing free zones			✓			✓																	2
Identify design life of different elements													✓	✓									2
Allow space for deconstruction and storage																		✓					1

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Appendix B

Detailed breakdown of materials quantities in design options

Option 1 (business as usual)

Steel Non-reusable: Composite with floor slab

Floor Non-reusable: Profile metal decking and concrete

All beams composite except edge beams. General reinforcement is minimum steel, extra steel provided as required.
No web openings
Assumed that core provides all stability. Concrete floor is a diaphragm
SDL=0.85 kN/m2 (5 on roof) BCO
LL=3.5 (2.5+1) kN/m2 (1.5 or 7.5 on roof) BCO
DL=Calculated by CSC Fastrak for the steel self weight and floor slab

	Material	Floors	Floor area	kg/m2	Total (kg)	**Total (tonnes)**
Metal Decking 1-5, Comflor 0.9	Steel	5	2592	13.25	171720	
Metal Decking R, , Comflor 1.2	Steel	1	2592	17.33	44919	**217**

	Material	Floors	Floor area	m3/m2	Density (kg	Total (kg)	**Total (tonnes)**
Concrete Floor, 1-5, 130 mm	Concrete	5	2592	0.121	2400	3763584	
Concrete Floor, R, 150 mm	Concrete	1	2592	0.141	2400	877132.8	**4641**

	Material	kg	**Total (tonnes)**
Beams	Steel	431459.74	
Columns	Steel	110564.61	**542**

General Reinforcement	Material	Floors	Floor area	kg/m2	Total (kg)	**Total (tonnes)**
A193 Mesh	Steel	6	2592	3.02	46967.04	**47**

Suplimentary Rebar	Material	Floors	Beams	Length of b	Centres	Bars	Weight kg/	Length of b	Total (kg)	**Total (tonnes)**
1st-5th, H10s at 400 c/c	Steel	5	26	9	0.4	23	0.616	2.25	4144.14	
Roof High Load, H10s at 200 c/c	Steel	1	14	9	0.2	45	0.616	2.25	873.18	
Roof Low Load, H10s at 400 c/c	Steel	1	12	9	0.4	23	0.616	2.25	382.536	**5**

Option 2 (designed for deconstruction)
Steel Reusable: Non-composite
Floor Non-reusable: Metal decking and concrete

No composite beams. General reinforcement is minimum steel.
No web openings
Assumed that core provides all stability. Concrete floor is a diaphragm
SDL=0.85 kN/m2 (5 on roof) BCO
LL=3.5 (2.5+1) kN/m2 (1.5 or 7.5 on roof) BCO
DL=Calculated by CSC Fastrak for the steel self weight and floor slab

	Material	Floors	Floor area (m2)	kg/m2	Total (kg)	**Total (tonnes)**
Metal Decking 1-5, Comflor 0.9	Steel	5	2592	13.25	171720	
Metal Decking R, , Comflor 1.2	Steel	1	2592	17.33	44919	**217**

	Material	Floors	Floor area (m2)	m3/m2	Density (kg	Total (kg)	**Total (tonnes)**
Concrete Floor, 1-5, 130 mm	Concrete	5	2592	0.121	2400	3763584	
Concrete Floor, R, 150 mm	Concrete	1	2592	0.141	2400	877132.8	**4641**

	Material	kg		**Total (tonnes)**
Beams	Steel	599337.25	139% of base case	
Columns	Steel	110564.61	100% of base case	**710**

General Reinforcement	Material	Floors	Floor area (m2)	kg/m2	Total (kg)	**Total (tonnes)**
A193 Mesh	Steel	6	2592	3.02	46967.04	**47**

Suplimentary Rebar	Material	Floors	Beams	Length of b	Centres	Bars	Weight kg/	Length of b	Total (kg)
Not required									

Option 3 (maximum recovery)

Steel Reusable: Non Composite

Floor Reusable: Concrete planks <u>without topping</u>

No composite beams composite. No reinforcement provided

No web openings

Assumed that core provides all stability. Plank joints to be grouted to ensure diaphragm and planks notched around columns (also grouted)

In most cases the Building Regulations will require that the planks are tied to the supporting structure.

SDL=0.85 kN/m2 (5 on roof) BCO

LL=3.5 (2.5+1) kN/m2 (1.5 or 7.5 on roof) BCO

DL=3.3 kN/m2 (4 kN/m2 on roof)

	Material	Floors	Floor area (m2)	kg/m2	Total (kg)	**Total (tonnes)**
Bison Hollowcore Planks, 1-5, 250 mm	Concrete	5	2592	336.3914	4359633	
Bison Hollowcore Planks, R, 300 mm (assumed over full roof to allow flat surface for drainage)	Concrete	1	2592	407.7472	1056881	**5417**

	Material	kg		**Total (tonnes)**
Beams	Steel	286156.56	66% of base case	
Columns	Steel	113094.76	102% of base case	**399**