London South Bank University

# IDENTIFICATION OF KEY FACTORS THAT AID THE DECISION ON WHETHER TO REFURBISH-REUSE OR DEMOLISH-REBUILD EXISTING AND NEWLY DESIGNED BUILDINGS AND HIGHWAYS

**BY**


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# Abstract

The demand for construction and demolition (C&D) of existing and new buildings have been increasing every year, as a result of this, a significant increase in waste has been witnessed. According to Defra, the UK is producing on average of 110 million tonnes of C&D waste every year since 2010. This indicates that a well informed decision is required for any building or site that is being considered for C&D works in order to reduce waste.

The aim of this research project is to identify the key factors that play a vital role in deciding whether to refurbish or rebuild any existing building and highway pavement that is reaching its design life and also newly designed buildings for future decision-making. The objectives are; to develop different sets of frameworks to identify the key factors and to achieve a well-informed decision criteria based on the identified key factors.

The methodology used to complete this research project, consists of two parts; investigation of different aspects of waste management and similar cases of some previously refurbished or reconstructed buildings, collection of waste statistics from different construction sites with the intention to develop different sets of framework for the identification of decision-making factors and secondly, the use of Revit (BIM) CAD software and Tally (LCA) tool for application of these factors, where these were applied to some of the existing or old and new buildings in order to check their reliability.

The reported research project has identified 11 key factors and their application on the existing/old and newly build structures. It has been observed that an enormous amount of waste can be prevented in the future at an early stage of project planning through making a proper and well informed decision about any existing building or a new development with the scope of future possibilities of amendments to it when nearing the end of design life. Following the application, an expert opinion survey was conducted for validation of the key factors, then these factors were arranged in a priority order by deciding a threshold for each of the factors. Pavement conditions are analysed and a decision on whether to refurbish or recycle is identified accordingly.

Following the application and validation of factors onto different buildings and highway pavements, it has been observed that the decision of whether to refurbish or rebuild vary in every case, given the scenario that how much design life is left and what is the current state of the building and most importantly, what would be the cost and environmental impact in each case. However, in some cases, it has been clearly observed that the decision to refurbish is more suitable than to rebuild due to design life being left is significantly higher and the proposed purpose of the building use complies with the current layout.


Key words: Construction Waste Management, Sustainability, Recycle, Re-use, BIM

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# Dedication

The one, who inspires me the most, the one, who have been there for me in every situation, always have supported and guided me through all phases of life, and because of whom, I have the courage and faith that I can never be alone even after my last breath because I know he is watching me and will always be there for me, though I cannot see him but I can truly feel his presence around me. In all my senses and from the depth of my heart, I would like to dedicate this project to the one and only **IMAM ALMEHDI (AJATF) Ibn Imam Alhasan Alaskari (A.S)**

## Declaration

I hereby declare and confirm that all the researched, documented and practical work in this report has been produced and complied in accordance with the rules and regulations of London South Bank University. The provided, highlighted and written data in the report is totally original except where it has been referenced from out-source in the text. Any opinions or suggestions explained/provided in the work are those of the author and in no way represent those of London South Bank University.

Signed: Syed Faisal Ali ………………………………………. Date: 02/06/2021

# Abbreviations

| | |
|---|---|
| **AI** | Artificial Intelligence |
| **AP** | Acidification Potential |
| **AR** | Augmented Reality |
| **ARP** | Acid Rain Potential |
| **ASMI** | Athena Sustainable Materials Institute |
| **BAM** | Building Asset Management |
| **BATNEEC** | Best Available Technology Not Entailing Excessive Cost |
| **BC** | Building Control |
| **BEES** | Building for Environment and Economic sustainability |
| **BIM** | Building Information Modeling |
| **BRE** | Building Research Establishment |
| **BREEAM** | Building Research Establishment Environmental Assessment Method |
| **BS** | British Standards |
| **BSI** | British Standard Institute |
| **CA** | Capital Allowances |
| **CAD** | Computer Aided Design |
| **CBECS** | Commercial Buildings Energy Consumption Survey |
| **CDM** | Construction Design Management |
| **CDMR** | Construction Design Management Regulations |
| **CDE** | Construction Demolition and Excavation |
| **CDEW** | Construction Demolition and Excavation Waste |
| **CDW** | Construction and Demolition Waste |
| **C&D** | Construction and Demolition |
| **CE** | Circular Economy |
| **C&I** | Commercial and Industrial |
| **CIB** | International Council for Research and Innovation in Building and Construction |
| **CIRCuIT** | Circular Construction in Regenerative Cities |
| **CW** | Construction Waste |
| **CWM** | Construction Waste Management |
| **DBRI** | Danish Building Research Institute |
| **DEFRA** | Department for Environment, Food & Rural Affairs |
| **DERB** | Department of Energy Reference Buildings |
| **DfD** | Design for Deconstruction |
| **DSL** | Design Service Life |
| **EDSL** | End of Design Service Life |

| | |
|---|---|
| **EA** | Environment Agency |
| **EEA** | European Economic Area |
| **EDL** | End of Design Life |
| **EIO-LCA** | Economic Input-Output based Life Cycle Assessment |
| **EOL** | End of Life |
| **EODL** | End of Design Life |
| **EP** | Eutrophication Potential |
| **EPA 90** | Environmental Protection Act 1990 |
| **EPA 95** | Environmental Protection Act 1995 |
| **EPBD** | Energy Performance of Buildings Directive |
| **EPD** | Environmental Product Declarations |
| **EPI** | Environmental Performance Indicator |
| **GER** | Gross Energy Requirement |
| **GHG** | Green House Gas |
| **GWP** | Global Warming Potential |
| **HIR** | Hot In-Place Recycling |
| **HMA** | Hot Mixed Asphalt |
| **HVAC** | Heating, Ventilation and Air Conditioning |
| **ILPD** | Integrated Lean Project Delivery |
| **IoT** | Internet of Things |
| **IPC** | Integrated Pollution Control |
| **IPPC** | Integrated Pollution Prevention and Control Directive |
| **ISO** | International Standard Organisation |
| **KPI** | Key Performance Indicator |
| **LCA** | Life Cycle Assessment |
| **LCC** | Life Cycle Cost |
| **LCEE** | Life Cycle Environmental Effects |
| **LCI** | Life Cycle Impact |
| **LCIA** | Life Cycle Impact Assessment |
| **LPA** | Local Planning Authority |
| **MEP** | Mechanical, Electrical and Plumbing |
| **MSW** | Municipal Solid Waste |
| **NBIMSPC** | National Building Information Model Standard Project Committee |
| **NOx** | Nitrogen Oxides |
| **NP** | Nitrification Potential |
| **ODP** | Ozone Depletion Potential |
| **PED** | Primary Energy Demand |
| **PFA** | Purified Fly Ash |

| | |
|---|---|
| **POCP** | Photochemical Ozone Creation Potential |
| **POP** | Photo Oxidant Potential |
| **PPS10** | Planning Policy Statement 10 |
| **RAP** | Reclaimed Asphalt Pavement |
| **RRC** | Resource Routing Calculator |
| **RSL** | Residual Service Life |
| **PSP** | Photo Smog Potential |
| **PVC** | Polymerising Vinyl Chloride |
| **RRC** | Resource Routing Calculator |
| **SBID** | Society of British Interior Design |
| **SBSA** | Scottish Building Standards Agency |
| **SETAC** | Society for Environmental Toxicity And Chemistry |
| **SFP** | Smog Formation Potential |
| **SLP** | Service Life Prediction |
| **SME** | Small Medium Sized Enterprise |
| **SRIF** | Special Rate Integral Features |
| **SWH** | Sam Wyly Hall |
| **SWM** | Site Waste Management |
| **SWMP** | Site Waste Management Plan |
| **SWMPR** | Site Waste Management Plan Regulations |
| **TP** | Toxicity Potential |
| **TRACI** | Tools for Reduction and Assessment of Chemicals and other Environment Impacts |
| **UKGBC** | UK Green Building Council |
| **VR** | Virtual Reality |
| **WFD** | Waste Framework Directive |
| **WM** | Waste Management |
| **WMC** | Waste Management Company |
| **WLC** | Whole Life Cost |
| **WPA** | Waste Planning Authorities |
| **WRAP** | Waste and Resources Action Programme |

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# Chapter 1. **Introduction**

Considering the economic and environmental impacts of the construction and demolition waste, there is an increasing need to search for a well informed decision on whether to refurbish or rebuild existing and newly designed buildings when they reach the end of their design life. The decision should primarily be based on the minimum waste generation to be expected from the construction and demolition (C&D) works on existing or proposed developments.

## 1.1 Aim and Objectives

The overall aim of this research project is to identify the key factors that play a vital role in deciding whether to refurbish or rebuild any existing or new building that is being considered for further improvements or redevelopment or reaching its design life. In order to achieve this aim, the following research objectives would be fulfilled.

a) Investigation and assessment of different aspects of construction waste management and similar cases of some previously refurbished or reconstructed buildings or highways with the intention to highlight the factors that were previously considered for the decision-making.

b) Further evaluation of the previously considered factors for the decision-making.

c) Development of different set of frameworks with BIM applications in order to identify the potential factors that would help in deciding whether it would be economically, environmentally, and socially feasible to demolish a building or refurbish or partially demolish and partially refurbish it. These factors will also be applicable on existing highways that are about to reach the design life. These factors would then be arranged by deciding a threshold for each of the factors, where the most important factor will have the priority over other factors and similarly, same procedure will be followed for the second most important factor and so on, till the last and the least important factor. For reliability and validation, these factors will be applied to some existing buildings.

d) The developed frameworks for identifying the key factors will be useful to help the designers and engineers to come up with a waste-efficient or minimum waste design for the new development project. The framework is also intended to be working in parallel with the application of Building Information Modelling (BIM) in order to let all the stakeholders (including principal designers, designers, principle contractors, contractors, engineers and management, procurement and clients) of the project to work collaboratively and specifically on each area of the waste management/reduction criteria that lead towards the decision-making strategy.

The idea behind the identification of these factors is to achieve the sustainability mainly in terms of environment, economy and reduction on social impact, as illustrated in Figure 1.1. All of the above listed objectives are aimed to generate the minimum waste and achieve maximum sustainability in terms of waste efficiency within the UK construction industry.

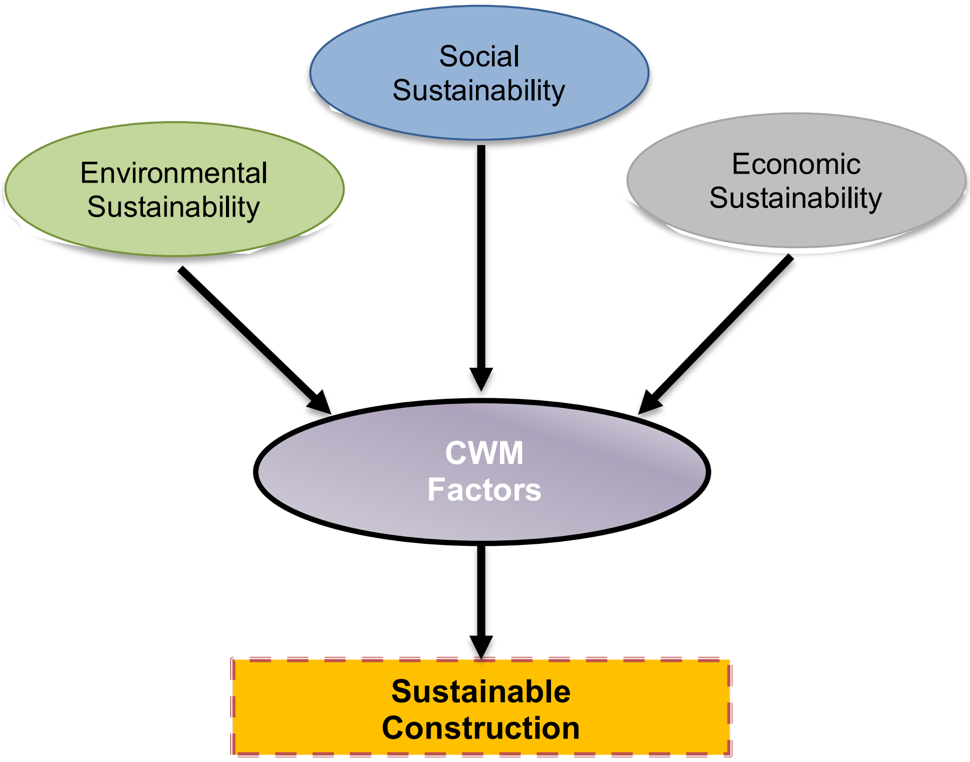


***Figure 1.1 Conceptual model for sustainable construction (Source: The Author)***

## 1.2 Research Questions

Considering the aim and objectives of this research project, the following set of research questions would be answered:

- Upon assessing all the phases of a construction project lifecycle, what are the primary causes of waste generation in each phase?
- How can waste be planned and minimised prior to commencement of the construction phase?
- What are the key factors that play a vital role in deciding the strategy for waste minimisation?
- How can these factors be applied through BIM tools in deciding whether to refurbish or rebuild an existing (a building that is about to reach the end of its design life) or a new building (a newly build structure, that is supposed to be considered with the scope of further works or redevelopment in the future or when reaching the end of its design life)?

- How to decide the condition of a highway pavement in terms of being sound, critical or failed pavement in any addition to related recycling methods?

## 1.3 Problem Statement

With the continuously increasing demand in the construction projects worldwide, certainly it was expected that the amount of waste will also be increased. This triggers for the need of a revised and more effective waste management plan, especially in bigger projects that have a fairly large tendency of producing more waste as compared to smaller sites (Mokhtar, et al., 2011). The completion of projects within budget and schedule are the goal of construction companies. Any additional efficiencies result in profit.

Over production, poor handling, incorrect storage, incorrect ordering, design change, manufacturing defects and rework are factors that contribute in material waste (Nagapan, et al., 2012). It has been recorded that around £1-1.2 million per mega project can be lost on waste (Gulghane & Khandve, 2015). Other factors that contribute in a way or another in the generating of construction waste are lack of training and poor workmanship. Due to the fact that raw materials wastage, ineffective management of waste is common on construction sites, waste minimisation became an important area of concern in the construction industry (Ali, et al., 2018b).

Waste Management on project sites have become a major focus due to construction waste's negative effect on land depletion and deterioration, energy consumption and noise pollution, and it has been considered to be a major source of environmental pollution for its solid waste generation and dust and gas emission (Bakchan, et al., 2019). All of these issues highlight the needs of waste management programs for construction companies and more importantly, the identification of factors that contributes to waste (Ali, et al., 2018b). For the step towards a better environment, this project analyses few of the waste management models that are being prepared prior to construction phase and then implemented on construction sites, with the aim to highlight and determine the key factors that play a vital role in the decision-making for waste reduction. These factors are then used to identify another set of key decision-making factors that aid the decision of whether to refurbish or rebuild an existing building, as the idea behind this theory is to come up with the minimum waste solution.

## 1.4 What is a Waste?

Taking account of the subject, 'waste' can be defined as: "any substance or object, which the holder discards or intends or, is required to discard", as mentioned in the Section 75 (2) of the Environmental Protection Act 1990.

*Table 1.1 Definitions of Waste (Source: The Author)*

| Authors | Definitions |
|---|---|
| (Formoso, et al., 2002) | Waste is the process and operational concept. The author also added that the definition of waste is resources used to produce a product but at the end has no value. |
| (Nagapan , et al., 2012) | Waste is unwanted products or materials. |
| (Rajendran & Gomez, 2012) | Waste can also be defined as any final products which at the end do not worth to the owner and the owner sees it as a waste. |

Like all other countries, UK also produces large amount of waste each year and most of the amount goes to landfill (Hobbs & Hurley, 2001; Ajayi & Oyedele, 2017). Better use of waste materials, specifically construction and demolition waste (CDW), to substitute primary materials is identified as one of the key elements in the reduction of waste nationally.

## 1.5 Types of Waste

The waste can be of any type, depending on the sector. As this study Is based on the construction sector, the types of waste discussed in this section relates to this sector. The major physical waste generated from the construction activity is identified in the form of material waste like concrete leftover, wood, gypsum, demolished debris, steel scrap and others. Following are the three main types of construction and demolition waste.

### 1.5.1 Material Waste

This can be classified as the waste that is generated from any type of construction work such as construction or erection of new buildings/structures, highways/pavements etc. Material waste can be described as, any substance, matter or thing, that is generated, has no use or left over as a result of construction work and abandoned.


***Figure 1.2 Construction site at Edgware Road, London (Source: The Author)***


***Figure 1.3 Allocated waste area on a construction site (Source: The Author)***

Waste arising from construction sites can be of different forms and types. Some of the waste goes for recycling and some goes to landfill. Although, all waste management companies have different criteria to treat the collected waste from construction sites. Some of the most common types of construction wastes are listed in the Table 1.2 below:

***Table 1.2 Types of construction waste (Source: The Author)***

| Material | Description |
|---|---|
| **Wood** | Loads of different type of new woods are expected to be extracted from any construction site especially from timber roof, floor and wall construction. These may include plywood, chip wood, dimensional lumber, treated timber, shavings and sawdust etc. |
| **Gypsum / Plasterboard** | Gypsum wallboard/plasterboard that is also a waste product from any new construction. Plasterboards are widely used for all internal partitions and ceilings. It comes in two sizes; 8'x4' (2400mm x 1200mm) and 4'x2' (1200mm x 600mm). |
| **Masonry** | Inert material such as brick, concrete, rock, and dirt that originated at a construction site. This masonry material was "cleaner" and "newer" than the demolition masonry materials. |
| **Metal** | Metallic material that were a waste product of new construction. This material consisted of new metal studs and metal beams and pipes. |
| **Plastic** | Plastic waste materials are widely used in new construction. This includes PVC plumbing pipe, PVC siding, Styrofoam insulation, and plastic sheet. |
| **Cardboard** | Cardboard boxes, box board, and cardboard packing material. |
| **Other** | Any waste material originating from new construction that do not fit into one of the categories above such as stones, paints, wiring, plumbing material and sanitary etc. |

In many instances, the construction material waste can be reused for other works. The ability to reuse and recycle materials salvaged from demolition and building sites for reuse and recycling depends on (BRANZ, 2017):

- local recycling facilities;
- market demand;
- quality and condition of materials and components;
- time available for salvage;
- emphasis put on reuse and recycling.

### 1.5.2 Debris Waste

This is the type of waste that is produced from demolition of existing buildings/structures, highways/pavements etc. Debris waste are large quantities generated over of short period of time as a main part of the demolition process (Hobbs & Hurley, 2001).


***Figure 1.2 Demolition site waste (Source: The Author)***

***Table 1.3 Types of demolition waste (Source: The Author)***

| Material Type | Description |
|---|---|
| **Wood** | The wood found in demolition sites could of different types such as, dry wood, stud, joist, timber decking, flooring/engineering wood, skirting, architrave, plywood, treated wood, door etc. and these woods can be typically weathered, painted, and most likely, nailed/joined with some other material. |
| **Glazing** | Mostly found in commercial buildings. It is fixed in a frame, which can either be aluminum or pvc depending on the size and quantity of the glazing. |
| **Window** | Windows are found in every demolition project regardless of the size. |
| **Drywall** | Gypsum wallboard, are mainly found on internal partition walls and false ceiling. |

| | |
|---|---|
| **Door hardware** | All types of ironmongeries are expected to be found in a demolition project. |
| **Roof material** | These normally consist of shingles, timber, concrete, damp proof membrane, trusses and steel etc. |
| **Insulation** | Mostly found in the demolition of domestic and commercial buildings. Insulation comes in different types as described in detail in 'Appendix B'. It can normally be found between the partition walls, external cavity wall, ceiling, roof, loft and floor slab etc. |
| **Masonry** | Inert materials such as brick, concrete, rock, and dirt that were removed from a demolition site. These materials were normally mixed with other demolition materials such as wood, drywall, etc. |
| **Metal** | Metallic items that were removed during the remodeling or demolition of a structure. |
| **Carpet / Flooring** | Carpet and other floorings such as laminate/wood and vinyl mat are often found during the demolition of houses or semi commercial buildings. These are usually disposed off during the remodeling and or demolition of a structure. |
| **Electrical Wiring & accessories** | Electrical wiring, conduits and boxes etc. are expected to be found in every demolition project. There is no such life left in the used electrical wires, however the fuse boxes can be reused. |
| **Plumbing Material & Sanitary** | These include drain pipes, soil pipes, taps, bathroom and kitchen sanitary. |

### 1.5.3 Excavation Waste

This can be classified as the waste that is produced from the earth affecting activities such as; digging of ground for basement, cleaning of sewer, digging of or some layers of pavements/highways etc.

***Figure 1.3 Excavation waste (Source: The Author)***

***Table 1.4 Types of Excavation Waste (Source: The Author)***

| Material Type | Description |
|---|---|
| **Wood** | Includes wooden palettes, crating, waste from wood processing and sawdust. |
| **Plastics** | All plastic resin waste including, processed waste, packing materials, and plastic resin sludges. |
| **Textiles** | Includes clothing, rags, and processed cloth waste. |
| **Metal** | Metallic waste material from a single waste generator. Does not include metal sludges, which were categorised as "other". |
| **Rubber** | Includes auto and truck tyres from shredders, and processed rubber waste materials and overruns. |

## 1.6 Difference between Construction Waste and Demolition Waste

Construction waste is normally combined with demolition waste and described as "construction and demolition" (C&D). For the purpose of this study, C&D waste is defined as;

**"The waste resulting from new construction, remodeling, or the demolition of a structure."**

Nevertheless there are some differences between construction and demolition waste. Construction waste loads can usually be transported to the landfill in open top roll-off containers, dump trucks, or open trailers. Usually the construction loads tends to be lighter, less weathered, more homogeneous (all wood, aluminum gypsum, PVC, wiring, etc.), and contained more cardboard boxes (usually from fixtures) as compared to the demolition waste loads because construction waste generates from the remains of the new material. Also, it separates the remains of material in construction waste in order to recycle. In most cases, it is relatively easy to visually differentiate between the construction and demolition waste.

The demolition component of C&D is quite different from the construction component. The demolition waste material tends to be mixed with a variety of materials, and more difficult to separate and recover. Demolition loads fit into two broad categories; remodeling and debris. The remodeling loads are often mixed with new construction materials. Residential remodeling waste includes a higher percentage of wood whereas commercial remodeling projects contains more metal.

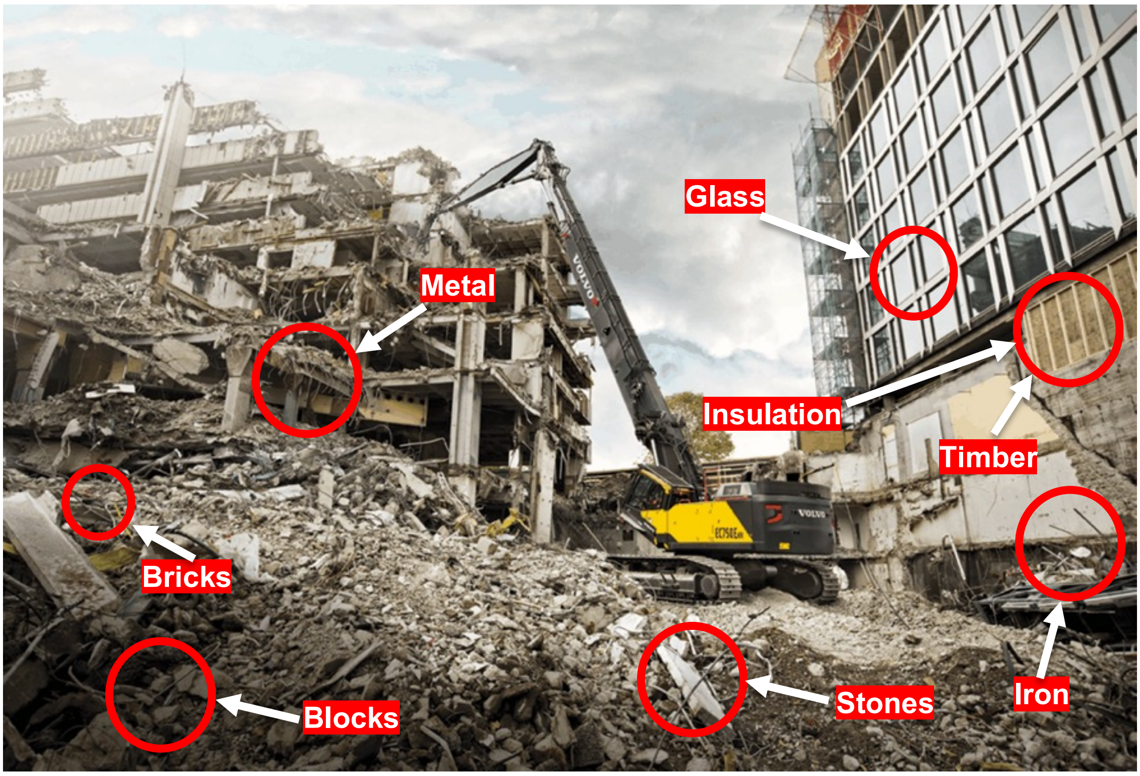


***Figure 1.4 Identification of demolition waste (Source: Google Images)***

As shown in Figure 1.6, debris loads resulting from demolition are essentially structures that are commonly knocked down by heavy equipment and then loaded onto dump trucks for transport to the landfill in a normal practice. Debris loads usually contains masonry materials (dirt, rock, concrete, and brick) that are mixed with wood, roofing, carpet, drywall and small amounts of metal, also highlighted in Figure 1.6. The materials are then mixed and usually shredded, broken, and smashed. Therefore, debris loads are much more difficult to recover materials. In many cases, a debris load consist of dirt, rock, or masonry materials.

Considering the fact that construction projects generate huge amount of waste, which can be predicted at an early stage, the findings of this research will also give an idea to the designers in developing a waste efficient design for any new development where minimum waste would occur during the construction phase.

### Requirements for Recycled or Reused Materials

In order to tackle the economical side of waste, a New Zealand based company, BRANZ REBRI has a Resource Routing Calculator (RRC) on its website that helps to calculate the economic value of sending different waste streams to landfill or to reclamation facilities (BRANZ, 2017). Factors include the following:

- cost of transport;
- cost of skip hire;
- value of material;
- weight/amount of material;
- amount of contaminants.

Every market has its own specifications for recycled or reusable materials. BRANZ REBRI allows used to obtain specifications from the recycling operators before starting deconstruction so that they know what to save and how to save it (BRANZ, 2017). The Resource Routing Calculator let the user to obtain the following:

- material type;
- acceptable and unacceptable levels of contamination;
- acceptable and unacceptable levels of damage;
- quantities accepted;
- transportation requirements;
- required documentation including waste tracking forms;
- sorting and handling requirements for each material type.

#### Things to check for Concrete

- Types of concrete and rubble accepted;

- Size of concrete pieces;
- Amount of preprocessing;
- Acceptable levels of bricks and tiles;
- Acceptable amount of contamination from materials such as glass, metal, soil;
- Some concretes products are too hard-wearing on crushing machines and some concretes are too soft to meet reuse specifications after crushing, so will not be accepted by operators.

**Things to check for Metal**

- Types of metal accepted;
- Contamination tolerances from materials such as plastics and leftover product in containers.

**Things to check for Plasterboard**

- New Zealand currently has no facilities for recycling plasterboard back into plasterboard;
- There are opportunities for use of off-cuts;
- Some composting facilities accept plasterboard – the gypsum content acts as a soil improver.

**Things to check for Timber**

- Types of timber acceptable (for example, treated, native, untreated);
- Minimum and maximum sizes of board and lengths of timber;
- Minimum and maximum quantities;
- Contamination tolerances from materials such as nails, paint, concrete;
- Any preprocessing requirements such as sorting or grading;
- How timber is to be received (for example, loose, stacked in containers or on palettes).

## 1.7 LEAN Construction

Lean construction can be defined as, "the application of lean thinking to the design and construction process, creating improved project delivery to meet client needs and improved efficiency for constructors."

### 1.7.1 Adopting LEAN in Construction

Since the mid-1990s, lean construction has emerged as a new concept, both in the discipline of construction management and the practical sphere of construction. There are two slightly differing interpretations of lean construction. One interpretation holds that the question is about the application of the methods of lean production to construction

(Ballard & Howell, 1998). In contrast, the other interpretation views lean production as a theoretical inspiration for the formulation of a new, theory-based methodology for construction, called lean construction.

While the goals of lean are similar across industries, the construction industry work process is notably different, i.e. it moves project to project rather than establishing an ongoing programme. That being said, there is certainly room and need for lean adoption within the construction industry (Sharman, 2017). By adopting lean techniques, the industry can:

- Communicate more effectively;
- Produce less waste, make fewer mistakes;
- Improve planning and forward scheduling;
- Determine value from a customer perspective, identify processes that deliver value and eliminate those that do not;
- Drive immediate and apparent change;
- Provide a cleaner, safer, more effective work site;
- Continually improve from one project to the next.

Lean implementation begins with leadership commitment and is sustained with a culture of continuous improvement. When the principles are applied properly, dramatic improvements in safety, quality, and efficiency can be achieved at the project level. Improvements at the process and enterprise levels are enablers that make improvements at the project level more successful and allow such improvements to be sustainable.

The lean ideal is to provide a custom product exactly fit for purpose and delivered instantly with no waste to the subsequent actions that may be necessary in order for projects to pursue that ideal (Aziz & Hafez, 2013). The ability of individuals and organizations to follow this process will vary with position and circumstances, but to the extent possible, the following should be implemented on projects: (1) Select suppliers who are willing to adopt lean project delivery; (2) Structure the project organization to allow money to move in pursuit of the best project-level returns; (3) Define and align project scope, budget, and schedule; (4) Explore adaptation and development of methods; (5) Make design decisions, with explicit alternatives against stated criteria; (5) Practice production control in accordance with lean principles; (6) Build quality and safety into projects; (7) Implement JIT and multi-organisational processes after site demand; (8) Use evaluations and planning on process that transform materials; (9) Use computer modeling to integrate product and process design; (10) Use 5S workshops: a tool for workplace organisation and promoting teamwork (S1) Sort through items, keep what is needed and dispose of what is not; (S2) Straighten: organise and label everything;

(S3) Shine: clean; which can also expose abnormal and pre-failure conditions; (S4) Standardise: develop rules to maintain the first three S's; and (S5) Sustain: manage to maintain a stabilised workplace and initiate continuous improvement when needed and (11) Apply Value Stream Mapping to make visible all the steps in process. These can be organised specially for projects and preceded by a pre-project phase (Construction Industry Institute, 2007).

### 1.7.2 Lean Principles

There are five fundamental principles for lean thinking, which have to be followed step by step to gain the maximum benefit of the lean success (Aziz & Hafez, 2013): (1) Specify Value: Specify value from customer's own definition and needs and identify the value of activities, which generate value to the end product; (2) Identify the Value Stream: Identify the value stream by elimination of everything, which does not generate value to the end product. This means, stop the production when something is going wrong and change it immediately. Processes which have to be avoided are miss production, overproduction (repeat production of the same type of product, etc.), storage of materials and unnecessary processes, transport of materials, movement of labor workforces and products, and finally production of products which does not live up to the wished standard of the customer as well as all kind of unnecessary waiting time; (3) Flow: Ensure that there is a continuous flow in the process and value chain by focusing on the entire supply chain (Aziz & Hafez, 2013). Focus has to be on the process and not at the end product. However, the flow will never get optimal until customer value is specified, and the value stream is identified; (4) Pull: Use pull in the production and construction process instead of push. This means produce exactly what the customer wants at the time the customer needs it and always prepared for changes made by customer. The idea is to reduce unnecessary production and to use the management tool "Just In Time"; and (5) Perfection: Aims at the perfect solution and continuous improvements. Deliver a product which lives up to customer's needs and expectations within the agreed time schedule and in a perfect condition without mistakes and defects. The only way to do so is by having a close communication with the customer/client as well as managers, and employees are between (Aziz & Hafez, 2013). Figure 1.7 summarises examples of lean tools already used in job sites.

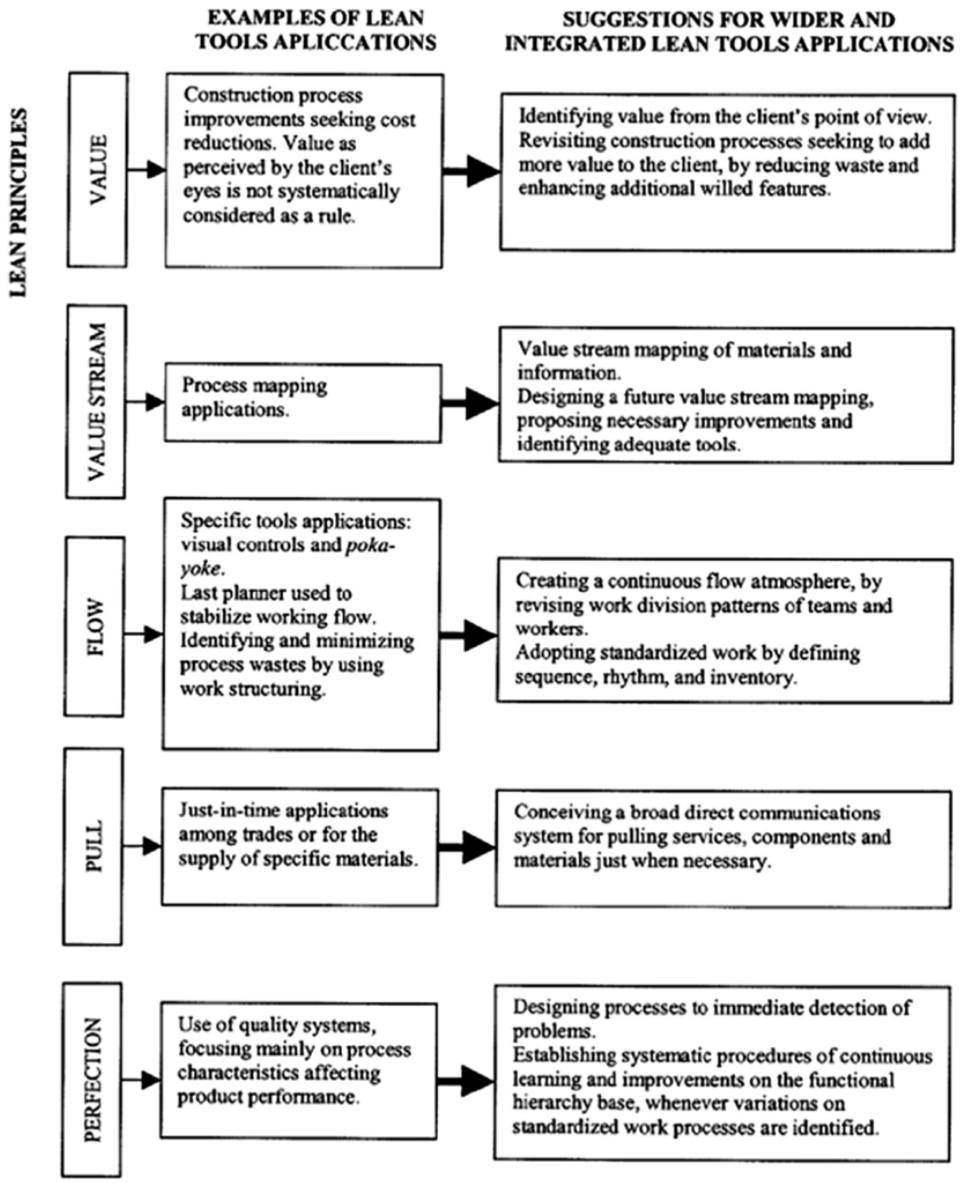


***Figure 1.7 Examples of lean tools in construction (Source: Aziz & Hafez, 2013)***

## 1.8 Background

The construction industry is the major contributor towards the economy of any country. Also, the demand for construction and demolition (C&D) of existing and new buildings have been increasing every year, as a result of this, a significant increase in waste has been witnessed. According to Defra, the UK was producing on average of 110 million tonnes of C&D waste every year since 2010 (Waste Statistics Team, 2015), this accounts to more than 60% of the total waste generated within the UK. The UK C&I sectors generated 43.9 million tonnes of waste in 2018 (DEFRA, 2022), of which 37.2 million tonnes (around 85%) was produced in England. By comparison, the 2016 UK C&I waste arisings figures was 41.0 million tonnes, of which 33.1 million tonnes was generated by England. Over two thirds of C&I waste is generated by the commercial sector, in both the UK and England. The latest estimates for England only, indicate that waste generation was around 37.2 million tonnes in 2019 and in 2018 (DEFRA, 2022). For

2017, the England estimated (36.1 million tonnes) was a relatively large increase from 33.1 million tonnes in 2016 (DEFRA, 2022). Similarly, other countries with large economies also generates hefty amount of C&D waste such as 40% in Brazil (Saraiva et al., 2012), 65% in Hong Kong (Esin & Cosgun, 2007), 35% in Canada (Kofoworola & Gheewala, 2009), and 44% in Australia (Shen & Tam, 2002). Large numbers of articles have been published in various journals related to waste management (WM) discussing sources of waste, cost of waste, and how to minimise waste. One of the primary causes of excessive and unexpected amount of C&D waste is poor decisions and planning prior to commencement of construction and during the construction process.

Construction is an important aspect of infrastructure and growth of industry in developing countries. Construction of buildings, roads, bridges, highways and other infrastructure play an important role in shaping the society's future (Shen & Tam, 2002). In this process the construction industry produces a vast quantity of waste which is environmentally unfriendly and costly to project budget. There seems to be a lack in the decision-making in various stages of the construction process.

Currently, the industry faces many challenges with issues related to construction waste. Construction waste has become a serious problem in many countries. Waste has negative impact on the environment, cost, productivity, time, social and economy. Production of construction waste in huge amount due to increasing demand of infrastructure; commercial buildings and housing development projects which has generated large amount of construction waste (Esin & Cosgun, 2007). Design, operational, procurement and material handling activities lead to site waste generation. This waste generation activities consume time and effort without adding values to the client thus resulting losses in material, delay in meeting the stipulated time and effort without adding values to client thus resulting losses in material, delay in meeting the stipulated time and execution of unnecessary work (Kofoworola & Gheewala, 2008). Therefore, to avoid overrun the cost of the project it is necessary to avoid the waste generation and proper waste management. Having a decision-making strategy or a framework will help the relevant stakeholders of the relevant project to avoid the generation of waste and to save the overall cost by deciding whether to refurbish/reuse or rebuild/recycle any existing building or structure.

The production of waste is a natural result of economic and social activity by businesses and consumers, and has been throughout human history. There are costs and benefits involved – the resources used in the production process and the benefits gained from consuming goods and services (Kofoworola & Gheewala, 2008). The key is to ensure that the value extracted from resources is not exceeded by the costs of using them, and therefore the excessive amount of waste shall not be produced. It is also important to make sure that waste is optimally managed, so that the costs to society of dealing with waste, including the environmental costs, are minimised.

Over the last 20 years, waste management in the UK has changed dramatically, as changes were made to further improve the waste management system over these years and so on. Some positive outcomes have been recorded from these changes as there has been a major decrease in the quantity of waste being disposed of to landfill and on the other side, an increase in recycling. Recycling the waste means less environmental impact and zero carbon. The key aim of the waste management plan for England is to set out work towards a zero waste economy as part of the transition to a sustainable economy. In particular, this means using the “waste hierarchy” (waste prevention, re-use, recycling, recovery and finally disposal as a last option) as a guide to sustainable waste management.

### 1.8.1 Relevant UK Legislations and Policies on Waste Management

It is vital to highlight and take into account, the waste management (WM) policies during the identification of the key decision-making factors. Waste legislation exists to ensure that the environment and human health is protected. Effective regulation provides a level playing field in which legitimate businesses can operate and invest with confidence and thus help to create markets. However, waste regulation can impose significant burdens on business but target against those with poor standards of compliance or who cause a nuisance or harm, and those who deliberately flout the law.

Prior to 1972, there were minimal controls over the disposal of wastes. The Public Health Act 1848 was the first attempt at national legislation in the UK. It was this Act which created the term "Statutory Nuisance" in relation to any accumulation or deposit which was prejudicial to health or a nuisance (Hobbs & Hurley, 2001). The Act enabled local government to take action on behalf of the public. Between 1848 and 1936 a series of Acts were enacted before the consolidating Public Health Act 1936. This Act gave local authorities the powers to police and inspect waste arising. It also gave authorities the power to remove household and trade waste and to inspect for, and require the removal of, noxious materials.

Waste legislation in the UK is derived from the European Union (EU) regulatory framework (Jordan, 2006). The overarching legislative framework for Waste Management (WM) in the EU is the EU Waste Framework Directive (WFD) (Directive 2006/12/EC on waste), which sets the obligations for member states on the collection, transport, recovery and disposal of waste (DEFRA, 2012). Currently amended by the Waste Framework Directive 2008 (Directive 2008/98/EC), it sets the obligation for member states to take appropriate measures to encourage firstly, the prevention or reduction of waste production and its harmfulness and secondly the recovery of waste by means of recycling, re-use or reclamation or any other processes with a view to extracting secondary raw materials, or the use of waste as a source of energy (DEFRA, 2012). Other Directives which affect CD&E WM are the Landfill Directive (1999/31/EC) and the Integrated Pollution Prevention and Control Directive (IPPC) (2008/1/EC). The aims of EU waste legislation are promoted by EU WM principles and the EU waste hierarchy (Strange, 2002; Clinch, 2000).

In the UK, a number of regulations exist, which transpose the requirements of EU waste legislation into UK law. The Environment Agency is the main regulator of waste management in England. The Agency also registers exemptions for low risk waste treatment (Environmental Resources Management and Eunomia Research and Consulting, 2006). Better regulation principles have already had significant impact on improving waste regulation. Some of the main policies of UK waste management are described below:

#### 1.8.1.1 The Environmental Protection Act 1990

The Environmental Protection Act 1990 (EPA 90) was the culmination of a long period of discussion of amendments to environmental law. The Act covers a wide range of environmental topics, not all of which are relevant to waste management (Hobbs & Hurley, 2001). Part I of the Act introduced the system of Integrated Pollution Control (IPC), which is applicable to the release of pollutants to air, water and land from certain processes, establishing the important new criteria of Best Available Technology Not Entailing Excessive Cost (BATNEEC). Part II of the Act deals specifically with the deposit of waste on land (most waste management activities fall under the provisions of Part II). Many of the provisions of the EPA 90 have been implemented by Regulations made by the Secretary of State for the Environment.

#### 1.8.1.2 The Environment Act 1995

This Act established the Environment Agency and the Scottish Environment Protection Agency. The creation of these Agencies represented a major step towards truly integrated environmental management and control, as they brought together the regulators responsible for Integrated Pollution Control, water management and waste regulation. The 1995 Act makes numerous amendments to the Environmental Protection Act 1990 (EPA 90) and the other major environmental statutes (Hobbs & Hurley, 2001). Many of these amendments relate to the powers and duties of the regulators, who now have greater scope to take preventative action when there is a likelihood of pollution (Hobbs & Hurley, 2001).

#### 1.8.1.3 Waste Strategy for England 2007

The Waste Strategy for England aims to break the link between economic growth and waste growth and put more emphasis on waste prevention and re-use. It also aims to meet and exceed the landfill diversion targets including for non-municipal waste. The strategy also seeks to reduce greenhouse gas emissions from waste management and to achieve an annual net reduction of at least 9.3 million tonnes of carbon dioxide equivalent per year compared to 2006 (DEFRA, 2007).

In 2009, to stimulate diversion of construction and demolition (C&D) waste from landfill, the Government considered in conjunction with the construction industry, a possible new target of halving the amount of waste going to landfill by 2012 as a result of waste reduction, re-use and recycling, but the desired results were not achieved by 2012, the amount of waste generation going to landfill could not be controlled.

#### 1.8.1.4 PPS10: Planning for Sustainable Waste Management

Planning Policy Statement 10 (PPS10) sets the overall planning framework for waste and seeks to drive waste management up the waste hierarchy, addressing waste as a resource and only disposing of it as a last resort (Environmental Resources Management and Eunomia Research and Consulting, 2006). PPS10 encourages implementation of Site Waste Management Plans for all proposed new developments to help in identifying the type of material to be demolished and/or excavated, opportunities for the re-use and recovery of materials and to demonstrate how off-site disposal of waste will be minimised and managed.

To achieve sustainable development, which advocates efficient allocation of resources and improved quality of life (Ofori, 1992), the EU waste legislation and policy set the goal to ensure 70% of all CD&E waste is reused, recycled or recovered by 2020. In the UK, the local targets are: to ensure a 50 percent reduction of construction, demolition and excavation waste to landfill by 2025 (previously extended from 2012 to 2025) in relation to 2005 levels and zero waste to landfill by 2020 (Ofori, 1992).

### 1.8.2 Relevant British Standards (BS) on the Design Life of Buildings

Considering the fact that this project aims to identify the key factors that aid the decision of whether to refurbish or rebuild an existing building or a structure, there is a need to determine the design life and exiting condition of the building. For this purpose, it is necessary to discuss the relevant British Standards (BS) on the design life of buildings, so that the decision-making factors can be identified and then prioritise in accordance with the relevant BS Standards.

#### 1.8.2.1 British Standard BS 7543 (2003)

British Standard BS 7543 (2003) ‘Guide to durability of buildings and building elements, products and components’ (British Standard BS 7543, 2003) gives guidance on durability, required and predicted service life and design service life of buildings and their components and/or parts. It applies primarily to new buildings and their components rather than repair and maintenance, so there is the indication that this BS Standard is most likely to be considered during the decision-making of the new structure or building. This Standard also gives guidance on presenting information on the service and design service life of buildings and their components when a detailed brief is being developed.

This Standard expresses durability as ‘design service life’ (DSL), which aligns well with the possible inclusion within Regulation 8 (British Standard BS 7543, 2003). There is an important information, which is required in order to determine the possible lifetime of a material or component:

a) time against which the durability is to be assessed;
b) conditions in which the material or component will have to perform;
c) Performance level at which the material or component is not to the required standard.

The above information would provide the initial detailed report of the building. However, in addition to these factors, issues such as maintenance levels and conditions of use should be estimated. Three levels of maintenance are described in BS 7543 (2003) and these are shown in Table 1.5. This Standard also includes detailed information relating to factors which can cause deterioration (British Standard BS 7543, 2003). Many examples of premature deterioration are also listed in addition to agents that can affect the service life of building components and materials.

Information on the predicted service life can be supplied by manufacturers. This should be qualified by considering additional information as follows:

a) Information on exposure. This is particularly important where the required service life is part of a performance specification presented to a manufacturer supplying external components for use in a building that is not known to him;
b) Details of adjacent materials and fixings. The movement of adjacent components and the chemical compatibility of materials is often critical to the durability of an assembly. These details are particularly important when the required life is given to a manufacturer of components in a performance specification. General statements and schematic details may not be enough to identify risks. It is essential that allowances are made for thermal and moisture movement and for isolating incompatible materials are fully described.

Providing a long-lasting and durable building often involves the use of high specification components and expensive materials. This can raise the cost of the project, however careful detailing and good workmanship can also provide long-term performance in some cases. A careful consideration and suitable amendments are required on this as this directly impacts the project economically.

***Table 1.5 Maintenance Levels (Source: British Standard BS 7543, 2003)***

| Level | Description | Scope | Examples |
|---|---|---|---|
| 1 | Repair only. | Maintenance restricted to restoring items to their original function after failure. | Replacement of jammed valves; reglazing of broken windows. |
| 2 | Scheduled maintenance plus repair. | Maintenance work carried out to a predetermined interval of time, number of operations, regular cycles etc. | Five yearly external joinery painting cycle. Five yearly recoating of roof membrane with solar reflective paint. |
| 3 | Condition based maintenance plus repair. | Maintenance carried out as a result of knowledge of an item's condition. [The condition having been reported through a systematic inspection (procedure)]. | Five yearly inspection of historic churches etc. leading to planned maintenance. |

#### 1.8.2.2 British Standard BS 8000

British Standard BS 8000 'Workmanship on building sites' has a number of 'Codes of Practice' which describe the various building practices (British Standards BS 8000, 2003). These include the following:

- Code of practice for excavation and filling (Part 1: 1989);
- Code of practice for concrete work. Mixing and transporting concrete (Part 2.1: 1990);
- Code of practice for concrete work. Site work with in situ and pre cast concrete. (Part 2.2: 1990);
- Code of practice for masonry (Part 3: 2001);
- Code of practice for waterproofing (Part 4: 1999);
- Code of practice for carpentry, joinery and general fixings (Part 5: 1990);
- Code of practice for slating and tiling of roofs and claddings (Part 6: 1990);
- Code of practice for glazing (Part 7: 1990);
- Code of practice for plasterboard partitions and dry linings (Part 8: 1994);
- Cementitious levelling screeds and wearing screeds. Code of practice (Part 9: 2003);

- Code of practice for plastering and rendering (Part 10: 1995);
- Code of practice for wall and floor tiling. Ceramic tiles, terrazzo tiles and mosaic (Part 11.1: 1989);
- Code of practice for wall and floor tiling. Natural stone tiles (Part 11.2: 1990);
- Code of practice for decorative wall coverings and painting (Part 12: 1989);
- Code of practice for above ground drainage and sanitary appliances (Part 13: 1989);
- Code of practice for below ground drainage (Part 14: 1989);
- Code of practice for hot and cold water services (Part 15: 1990).

The information contained within each of these parts of the standard gives guidance on construction details and methods for all aspects of building. This guidance gives details on the quality of workmanship required which is also described in Regulation 8. Codes of practice for the installation of materials and components are a vital part to ensuring the completed building is fit for purpose and can meet the lifetime requirements of the occupants.

Many of the sections within BS 8000 are up to fifteen years old, however they are still applicable in today's construction industry as they describe all of the 'traditional' building methods used in the UK (British Standards BS 8000, 2003). The parts of the standard describing structural elements may be of greater importance when estimating the design service life of a building. These are often viewed as the elements, which will govern how long a building will perform to its design level and how the durability of the materials will be affected during the lifetime of the structure.

#### 1.8.2.3 BS ISO 15686-1 (2000)

BS ISO 15686-1 (2000) 'Buildings and constructed assets – Service life planning: Part 1 – General principles' provides a methodology for forecasting the service life of buildings and estimating the necessary maintenance and replacement of components (BS ISO 15686-1, 2000). A major factor in the development of this standard was concern over the industry's need to forecast and control the cost of building ownership, as a high proportion of the life cycle costs of a building may be set by the time the building is complete (BS ISO 15686-1, 2000). Where there is a large stock of older buildings, more than half of all construction expenditure will be spent on maintenance and refurbishment (BS ISO 15686-1, 2000). For countries currently developing their building stock, the risk is that a similar pattern will occur if long-term performance is not taken into account at the outset and also it will impact the overall economy and the environment, considering the amount of rework required on a particular building.

The standard states that service life planning aims to reduce the cost of building ownership. An assessment of how long each part of the building will last, helps to decide the appropriate specification and detailing. When the service life of the building and its parts are estimated, maintenance planning and value engineering techniques can be applied.

BS ISO 15686-1 provides a means of comparing different building options. It also allows checking that performance is not unacceptably reduced to meet financial constraints during the stages of development and planning (BS ISO 15686-1, 2000). The standard is primarily intended for the following:

- Building owners and users;
- Design, construction and facilities management teams;
- Manufacturers who provide data on the long-term performance of products;
- Maintainers of buildings;
- Valuers of buildings;
- Technical auditors of buildings;
- Those who develop of draft product standards.

Based on the description above, this BS Standard is considered to be applicable on both the decision-making the existing and new structures, so primarily, this will be taken into account during the identification and application of the key decision-making factors for both scenarios.

#### 1.8.2.4 BS ISO 15686-2 (2001)

British standard BS ISO 15686-2 (2001) ‘Buildings and constructed assets – Service life planning: Part 2 – Service life prediction procedures’ describes the principles for service life predictions (SLPs) of building components (BS ISO 15686-2, 2001). The SLP methodology has been developed to be universally applicable to all building types. It can be used in the planning of SLP studies regarding new products or components where the knowledge of their performance may be limited. This part of BS ISO 15686 is intended for the following (BS ISO 15686-2, 2001):

- Manufacturers, who wish to provide data on the performance of their product(s);
- Test houses, laboratories and technical approval organisations;
- Those who develop or draft product standards.

This part of the standard can be used as a stand-alone document (BS ISO 15686-2, 2001), however it is recommended by the British Standard Institute (BSI) that the other parts of BS ISO 15686 are considered (particularly BS ISO 15686-1) before implementation.

Similar to BS ISO 15686-1, this BS Standard is also applicable in both the decision-making of new and existing buildings. However, this Standard further adds the planning of the service life of building, which is more relevant in the decision-making of new buildings. This Standard further adds value to the importance of key factors that are identified in the Chapter 5 of this research project.

### 1.8.3 Waste Management Hierarchy

The 2011 Regulations require everyone involved in waste management and waste producers in England to take, on the transfer of waste, all reasonable measures to apply the waste hierarchy except where, for specific waste streams, departing from the hierarchy is justified by lifecycle thinking on the overall effects of generating and managing the waste. The waste hierarchy needs to be followed in every construction and demolition project (Price & Joseph, 2000). In a bid to identify the key decision-making factors, the waste hierarchy is required to be considered during different stages of the factors identification, as this hierarchy is being followed widely within the industry, especially the waste management (WM) companies that complies with this hierarchy during the process of sorting out of the waste. However, not many companies follow it strictly and have some leniency towards the management of waste, which results in extra amount of waste being generated (Brent, et al., 2007). The global waste hierarchy is depicted in Figure 1.8 and explained below.

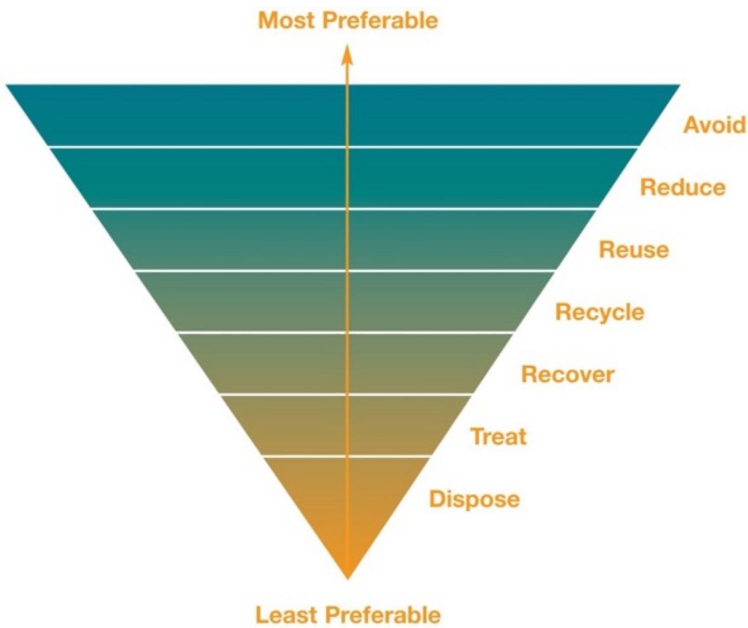


***Figure 1.8 Waste Management Hierarchy (Source: Ali, et al., 2018)***

**Avoid –** The first criteria of the waste hierarchy. It is very less likely to avoid the generation of waste on most of the C&D sites, especially on demolition sites. However, this should be the first priority on all sites, to avoid the waste as much as possible.

**Reduce/Minimise -** The Government's aim is to reduce the amount of waste produced across the country whilst supporting economic growth. Adopting the principles of good practice to minimise the waste on a project can demonstrate a firm commitment to sustainable construction and environmental management. If implemented correctly, good practice of waste reduction can deliver a range of benefits in addition to improvements in material resource efficiency. Some of the key benefits include:

- **Reduced material and disposal costs –** less waste generated means that a reduced quantity of materials will be purchased, and less waste taken to landfill will reduce gate fees for disposal. Cost savings will stimulate the adoption of improved recovery practices and motivate a sustained change in waste management practice;
- **Increased competitive differentiation –** benefits both developers and contractors, particularly where this will help to meet prospective client's sustainability objectives.

**Reuse –** Excavated material (soils) will be retained on site for re-use as backfill while hard rubble will be crushed and re-used on site. Where the product can be sold on as a viable resource it will be stored until market conditions improve. Unsuitable material for engineering fill will be used for landscaping (Brent, et al., 2007). Drainage arising will be used in engineering fill/and or landscaping. Top soil will be limited.

**Recycling –** It is expected that some concrete and tarmac will arise from the re-working of the access road. In addition there will be inert materials from the MRF facility. This material can be treated to produce high quality recycled aggregates either by using crushing and/or screening processes off site or on site. Once treated the recycled concrete aggregate will be used as hardcore or back fill in excavated areas to substitute virgin aggregates (Van Ewijk & Stegemann, 2016). Concrete can be used as hardcore and back fill where high strength and aesthetics are not of importance.

**Recovery –** This includes CDE waste and energy recovery, gasification and pyrolysis, which produce energy (fuels, heat and power) and materials from waste; some backfilling operations;

**Treat –** This is the second last resort, where the waste is tried to be recovered by treating it at the recycling yard.

**Disposal –** Waste that cannot be re-used or recycled is likely to end up in landfill. Any hazardous waste arising will be dealt with by a licensed operator and disposed of at a secure site (Brent, et al., 2007).

Application of this waste hierarchy does play an important factor in the reduction of waste from the sites. However, this hierarchy lack some of the key implications and needs further clarification on the following:

- What stage of waste hierarchy to consider on which stage of a construction process?
- Inter-relation between the stages of the waste hierarchy and when and how to implement them together on complex construction sites?

Solutions to the above questions and revisions to this waste hierarchy have been proposed in the case study one of chapter 5 of this thesis, which are then implemented onto the proposed frameworks used towards the identification of the key decision-making factors.

## 1.9 When is Refurbishment a Low-cost Alternative?

It is often assumed that refurbishment is a low-cost alternative to redevelopment/rebuild. But the costs of refurbishment can be influenced by a myriad of factors that will vary greatly from project to project. Key differences between refurbishment and redevelopment where cost savings may be made include:

### 1.9.1 Planning and Legal Cost

Refurbishment works are likely to see faster progress through the planning system and building regulations requirements may be less rigid than with new-build (Ryu, et al., 2019). Existing buildings may offer significant planning advantage in terms of car parking and permitted development densities. In addition, the burden of Section 106 agreements may be avoided.

### 1.9.2 Demolition Costs

Demolition and waste disposal costs will, in most cases, be lower in a refurbishment project due to the reuse of building materials (Ryu, et al., 2019). An associated benefit is the reduction in waste, resulting in savings from disposal costs and landfill tax.

### 1.9.3 Building Material Costs

As suggested in many studies, lower and overall building material costs can be achieved through the retention and recycling of existing building materials. This factor determines part of the economic impact, however other relevant aspects of this impact are also discussed in detail in Chapter 4 and 5. The preservation of architectural features may also enhance value to potential occupiers (Tallini & Cedola, 2018).

### 1.9.4 Maintenance of Income

A phased or partial refurbishment may mean that parts of an existing building can remain in occupation while works are carried out, perpetuating income for the owner (see an example of this in the review of case study one in Chapter 2). Refurbishment is often quicker to complete than redevelopment, reducing the void period, but this is solely based on the type of building's planned use, which in most cases, is up to the owner's decision (Tallini & Cedola, 2018). If the proposed planned use is different than the current use, then refurbishment may not a feasible option.

### 1.9.5 Tax Relief

Property tax relief in the form of Capital Allowances (CA) offers a range of financial advantages including Plant and Machinery Allowances, Special Rate Integral Features (SRIF) (Plant & Machinery) Allowances and the highly beneficial Enhanced Capital Allowances (Kincaid, 2003). Refurbishments offer one of the highest levels of tax relief available, with potentially 60 - 80% of a project's total expenditure qualifying for one category or another (Jeffrey Boyer, 2013). If the project is in a disadvantaged area of the country and the refurbishment brings the property back into use, 100% tax relief could be realised through Business Premises Renovation Allowances (Kincaid, 2003). This factor is not considered as a key factor in this project, as this proposed research is about considerably big residential and commercial projects, where tax relief may not make a huge difference to the overall cost saving of the construction or demolition project, so this factor is voided and will not be discussed in the main chapters of this research project.

## 1.10 Scope and Limitations

As highlighted, the overall goal of this study is to investigate the design, procurement, waste management plans and construction strategies for waste-efficient construction and demolition projects. As such, data was collected from different C&D sites and survey was conducted to get the opinion and experience from relevant stakeholders such as designers, planners, suppliers, contractors, managers, supervisors and waste management experts, among others. Meanwhile, activities of the construction industry are diverse, and it is divided into two, which are building construction and infrastructural facilities. The scope of the project is limited to building construction projects.

Within the context of LEAN, waste is studied both in terms of materials and non-materials waste such as time loss. The materials aspect of waste has been one primary focuses of this study, and no attempt has been made to look into process waste within its context, especially as the physical waste constitutes increasing environmental impacts (Faniran & Caban, 1998). Similarly, Skoyles (1976) categorised waste as direct waste which involves complete loss of materials due to damages or other physical activities, and indirect waste which may be as a result of over thickness of building elements resulting in excessive use of materials. In this study, several decision making factors have been discussed and identified but only those with the tendency of playing an important role for reducing the waste have been included to the list of key factors that will decide whether to refurbish or rebuild.

## 1.11 Significance of the Study

The UK construction activities contributes about 44% of total landfill waste (Paine & Dhir, 2010; Ajayi, et al., 2016). US landfill site consists of about one-third waste of construction origin (Yuan, et al., 2012), where 569 million tonnes of C&D waste was generated in 2017 only in the US (Cho, et al., 2022), while a typical Australian landfill site has up to 44% waste from Construction Demolition and Excavation (Shen & Tam, 2002; Hyder Consulting, 2011). A total of 19.0 million tonnes of construction and demolition (C&D) waste was generated in Australia in 2008-09. Of this total waste stream, 8.5 million tonnes was disposed to landfill, while 10.5 million tonnes, or 55%, was recovered and recycled (Hyder Consulting, 2011). The figure slightly went up to 20.4 million tonnes of C&D waste in 2017 in Australia (Newaz, et al., 2020). And similar figures were generated in other countries too. The impending problems of continuous waste landfilling are clear. While building related activities consumes about 50% of materials taken from nature, wastage of the materials results in continuous extraction, with tendency of materials depletion (Anink, et al., 1996; Manfredi, et al., 2009). Also, it is commonly known that resource excavation and waste landfilling contribute to environmental pollution (Manfredi, et al., 2009). Equally, waste reduction and reduced resource excavation have significant economic benefits (Coventry & Guthrie, 1998; Yuan, et al., 2012). Evidence shows that reducing construction waste by 5% could save up to £130 million in the UK construction industry (BRE, 2003). However, many measures have been taken to control this figure, but there is no significant improvement in this cause. As mentioned in this project, there is a need for the decision-making criteria that would aid the decision of whether to refurbish/re-use or rebuild/recycle, and the decision-making criteria should mainly be based on the environmental factor to help protect the environment with less generation of waste. This will significantly reduce the amount of waste and therefore, it is imperative that further studies should be carried out not only to find solution to managing waste after it occurred but to provide construction professionals with relevant knowledge, guidelines and the criteria for preventing and minimising waste.

Findings of this study will have a positive impact on the construction and demolition (C&D) industry, contributing to the field of practice as well as the body of literature and knowledge base of preventing the waste effectively with the help of key decision-making factors that would aid the decision of whether to refurbish or rebuild, this criteria would boost the economic and environmental impacts related to the existing building project or proposed development. In waste management, the research would enhance professional practices by providing practitioners with a framework for understanding measures for improving waste efficiency of design, procurement, waste management and construction processes including rebuild and refurbishment projects. The study also provides designers and contractor with the strategies for mitigating waste using the set of proposed frameworks in Chapter 4; thereby enhancing waste-efficient/minimum waste project delivery with the help of key decision-making factors/criteria, which will indeed also benefit the project economically and environmentally. In short, the key factors provides the user to make a decision for any existing building that is about to reach the end of design life (EODL) and also for the new development, when it will reach the end of design life.

According to Hao, et al (2008), previous studies on waste minimisation have been carried out at a unitary level while causes of waste are dynamic and multiplicity in nature. This research project contributes to the existing body of knowledge, decision-making, industrial practice and research by carrying out case studies on existing structures and newly proposed developments that helps in the identification and application of the key decision-making factors that aid the decision of whether to refurbish or rebuild with the consideration of less waste generation, this further improve the overall decision-making strategy with the implementation factors into a BIM model in order to make a bridge between the key factors and BIM for future research purpose on the subject, then conducting an experts opinion survey to validate the key identified factors.

## 1.12 Research Design

To answer the fundamental questions posed by this research, a quantitative approach to research, which is based on an interpretivist research paradigm was adopted. Same approach was also followed in the factors validation process. According to (Creswell, 2009), a quantitative approach allows one to have an in-depth study into a particular phenomenon to answer questions of 'how' and 'why'. To have an in-depth view of construction and demolition waste management practices of the UK firms, their approach towards the decision-making on the reduction of waste and how they meet the expected outcomes of government legislation, a multiple case study approach was followed, which allows the investigation of real world phenomenon within its natural context and the factors (if any) that were considered by these firms in the reduction of waste (Creswell & Clark, 2007) (Yin, 2013). This approach and the relevant legislations and British Standards have been considered during the development of the frameworks in Chapter four that leads to the identification of the key decision-making factors in Chapter five. As reported in (Proverbs & Gameson, 2008), the use of case studies is very relevant in the construction industry; a project driven industry made up of many different types of organisations and businesses. The use of multiple case studies gave a holistic view of the subject (Barbour, 2001), and allowed for the use of multiple sources of data. The use of multiple sources of data helped to achieve triangulation of results, which ensures the quality of the evidence, generates strong evidence in support of key findings and makes the findings more reliable (Yin, 2013). The research framework/structure, which gives a summary of the research design, is shown in Figure 1.9.

From a synthesis of the major issues identified in the literature, a conceptual framework in Chapter four, for measuring the extent to which current decision-making of any existing or planned construction, demolition and excavation (CD&E) works that meet the intended goals of WM legislation (reduced waste/zero carbon) was first developed, this was the first step towards the identification of the key decision-making factors. This formed the basis for the design of the research instruments in Chapter five. Data collection was based on the use of multiple case studies with embedded units of analysis (Yin, 2013) involving Tier one contractors/companies awarded for their environmental management and sustainability performance to help in gathering best practices from the industry. Data collection was by means of in-depth opinions of the industrial experts with a total of 38 corporate and project level staff, having experience of over 20 years in the industry; site visits (observations) of six live construction projects; and analysis of company waste data and relevant documents.

The findings of the research led to the development of a best practice framework for sustainable management of construction, demolition and excavation and the identification of the decision-making factors that helps in the decision of whether to refurbish or rebuild an existing building or new building when it reaches the end of design life. To ensure the value and usefulness of the key identified factors to the industry, the views of selected sustainability, environmental, project managers and other construction professionals were used to validate them.

## 1.13 Structure of the Thesis

This thesis consists of seven chapters, which are structured in the following way:

- **Chapter one –** sets background, theories and principles, and justifies the needs for the study;
- **Chapter two –** reviews literature including some past carried researches, papers and journals and, carries in-depth analysis of the similar case studies that included the decision-making factors and criteria for refurbishment and rebuilding;

- **Chapter three –** highlights both theoretical and methodological approaches to the study that includes philosophy, epistemology, strategies and an introduction to the use of relevant software;
- **Chapter four –** includes data collection from multiple sites to conduct case studies and the development of decision-making frameworks for existing and new buildings;
- **Chapter five –** includes the identification, application and validation of the key decision-making factors using the decision-making framework, Tally LCA (a plugin for Revit/BIM software) and the experts opinions respectively;
- **Chapter six –** discusses and analyses the findings of this study;
- **Chapter seven –** provides a concluding section for the study.

Figure 1.9 below illustrate the main elements of this research project and a detailed structure of the thesis.

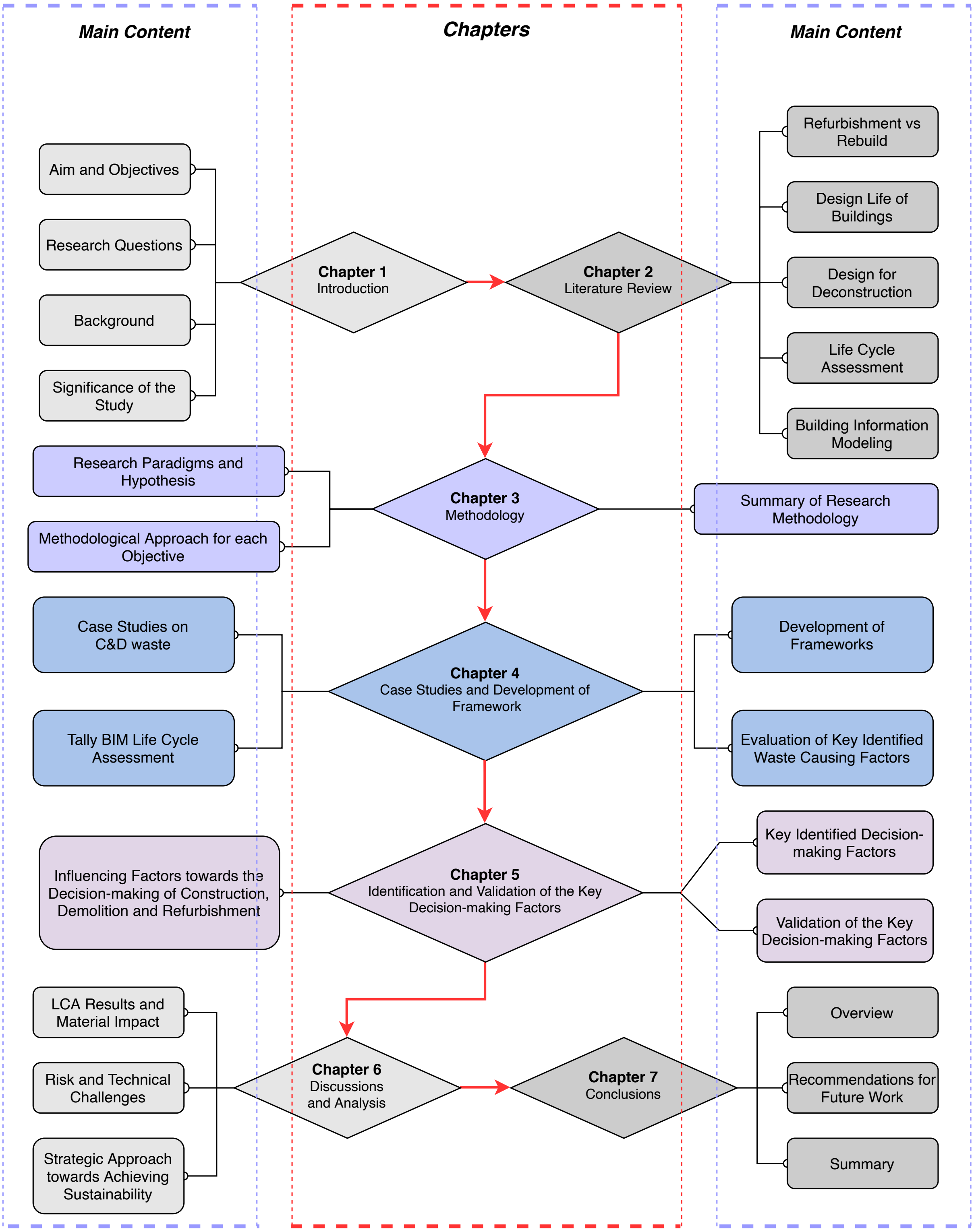


***Figure 1.9 Structure of the Thesis (Source: The Author)***

# Chapter 2. **Literature Review**

## 2.1 Chapter Overview

There is a need to understand the rudiment of waste generation and management in the construction industry informed this chapter, which initially provides an overview of the global construction industry, with some bias in the UK. This Chapter is intended to highlight the important statistics on C&D waste with detailed discussion about its impact worldwide, following with an overview of the global construction industry. It also discusses some of the past and recently published papers and journals within the relevant topic that highlights the severity of the subject and its core elements on the basis of waste minimisation techniques that have been implemented and suggested. Each of the categories is then evaluated to determine their contribution, effectiveness and weaknesses towards tackling the menace of waste in the construction industry. It then looks into impacts of the industry from economic and environmental perspectives as well as its contribution to the global development. Further, it highlights the application of Building Information Modeling (BIM) in different aspects on the construction waste management, particularly in the decision-making scenarios. Following in the introduction and implementations of BIM, there is a discussion on the current practices of highways construction, demolition and repair/maintenance, which is then used to create a connection between the highways and buildings/structures and how to utilise the waste of these two sectors by using it on to the sites of one another, when needed. Overall, this chapter forms a theoretical foundation and methodological guidelines upon which the study is built.

## 2.2 Waste Statistics

As the technology advances, there is a significant increment in the living standards and this demands more improvements and increased numbers of the infrastructure projects. This growth has contributed extensively in waste generation, which has become serious problem for every nation. Several researchers and practitioners indicate that waste emanates during planning, design, procurement, and construction stage. The waste also influences economical dynamics of society and also has an enormous impact on the environment and surroundings.

Through variable resources and data collection from various construction sites, it has been concluded that the volume/quantity of construction and demolition waste (CDW) generated in the today’s world, is significantly high and causing the series of severe issues. CDW in the United States is estimated at around 600 million tonnes (EPA, 2018). While in 2015, this figure went up to approximately 262 million tonnes (EPA, 2018). Eurostat estimates the total for Europe to be 970 million tonnes per year, representing an average value of almost 2.0 tonnes per capita (Sonigo, et al., 2010). It should be noted that the figures for CDW generation per capita in Europe have a wide geographical variation (e.g. 0.04 tonnes for Latvia and 5.9 tonnes for France). These figures must be viewed as lower estimates, as this type of waste is often dumped illegally. The data are also hard to interpret because of the different waste definitions and reporting mechanisms in different countries (Sonigo, et al., 2010).

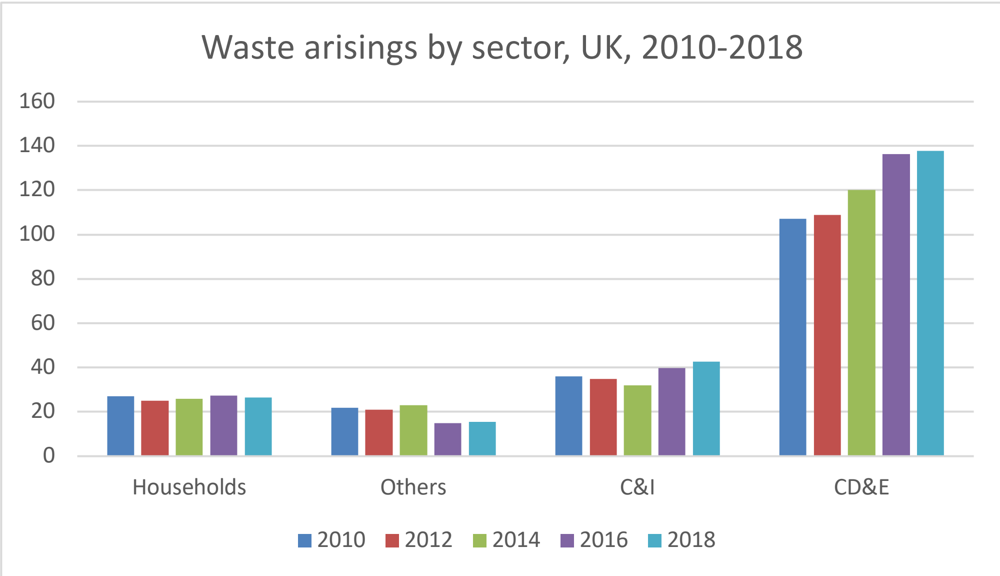


**Figure 2.1 Waste arising by UK sector (Source: DEFRA, 2022)**

Considering the facts from the Figure 2.1, Construction, Demolition and Excavation (CD&E) activities have been the highest contributor of waste as compared to all other sectors. However, many techniques and policies are still being introduced and revised every year in order to control and reduce the waste, but the generation of waste within the construction industry seems to be uncontrollable as the Figure 2.1 indicates that the increase in waste within the construction industry has been recorded every year since 2010. One of the main reasons behind this sudden increase is the increase in the demand of CD&E projects (Ali, et al., 2018a). Most of the contracting companies do not have a Site Waste Management Plan in place and also, they lack in planning the management of waste before the commencement of works on site.

Furthermore, the hazardous waste is another factor that is causing a very negative impact and again, this waste is largely generated within the construction industry (Ali, et al., 2018a). However, industrial sector also generates the high amount of hazardous waste, but this can be avoided within the construction industry, as many alternatives of hazardous materials are available.

*Table 2.1 Hazardous waste arising from construction sector - million tonnes (Source: Defra Statistics 2014)*

| 2004 | 2006 | 2008 | 2010 | 2012 |
|---|---|---|---|---|
| 225 | 586 | 1,258 | 1,018 | 1,057 |

For the better environment and for carbon free future, there is a need to control the use of hazardous waste within the construction industry (Ali, et al., 2018a). As indicated in the Table 2.1, there has been a massive increment in the hazardous waste generation from the year 2004 to 2006 and from 2006 to 2008, as the difference has exceeded by 361 and 596 million tonnes of extra hazardous waste per year respectively. This itself is indicating that there has been an increase in the C&D projects in the UK within these years, but not many existing policies have been revised nor any new policies have any significant impact on the controlling of hazardous waste. Also, this increase in hazardous waste is an alarming sign and needs to be addressed and resolved with proper consideration towards the betterment of the environment and lesser $CO_2$ emissions.

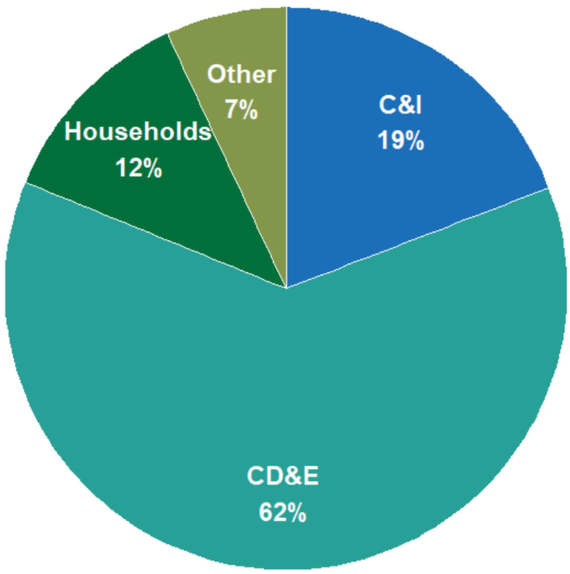


*Figure 2.2 Waste generation split by source, UK, 2018 (Source: DEFRA, 2022)*

Considering the fact that the construction industry is the highest contributor to waste in the UK (62%) as compared to all other sectors as shown in Figure 2.2 (DEFRA, 2022), the need to identify and resolve the reason behind this massive waste contribution is necessary. The UK waste statistics need to be collected from various sites for analysing the factors behind the generation of C&D waste (Ali, et al., 2018a). Those factors can then be addressed and resolved individually. Similarly, the proposed decision-making framework in the research, will consist of several factors that will contribute towards decision-making strategy and will allow the designer come up with a waste efficient design for new development or reduced waste strategy for any existing building or site.

***Table 2.2 Waste generation split by responsible economic activity, UK and England, 2012-14 - proportion of tonnages (Source: Defra Statistics 2014)***

*% of total waste tonnage and % point change between years*

| | | C&I | CD&E | Households | Other | Total |
|---|---|---|---|---|---|---|
| **UK** | **2012** | 16.9% | 56.2% | 14.1% | 12.8% | 100.0% |
| **UK** | **2014** | 13.7% | 59.4% | 13.7% | 13.3% | 100.0% |
| **UK** | **Change** | **-3.3%** | **3.2%** | **-0.5%** | **0.5%** | |
| **England** | **2012** | 15.4% | 59.7% | 14.5% | 10.4% | 100.0% |
| **England** | **2014** | 11.8% | 64.2% | 13.8% | 10.2% | 100.0% |
| **England** | **Change** | **-3.6%** | **4.4%** | **-0.7%** | **-0.2%** | |

Table 2.2 shows that the UK generated 202.8 million tonnes of total waste in 2014. This represents an increase of 4.6% from 2012. England generated 167.6 million tonnes of total waste in 2014.

Table 2.2 and Figure 2.2 also indicates that Construction, Demolition and Excavation (CD&E) waste (including dredging) produced over half (64%) of total UK waste in 2014. The remaining waste generation was fairly and evenly divided between 'Commercial & Industrial', 'Household' and 'Other' activities. In England, the share of construction waste was considerably higher both in 2012 and 2014 (Ali, et al., 2018a). Though, this has been case every year as factually, the construction industry specifically deals with huge amount of material handling every day. Simply, the material becomes waste when it is no longer required on a construction site, where it was initially delivered to.

## 2.3 Recycling of Construction and Demolition Waste

In order to reduce the environmental pressure, recycling of construction and demolition waste (CDW) is of paramount importance. Currently, the UK government is keen on introducing new policies and frameworks for the recycling of C&D waste (Wang, et al., 2010). Many legislations have already been done and implemented for the recycling of C&D waste. Recycling of waste prevents an increase in the area needed for waste disposal and also avoids the exploitation of non-renewable raw materials. Environmental impacts caused by the extraction of non-renewable raw materials include extensive deforestation, top- soil loss, air pollution and pollution of water reserves. It should be noted that 40% of all materials are used by the construction industry (Kulatunga, et al., 2006). Wang, et al., (2010) records that construction in China consumes approximately 40% of total natural resources and around 40% of energy. It has been forecasted that demand for materials will reach at least double the current levels by 2050 (Allwood, et al., 2011). In the context of housing life-cycle assessment (LCA), the environmental gains associated with the recycling of CDW constitute a very small fraction (just 3% in the UK) of the total global warming potential (GWP). 90% of the GWP relates to the use stage (Cuéllar-Franca & Azapagic, 2012). This situation is not confined to the UK residential sector and applies generally in Europe and in other parts of the world where high energy-efficient buildings are the exception (Pacheco-Torgal, et al., 2013). However, the recast of the Energy Performance of Buildings Directive (EPBD), which was adopted by the European Parliament and the Council of the European Union on 19 May 2010, initially sets 2020 as the deadline for all new buildings to be 'nearly zero energy', which was then moved to 2025.. This will dramatically increase the percentage (Pacheco-Torgal, et al., 2013).

The benefits of effective CDW recycling are economic as well as environmental. For example, the Environment Agency of the US (U.S. Environmental Protection Agency, 2002) states that the incineration of 10,000 tonnes of waste could mean the creation of one job, landfill can create six jobs, but recycling the same amount of waste can create 36 jobs. According to one report 'Strategic Analysis of the European Recycled Materials and Chemicals Market in Construction Industry', the market for recycled construction materials generated revenues of €744.1 million in 2010 and was estimated to reach €1.3 billion by 2016 (Frost and Sullivan, 2011). This is a low estimate as it does not take into account a near 100% CDW recycling scenario, which will be the future of construction (Phillips, et al., 2011).

During the last 15 years, investigations in the field of CDW have focused on three major topics: generation, reduction and recycling. This is guided by the '3Rs' principle (Lu, et al., 2011). However, as it is a more complex issue, zero waste will demand a much wider approach requiring 'strong industry leadership, new policies and effective education curricula, as well as raising awareness and refocusing research agendas to bring about attitudinal change and the reduction of wasteful consumption' (Zaman & Lehmann, 2011).

Recycling of waste is one of the key factors to be considered for the decision-making framework. Addition of waste recycling in the proposed decision-making framework will play an important role in deciding the recovery of useful waste or material from the existing building that is due to be considered for demolition or refurbishment. It will also be beneficial for the new development as it will help the designers to come up with a minimum waste design.

### 2.3.1 EU 70% recycling target for 2020

The recovery rate from non-hazardous construction and demolition waste in the UK in 2014 was 89.9%, which further went up to 93.2% in 2020 (DEFRA, 2022). There was an EU target for the UK to recover at least 70% of the total construction waste by 2020 initially. This clearly indicates that the 70% target was achieved for the non-hazardous waste. However, the exact quantities of recovered waste cannot be figured out, as many of the waste from the SME (small medium-sized enterprise) companies goes unaccounted and these quantities does not count towards the total waste recovery percentage.

CDW is often used as aggregates in road fill, constituting a down-cycling option. Worldwide aggregate consumption is around 20,000 million tons/year and an annual growth rate of 4.7% is expected. The environmental impact of primary aggregates includes the consumption of non-renewable raw materials, energy consumption and more importantly, the reduction of biodiversity at extraction sites. The cost of aggregates is dependent on transport distances and the price per ton doubles for every 30 km (den Heede & De Belie, 2012). Extraction operations therefore have to be near construction sites, which increase the number of quarries and the biodiversity impact. More than one-third of aggregate consumption is related to the production of concrete, which is the most widely used construction material, currently standing at about 10 km 3/year (Gartner & Macphee, 2011)

Although the use of CDW as recycled aggregates in concrete has been studied for almost 50 years, there are still too many concrete structures made with virgin aggregates (Pacheco-Torgal & Jalali, 2011). This is due to their low cost, lack of incentives, low landfill costs and in some cases, a lack of up- to-date technical regulation (Marie & Quiasrawi, 2012). Recycled aggregates also contain impurities, which can be deleterious in Portland cement concrete. It is therefore difficult for the concrete industry to use these materials unless uncontaminated recycled aggregates are used. This issue highlights the importance of developing new binders, which are more suitable for CDW recycling. The WFD 70% target increases the need for effective recycling methods and it is the purpose of this book to make a contribution in this area. It also addresses new techniques for the remediation and/or immobilisation of hazardous wastes such as asbestos and for CDW prevention/reduction, which remains the best option.

The Mayor of London's Business Waste Strategy, “Making Business Sense of Waste”, also published in 2011, sets out the following targets:

- Achieve 70% re-use, recycling and composting of commercial and industrial (C&I) waste by 2020, maintaining these levels to 2031.
- Achieve 95% re-use, recycling and composting of construction, demolition and excavation (CDE) waste by 2020, maintaining these levels to 2031.

## 2.4 Common Practice for Waste Collection & Transportation

Key to delivering the objective of reducing Construction, Demolition and Excavation Waste (CDEW) to landfill is the development of efficient logistics systems from the point of collection to delivery for onward transfer or recovery (Entec UK Ltd, 2010).

Two main collection methods have been identified through online and offline/on-site research:

- **Single modal (skip) collections –** Where an empty container is exchanged for a full container on site with subsequent delivery to the point of transfer, recovery or disposal; and
- **Multi modal collections –** Where a number of containers are collected from multiple sites with the material compacted in the vehicle.

Taking account of the current site waste management strategy, it has been noticed that the triggers for a collection to occur are found to vary considerably, although the underlying requirement for all sites is to ensure that waste generation does not exceed available storage capacity and/or impact upon the progress of the project. Some construction sites request an ad hoc (as and when) collection whilst others request a scheduled or regular collection (depends on the nature of the project). However, for massive construction and demolition projects, there is a trend towards scheduled collections, whilst the medium and smaller sites order to skip collections only when required as this has been noticed as the most common practice on all small C&D sites throughout the UK (excluding the big/multinational companies).

It is important to acknowledge that the waste profile changes during the various phases of construction, from typically non-compactable wastes early on in the project such as wood and steel, to compactable wastes at the mid and end phases of the construction project such as plastic packaging (i.e. once the infrastructure has been built) and also on refurbishment projects (Entec UK Ltd, 2010). Hence different approaches and trigger frequencies may be required at various phases of construction, as well as on different project sizes.

### 2.4.1 Scheduled Vs Reactive Collection

Scheduled collections are preferred by some waste collection companies/skip providers as they can plan the resource requirements in advance. However, this can often result in containers being collected half full or indeed over full. Depending on how the waste collection service is charged in these scenarios typically result in lost value for one or more of the two parties to the contract (Entec UK Ltd, 2010).

In every construction site, there is a dedicated space for skips. There is normally an exercise of judging the likely volumes to be produced versus the space available, and as such the most economic option is not always chosen. Often this is overcome by a ‘wait and load’ collection where a vehicle or container is filled whilst the skip collection truck is on site and waits for the skip to be filled with waste.

### 2.4.2 Containment Vs Vehicles

The typical types of containers/skips used are 8m$^3$, 10m$^3$, 12m$^3$, 14m$^3$, 18m$^3$, 20m$^3$, 26m$^3$ and 40m$^3$ containers (typical builders and bulk skips). Out of these, small size skips (8m$^3$ to 20m$^3$) as shown in Figure 2.3, are demountable and will be either exchanged on site or a ‘wait and load’ collection can occur (Entec UK Ltd, 2010).


***Figure 2.3 Sizes of medium-sized skips (Source: Hintons, 2015)***

Small container skips (as shown in Figure 2.3) are commonly used in small-sized construction projects such as residential house/dwelling construction or extensions.

The 26.8m$^3$ roll-on roll-off (Ro-Ro) containers are typically collected by a 32 tonnes vehicle with up to 4 axles where a payload of 15 tonnes is typically achieved (see Figure 2.4). During waste data collection from construction sites and the skip collection companies, it has been noticed that the density of the collected material is considered to have a considerable impact upon the loads carried. Mixed loads of waste with a proportionally high content of rubble would have a far higher load density than those loads containing plastic and paper packaging. This itself indicates the amount of carbon emitting from these works. Also, as the collected waste is of mixed material, it includes toxic and harmful waste too.


*Figure 2.4 Ro-Ro skip container (Source: LKM Recycling, 2014)*

### 2.4.3 Single Mode (Skip) Collections

A single mode collection is where a single container is typically collected using one vehicle; this includes the traditional skip style containers of different sizes and the Ro-Ro containers. The delivery of containers is generally one at a time and normally as an exchange to the container being removed from site for the disposal of the waste. There is potential with stackable traditional skip containers to stack up to three for delivery (Entec UK Ltd, 2010). However, this option is not possible with a Ro-Ro container. Some waste management operators use skips vehicle with trailers and there are some emerging new vehicle technologies with two small skips on the back of a single vehicle. Several skip companies often run low on stock of the containers and will often undertake ‘wait and load’ collections. This service format is preferred by some construction sites despite being inefficient in terms of loading time. Most skip collection companies usually charge for the ‘wait and load’ time on site where it is dictated by the customer. These collections should not be confused with ‘collect and return’ collections where the same container is collected and returned to the same site.

Single mode collections are suitable for both compactable and non-compactable material and this type for collection may be either ad hoc or scheduled. The collections are achieved by exchanging the container leaving an empty container on site and tipping the full container to be taken to the next site for exchange. Exceptions to this are the ’wait and load’ service.

### 2.4.4 Multi Modal Collections

A multi modal collection is where a container is emptied on site into the main body of the vehicle for compaction on a collection round.

This mode of collection can only collect compactable wastes and would not be suitable for large pieces of wood or high density materials and is predominantly scheduled with regular collections occurring anywhere between once per week and daily (sometimes more than once per day).

The scheduling and routing of collections is the same for this mode of collection as it is for the single mode collections (Entec UK Ltd, 2010). The main benefit with the multi modal collection format is the increased number of collections that can be achieved in a day due to the (logistically) more efficient collection round approach.

A typical project where an existing building is being demolished and the new building is being constructed will experience a number of phases of waste production. Initially, during the demolition phase, high density and non-compactable materials such as rubble will be produced. In later phases when the new building is being constructed, packaging wastes such as card and plastic, gypsum, wood, etc. will dominate the waste streams out of which, most of the waste is compactable (Cox, 2016).

### 2.4.5 Service Cost

The methodology for charging for CD&E waste collections is dependent upon the mode of collection. The multi modal method of collection tends to be priced per bin lifted with a rental cost for the container. The skip and the Ro-Ro collections are priced differently, often on the basis of separate transport and disposal costs. The transport costs are normally based upon time (or mileage) and the tonnage disposal rate is charged per tonne, with a minimum tonnage to be charged.

The consensus view of the skip providers is that larger containers with mixed construction waste or multi modal collections generally represents the cheapest option to the client, requiring less resource to collect and move a given amount of waste. This approach has been considered by the most skip companies to have environmental benefits due to the reduced mileage and hence achieving reduced $CO_2$ emissions.

For the single mode container (e.g. 10.7m$^3$ skip and 26.8m$^3$ Ro-Ro), the transport of the containers is typically charged at an hourly rate for most collections rather than by distance (Cox, 2016). The prices charged for the transport are in the range of £55 to £70 per hour. The disposal pricing ranges between £22 and £60 per tonne (including landfill tax) with a minimum tonnage stipulated. The minimum tonnage ranges (on which the minimum charges are based) are between two and three tonnes depending upon the operator, where the waste density is low the minimum tonnage may exceed the actual weight (Entec UK Ltd, 2010). The rental prices for the containers again showed variability, as per the multi modal collection options, where rental (26.8m$^3$ Ro-Ro) is charged at £5 per week based upon various researches and data collections.

Generally, an average skip of 8 cubic yard costs around £180 + VAT, which is mostly required on domestic or small commercial construction sites. For larger construction sites, more than 12 cubic yard of skips are required frequently (about in every 4 days, depending on the nature and size of construction or demolition), which costs about £320 + VAT (Entec UK Ltd, 2010). Taking account of the type and amount of material and waste in these skips, the average cost of what is being thrown away is estimated at over £1,500 or £1,600. However, these figures are not accurate and can rise up or down as it is totally dependent on the nature and size of the project. But it is more likely that these costs would rise in the major construction projects. Also, there are environmental factors included in the waste management. Thus, management of construction waste is an important feature of any type of project that should be ensured by the construction contractor, principal contractor or even principal designer when planning the pre-construction phase. The cost of waste can be as much as £43/m$^2$ in typical construction projects. 10 million tonnes of construction products are wasted every year, at a cost of £1.5 billion. A reduction of 1% of this would save £15 million and 104,000 tonnes of product a year.

All in all, waste collection and transportation seems to be one of the prime factors from the environmental and economic perspective. Be it a small, medium or large scale construction, waste collection and transportation makes a huge impact on the overall cost of any construction or demolition project. Thus, there is a need to have a fine balance between the economic and environmental impacts of waste collection, which can be made possible via proper planning of waste before and during the construction phase.

## 2.5 State of the Art: Refurbishment versus Rebuild

The issue of whether to demolish/reconstruct or refurbish/re-use old and/or existing buildings has been debated for over a century, but the evidence on whether demolition/reconstruction or refurbishment of existing buildings would be the most environmentally sound decision is still unclear (Power, 2008). The past and ongoing researches on this topic have mainly focused on the life cycle impact (LCI) of the buildings to make this decision. As discussed, this research project is aimed to focus on all the factors that contributes to the decision-making and then, the main key factors will be identified and prioritised for the decision-making of whether to refurbish or rebuild an existing building that reaches the end or its deign life or a newly build design that will in future, reaches the end of design life.

Looking at some of the past researches and investigations on the subject, Power (2008) argues that upgrading the UK building stock to high environmental standards can be achieved at a lower cost than demolishing it, and with as significant carbon reduction.

Also mentioned by Power (2008), the German Federal Housing, Urban and Transport Ministry had announced an ambitious energy reduction programme that will upgrade all pre-1984 homes in Germany by 2020 (an estimated 30 million units). However the target was not achieved, the works and efforts are still under way as the deadline to achieve this goal has been extended. This programme is based on the outcomes of several $CO_2$ reduction programmes since 1996, showing the feasibility of retrofitting. An 80% cut in energy use was achieved, making the performance of the renovated homes at least as good as Germany's current new building standards explain that the decision to demolish or to retrofit an existing building depends upon numerous factors such as the initial state of the building, the targeted energy performances or the aesthetic and patrimonial quality of the building (marique & Rossi, 2018). The 'initial state of the building' factor has more weight as compared to other factors, as it determines the overall condition of the building on which the decision to rebuild or refurbish is primarily based. However, Dubois and Allacker (2015) concluded that significant reductions in $CO_2$ emissions can only be obtained through demolition/reconstruction of buildings. Boardman (2007) suggested to increase the current rate of demolition (stock turnover) of inefficient houses, in the UK context.

To objectivise the interest of refurbishment versus demolition/reconstruction of existing buildings, from an environmental point of view, the use of LCA tools seems to be of huge interest. The general LCA methodology is well defined in the International Standard Organisation (ISO) norms (ISO 14040, 1997) . Despite some current limitations of LCA, namely summarised by Pomponi and Moncaster (2016) on the basis of a systematic literature review, LCA tools are recognized as one of the best tools for environmental assessment of products and processes (Crawford, 2008) and are thus widely used in various domains related to the sustainability of built environments such as, waste management (Bovea & Powell, 2006), wood utilisation (Höglmeier, et al., 2015), pavement infrastructures (Inyim, et al., 2016), urban transportation (Kliucininkas, et al., 2012), materials (Anon., 2012; Kohler, 1995; Turk, et al., 2015). LCA has also been identified as a promising framework for the environmental assessment of territories (Loiseau, et al., 2012) or urban blocks (Stephan & Athanassiadis, 2017). LCA tools, specifically dedicated to buildings, have also progressively emerged as practical tools to assess and compare the environmental impacts of different scenarios, in the current debates about energy efficiency of our built environment. These LCA tools have today mainly been used to evaluate energy consumptions and/or greenhouse emissions in buildings, during the use phase or along the whole life-cycle of the building (Asif, et al., 2007; Ji, et al., 2014). A great number of studies have been achieved on the development of LCA tools and on their application to buildings. And several review papers have recently been published to summarise the evolution, interests, limitations and results of buildings LCA (Bribián, et al., 2009; Buyle, et al., 2012; Cabeza, et al., 2014; Sartori & Hestnes, 2007). But, as stated by Pomponi and Moncaster (2016), even if incomplete assessment is better than no assessment (Hertwich, et al., 2000), extra care is required when using and comparing results from published LCAs, which might be both partial and short sighted, due to the current limitation of these tools.

Amongst their numerous advantages, these LCA approaches can account for a large number of parameters that are known to act on the energy consumptions of a system and can be used to examine the influence of several energy efficiency strategies. However, as highlighted by Gaspar and Santos (2015), LCA of buildings mainly concentrate on the analysis of new and very efficient buildings, most of the time neglecting the existing building stock. Moreover, most studies dealing with the refurbishment of buildings only compare the environmental gains in comparison with the initial building, and not with a new equivalent construction (Ferreira, et al., 2015). Using LCA to compare refurbishment scenario to demolition/reconstruction scenario has currently not yet been achieved and the assessment of demolition, construction and end-of-life phases (including the recycling phase) in buildings LCA has yet been assessed.

In his analyses of a residential building in Turin (Italy), Blengini (2009) considered the pre-use phase (production and transportation of materials), the use phase and the end-of-life phase (recycling and elimination of waste) and concluded, in this case, that the use phase is the most harmful one. This result is also highlighted in other papers related to existing buildings (Ferreira, et al., 2015; Rossi, et al., 2012a; Rossi, et al., 2012b; Sartori & Hestnes, 2007). Recent studies related to new buildings have however highlighted that when high energy consumption standards (such as the passive standard, the (nearly) zero-energy standard or even the positive standard) are reached, this general trend is reversed. In this case, the other environmental impacts (related to the construction phase for example) become significant (Andrade, 2010). It also worth mentioning that the assessment of the embodied energy in buildings can vary substantially, especially due to a quite high variability in the cradle-to-gate materials data (although those differences usually remain tolerable (Blengini, 2009)), the local energy mix (Rossi, et al., 2012a; Rossi, et al., 2012b) or the chosen service life time (Sartori & Hestnes, 2007; Wallhagen, et al., 2011).

Ortiz, et al. (2010) studied an apartment building located in Barcelona (Spain). They assessed the impacts of the construction phase (fabrication and transportation of materials, energy use for equipment and waste management) and compared several types of internal and external walls as well as several scenarios dealing with the management of waste (dump, burning, recycling).

Several studies have assessed the environmental impacts of refurbishment works in comparison with the initial situation, and conclude that refurbished buildings have lower life cycle impacts than the initial solution. For example, in Ardente, et al. (2011), LCA approach was used to assess the environmental impacts and energy efficiency of several types of refurbishment and to highlight the significant benefit of:

1. improving the envelope thermal insulation;
2. replacing lighting and glazing components and;
3. renovating the heating, ventilation and air-conditioning (HVAC) plants.

Whereas, in Larriva, et al. (2014), a LCA was used to quantify the environmental benefits of five refurbishment scenarios with the initial situation, putting a particular emphasis on the comfort of occupants.

Amongst the few studies comparing demolition and/or refurbishment with the construction of a new building equivalent in terms of size and/or functions, Gaspar and Santos (2015) concluded that, for their case study house located in Southern Europe, the refurbishment was a more sustainable strategy because the quantity of materials and, hence, embodied energy was lower. Ferreira, et al. (2015) studied a heritage building in Lisbon (Portugal) and also highlighted that structural refurbishment works are more sustainable than the construction of a new equivalent construction (with a similar architecture and similar demands and project constraints).

More specifically, as stated by Pomponi and Moncaster (2016), extending the life span of building through refurbishment would also intuitively delay and therefore reduce energy uses and $CO_2$ emissions associated with deconstruction and demolition, which have been investigated in few studies, for e.g. (Tingley & Davison, 2011; Toller, et al., 2011; Yung & Chan, 2012).

Furthermore, a strategy for demolish or re-use was developed by the Circular Construction in Regenerative Cities (CIRCuIT), where CIRCuIT addressed the challenges of re-use in its ‘Extending Lifecycles’ workstream, which aimed to enable transformation and refurbishment in cities through investigating innovative design strategies, principles and methodologies (CIRCuIT, 2021). UK Green Building Council (UKGBC), a partner on CIRCuIT, contributed to data collection in support of these aims, in part by interviewing nine leading developers within the UKGBC member network, to gather their insights into decisions of whether to demolish or re-use buildings (CIRCuIT, 2021). The results fed into the development of an evidence-based systematic methodology proposed by CIRCuIT to identify obsolete and transformable buildings and help the project to create replicable design strategies and principles that encourage transformation or refurbishment over demolition.

The highlights from the interview, shared by the UKGBC hoped that they could shed additional light on the re-use landscape in the UK and identify where barriers emerge. The results were intended to help inform future studies and policy decisions and enable developers to compare their re-use processes with wider industry. The article covered interviewee responses to the following questions (CIRCuIT, 2021):

1. When does your organisation define a building as obsolete?
2. What are the key factors guiding your decision to demolish or refurbish a building?
3. What might change your decision to demolish or refurbish a building?
4. Do you have any key insights into this topic, gleaned from your own project portfolio?

Based on the responses from the interviewees, a framework consisting of the key factors was developed (see Figure 2.5) in order to gain more insight into the specific factors leading to demolition or re-use, the developers were asked to expand on the key factors that could sway this decision (CIRCuIT, 2021). The factors identified were broadly split into the three categories as shown in Figure 2.5.

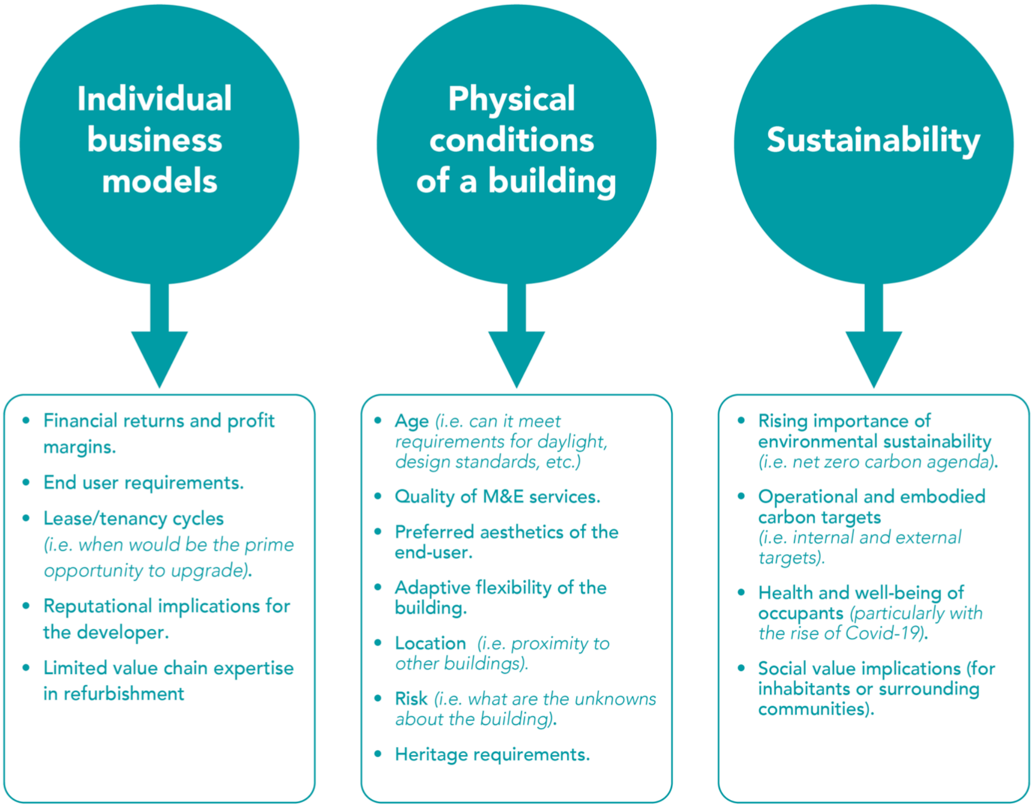


***Figure 2.5 Key factors guiding a choice to demolish or re-use (Source: CIRCuIT, 2021)***

The forecasted financial returns on investment factored significantly into the decision-making process for every developer. The final decision-makers (generally investors and board members) were unlikely to provide their support for any refurbishment works without being presented with a positive financial business case (CIRCuIT, 2021).

Another developer acknowledged that the only factor that might out-weigh costs would be very strict heritage requirements to retain a building, or parts of it. Brownfield land tends to be cheaper and without a detailed and full record of the building, it can be difficult to estimate the damages (CIRCuIT, 2021). Refurbishment/re-use is therefore not always the cheaper option.

As for the environmental and social aspect, it was acknowledged by several interviewees that implementing circular principles, such as the re-use and refurbishment of buildings, was an increasingly popular mechanism to meet these goals, particularly for the reduction of embodied carbon (CIRCuIT, 2021).

However, some acknowledged that this link could be unsubstantiated and further evidence was needed in order to ensure that there would be no unintended consequences of increasing carbon. Two developers questioned whether it would always be the case that a refurbished building could meet operational emissions and social value targets, even if embodied carbon were reduced compared to a new build. While certainly not a reason to discount refurbishment, the life cycle link between re-use and embodied carbon must be considered (CIRCuIT, 2021).

Limited information about the structure or constituent materials of an existing building impede the potential for re-use. Structural safety was highlighted by the interviewees as a key factor underpinning potential obsolescence of a building, and the comprehensive surveys required to assess the level of risk in re-using an older building might not always be financially feasible or possible within the time constraints of a project. It was also highlighted by one of the developers that there were often unforeseen safety problems that emerged only once the refurbishment project was underway (CIRCuIT, 2021). This reduced the incentive to consider re-use in the project given the increased management costs.

In terms of policy, regulations and reporting, the early stages of a project are critical for embedding re-use into its strategy and ethos, with the viability of re-use becoming increasingly challenging as a project progresses. One common strategy to promote re-use put forward by the interviewees was a requirement to demonstrate in planning applications why a building and its materials cannot be retained before permitting demolition (CIRCuIT, 2021). Shifting starting assumptions so that all buildings are assessed from the same perspective can incentivise innovation, where otherwise demolition might have been the status quo. The importance of incentives was also highlighted, with one interviewee citing that this would be preferable to regulation. Currently, there are few incentives in the planning process to encourage developers to retain buildings (CIRCuIT, 2021).

Additional recommendations in this investigation by the CIRCuIT included:

- Reducing the 20% VAT rate for refurbishments so it is on par with new builds or lower;
- Faster planning application processing for projects including reuse at significant scales;
- Consistent definitions and rules across councils and governments (ex. for heritage retainment requirements).

Importantly, it was acknowledged that any changes to planning or legislation ought to come with increased training for authorities to properly assess applications so that they acknowledge the potential challenges or knock-on implications of reuse and refurbishment. For example, retaining a building's original superstructure can make meeting operational energy requirements more costly or challenging, or the required number of units/dwellings may become unfeasible to deliver (CIRCuIT, 2021).

Following the review of the past studies on refurbish or rebuild scenarios, there seems to be a clear gap between the consideration of factors for the decision-making. By identifying the key decision-making factors, this gap can be filled. And in order to fill this gap, there is a need to consider different scenarios for every type of building.

## 2.6 Review of Past Studies on Effective Waste Minimisation

This section highlights some of the past case studies based on the development of effective waste management plan and its evaluation by Building Research Establishment (BRE), that aims to achieve the minimum waste on C&D projects. Through the review of these case studies, the initial factors will be highlighted that causes waste. The identification of key decision-making factors is partially based on these case studies.

### 2.6.1 Case Study by Building Research Establishment (BRE)

In a study conducted by Building Research Establishment (BRE), construction, refurbishment and demolition waste data was collected from different projects across the UK. One of the main aims of BRE is to provide the C&D industry with effective solutions for C&D waste management. According to BRE, the primary purpose of this data collection was to propose an strategic approach towards effective management towards the reduction of a construction waste (Waste Statitics Team, 2016).

In this study, the waste data was collected from 23 housing projects that were in the final stages of construction (Waste Statitics Team, 2016). Thus, it has to be taken into account that the proposed strategic approach in this study by BRE would be more suitable and workable on residential projects.

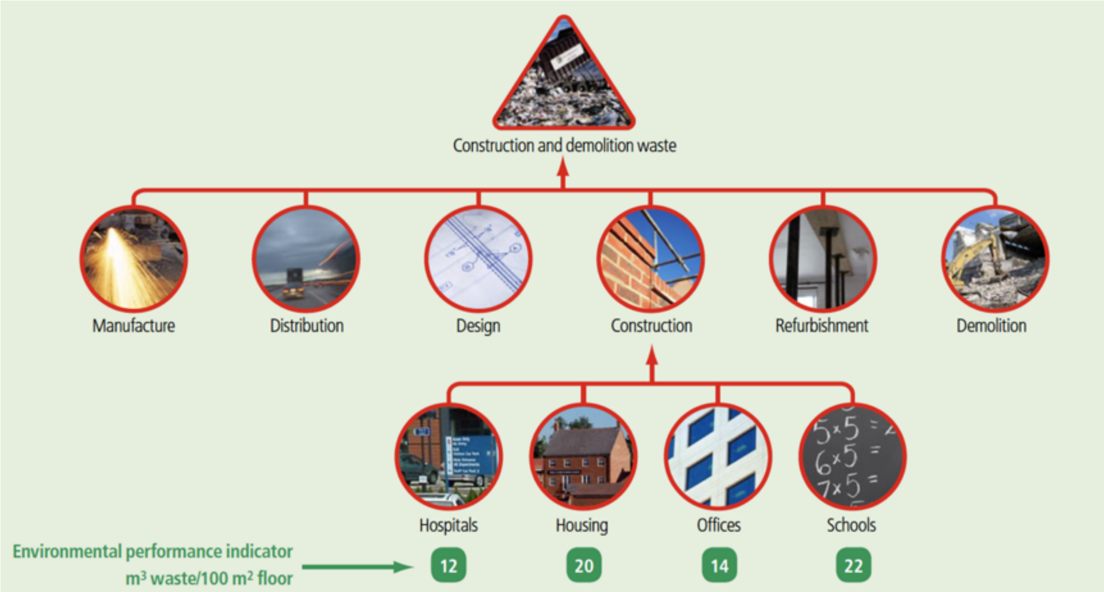


***Figure 2.6 Construction and demolition waste overview (Source: Waste Statitics Team, 2016)***

Some initial Environmental Performance Indicators (EPI) were generated (see Table 2.3) from the waste data collected from different types of construction project. The waste data in Table 2.3 is measured in $m^3$ waste per $100m^2$ floor area, which allows for like for like comparison; and $m^3$/£100,000, which can be greatly influenced by the regional, design and material costs (Waste Statitics Team, 2016). For better understanding, construction and demoition waste overview by sector is highlighted in Figure 2.5, which also indicates the environmental performance by four sectors. Housing sector takes the lead with $12m^3/100m^2$ waste per area. Understandably, the housing sector has one of the highest percentages of construction works, the waste figure also has to be considerably high as compared to other sectors.

***Table 2.3 Environmental Performance Indicators (EPI) (Source: modified from Waste Statitics Team, 2016)***

**D = Demolition**
**E = Excavation**
**G = Groundworks**
**M = Mainframe**
**S = Services**
**P = Partitions**
**F = Fit-out**

| | Civil Engineering | Leisure | Health Care/Hospitals | Residential | Office | Schools |
|---|---|---|---|---|---|---|
| **Benchmarks** | E, G, M | G, M, S, P, F | G, M, S, P, F | G, M, S, P, F | G, M, S, P, F | G, M, S, P, F |
| **Key Performance Indicator (KPI) = $m^3$/£100,000 project value** | 52.3 | 6.1 | 7.9 | 17.3 | 8.4 | 13.2 |
| **EPI = $m^3/100m^2$** | 61.7 | 3.7 | 11.7 | 19.2 | 14.1 | 22.2 |

#### 2.6.1.1 Amount of Waste Per House

In this study by BRE, the amount of waste per house was calculated via the benchmarking data submitted by each construction site. Based on the type of material waste, the EPI was then calculated for the waste collection from 23 housing projects as shown in the Table 2.4. The findings of this study are informative and factors considered for this strategic approach will also contribute towards the development of a decision-making framework, which further lead towards the identification of the key decision-making factors to decide between refurbishment or rebuilding of a structure.

***Table 2.4 Benchmarking Data (Source: modified from Waste Statitics Team, 2016)***

| Project Type | Housing EPI ($m^3$ waste/$100m^2$) | | |
|---|---|---|---|
| | Average | | |
| **Waste Group** | Residential x 23 no | Conversion factor | Tonnes |
| **Timber** | 1.3 | 0.3 | 0.39 |
| **Concrete** | 2.5 | 1.11 | 2.775 |
| **Inert** | 1.1 | 1.3 | 1.43 |
| **Ceramic** | 2.8 | 0.78 | 2.18 |
| **Insulation** | 1.0 | 0.16 | 0.16 |
| **Plastic** | 0.6 | 0.22 | 0.132 |
| **Packaging** | 2.9 | 0.55 | 1.59 |
| **Metal** | 1.3 | 0.8 | 1.04 |
| **Plaster & Cement** | 3.2 | 0.4 | 1.28 |
| **Miscellaneous** | 2.5 | 0.4 | 1.0 |
| **Total EPI** | 19.2 | | 11.997 |

Now, considering the fact that around $19.2m^3$ of waste per $100m^2$ of area (the environmental performance indicator – EPI) from these construction sites, this waste figure is quite huge and more importantly, the calculated amount of waste is only of 23 sites, while there are several other construction projects running throughout the UK, some of which are even run by the small medium-sized enterprise (SME) companies, where in most cases, the workers or managers are inexperienced and do not have a proper waste management plan in place, neither do they follow the waste hierarchy in order to reduce the waste generation.

Taking this figure into account and applying it to a typical semi-detached house of $80m^2$ gives an average material waste generation of $15.36m^3$ of waste per house. When adding in an average 50% void space in the skips that would collect this waste – this equates to around $30m^3$ of skipped waste. A typical small-size skip has a volume of $6.125m^3$ (see Figure 2.3), so around 5 skips are needed to contain the waste from one house. Based upon the Environment Agency (EA) conversion factors, the weight of waste from a generic house is 9.6 tonnes.

#### 2.6.1.2 Cost of waste per house

According to the BRE, a typical construction skip costs around £1,343. This figure also takes account of the cost of the labour and materials that fill the skip. Following is the detailed breakdown:

- Skip hire £85 (quite low compared to current prices) – 6.4% of cost;
- Labour cost (required to fill the skip) £163 – 12.1% of cost;
- Cost of material in skip £1,095 – 81.5% of cost.

So, based on the above skip cost, the waste estimation per house can be estimated as:

- 15.36m$^3$ of waste per house = 5 skips or 9.6 tonnes of waste.

A typical house = 80m$^2$.

- Waste cost per house = £6,715 (according to the BRE).

Breakdown of £6,715:

- Cost of material = £5,439;
- Labour cost = £812;
- Skip Cost (5 skips) = £430 (will continue to rise further).

#### 2.6.1.3 Carbon dioxide equivalent/embodied energy of waste product per house

The products and materials that were wasted during the construction process have life cycle impacts associated with their material extraction, production and distribution. It is even more difficult to make estimates here due to the lack of data in both the material composition of this waste stream and the life cycle impacts associated with the production, distribution and installation of the associated wasted products. A possible approach could be as follows (BRE, 2003):

- Convert the 9.6 tonnes of materials in each category to number of ecopoints;
- Combine all the ecopoints and then convert these to an equivalent tonnes of carbon dioxide.

The end result is that the 9.6 tonnes of waste produced by a generic house has a $CO_2$ equivalent of around 5.44 tonnes.

Wasted product per house:

5.44 tonnes of carbon dioxide (CO2) equivalent

Home built to Part L of the Building Control (BC) Approved Documents have estimated emissions relating to heating and power of around 2 - 4 tonnes $CO_2$ per year.

#### 2.6.1.4 Baseline for new housing and construction waste

Around 190,000 houses were built in the 2004/05 financial year. If this continues to be the case, the impact for new housing alone is very approximately:

Per year:

- 2,918,400$m^3$ of waste;
- 1,824,000 tonnes or 950,000 skips;
- £1,275,850,000 (includes £1,039,817,750 cost of wasted product);
- 1,033,600 tonnes $CO_2$ equivalent. This amount represents 0.18% of UK $CO_2$ emissions for 2004.

#### 2.6.1.5 Solution 1 – Current best practice – New housing

As suggested by BRE, following best practice in terms of reuse, take back of offcuts, recycling and reducing waste through site practices could have the following effect on new housing waste.

Baseline 2,918,400$m^3$ of waste or 1,824,000 tonnes assume:

- 15% reduced, 5% reused, 60% recycled and 20% landfilled.

Waste reduction is 273,600 tonnes. Applying the zero net waste principle, 364,800 tonnes of recycled content would be needed. Savings from reduction (£1,343 per skip) and not paying landfill tax (£40 per skip) – **£214,177,500**.

BRE (2003) suggested that the reduction in $CO_2$ equivalent through reduction of new housing waste only could be in the region of **155,040 tonnes per year.**

#### 2.6.1.6 Solution 2 - Current best practice and reduce waste by 50% – new housing

Reducing waste by 50% is more difficult to achieve but is essential if significant financial and $CO_2$ equivalent reductions are to be attained.

Baseline 2,918,400$m^3$ of waste or 1,824,000 tonnes, assume:

- 50% reduced, 40% recycled, 10% landfilled (This was proposed by the BRE (Building Research Establishment) and the reason for highlighting this within this research project was to figure out the waste management hierarchy within BRE in order to tackle waste generation).

Waste reduction is 912,000 tonnes. Applying the zero net waste principle, 364,800 tonnes of recycled content produces a positive net waste i.e. higher recycled content than waste sent to landfill. Savings from reduction (£1,343 per skip) and not paying landfill tax (£40 per skip) – **£653,125,000**.

Reduction in carbon dioxide equivalent through reduction of new housing waste only could be in the region of **516,000 tonnes per year.**

#### 2.6.1.7 Refurbishment Waste Statistics (Housing)

Capital refurbishment works to local authority dwellings in England are currently generating an estimated 470,000m$^3$ of waste from around 750,000 refurbishment packages per year. Decent Homes refurbishments are expected to continue into the future on a rolling programme at similar levels until 2025 and beyond. Table 2.5 summarises expected arising of principal waste categories by refurbishment package.

***Table 2.5 Expected principal waste arising categories by refurbishment package (2004 – 2005) (Source: modified from DEFRA, 2007)***

| Waste Group | Estimated annual waste volume m$^3$ by refurbishment package, England LA dwellings* | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Rewiring | Roof structure | Roof covering | Windows | Doors | Central heating | Kitchens | Bathrooms |
| **Timber** | | 18039 | 12042 | 33062 | 45131 | | 42222 | 7661 |
| **Concrete** | | | | | | | | |
| **Inert** | | | | | | | | |
| **Ceramic** | | | | | | | | 22984 |
| **Insulation** | | | 12026 | | | | | |
| **Plastic** | 4672 | | | | | | | 15322 |
| **Packaging** | 9345 | | | | | 28013 | 21111 | 15322 |
| **Metal** | 9345 | | | | | 70033 | | |
| **Plaster & cement** | | | | 13224 | 11283 | 14006 | 31666 | 22983 |
| **Miscellaneous** | 9345 | | | 3967 | | | | |
| **Totals** | 32707 | 18039 | 24068 | 50253 | 56414 | 112052 | 94999 | 84272 |
| Based on actual work carried out 2004-5, data from local authority Business Plan statistical returns to DCLG. | | | | | | | | |

A fairly high proportion of waste is believed to be consist of composite products with little or no reclamation value and limited recycling potential. Small volumes of recyclable materials may be segregated off-site and recycled (DEFRA, 2007). Skip void space is likely to be higher than for construction waste, given both the nature of the waste (which will include removed items and assemblies with built-in voids) and logistics (different waste materials generated at same time, no intermediate storage available).

These factors tend to increase the direct costs of waste disposal from refurbishment compared to that from new construction, and at the same time to limit towards zero opportunities for on-site segregation (DEFRA, 2007). At the same time, the financial value of materials skipped will be lower than for construction, assuming that 80% of these are end-of-life materials whose costs have already been apportioned over their purchase and use. Factoring in the above inefficiencies and material values, DEFRA (2007) proposed a ‘true cost’ of £562 per 6.125m$^3$ skip, broken down as:

- Skip hire £150 plus added 20% for increased voids = £180;
- Labour to fill £163;
- Cost of new materials in skip (20% by volume) £219.

Given the small scale of many refurbishment projects, this figure of £562 may represent a minimum waste disposal cost. This needs to be established empirically. It can be rightly said that the refurbishment cost less than the rebuilding, however the long terms effects may vary and could favour rebuilding.

#### 2.6.1.8 Carbon dioxide equivalent/embodied energy

Based on the waste profile for the Decent Homes refurbishment packages above, it is possible to put a tentative figure on the $CO_2$ impacts represented by the embodied energy of the waste materials (DEFRA, 2007). Each $m^3$ of refurbishment waste matching this profile is associated with emissions of approximately 750kg $CO_2$. Average $CO_2$ impact per refurbishment package is approximately 500kg.

#### 2.6.1.9 Baseline for housing refurbishment

Based on the projected refurbishment scenario outlined above, the total annual UK impacts for domestic refurbishment alone are certain to exceed:

- 5,148,280$m^3$ of waste, equivalent to 367,685 tonnes or 840,000 skips;
- Emissions of 4 million tonnes $CO_2$;
- Disposal costs of £472 million.

A major caveat is that refurbishment drivers in the owner-occupied and private rented sectors are very different, and the profiles of refurbishment work and waste arising will also differ. Extension and renovation works by owner-occupiers will produce significant quantities of inert, concrete, ceramic, cement and plaster waste not predicted by the Decent Homes refurbishment pattern (DEFRA, 2007). This will affect overall waste volumes and composition of relative material masses and carbon impacts. This needs further investigation (DEFRA, 2007).

There is a lack of data concerning the recycling and disposal routes for refurbishment waste; the situation being further complicated by the fact that a significant but unverifiable proportion of segregation currently takes place off site (DEFRA, 2007). At present, there is insufficient confidence in the baseline data to consider future options and targets (DEFRA, 2012).

#### 2.6.1.10 Demolition Waste Statistics (All Sectors)

An estimated 26 million tonnes of demolition materials were produced each year till 2005 – please note this is based on best data available and should be used for guidance only (DEFRA, 2007; DEFRA, 2012). This is broken down in Table 2.6 below.

***Table 2.6 Demolition material (Source: modified from DEFRA 2007)***

| Type | Amount arising (tonnes) | Percentage | Data source |
|---|---|---|---|
| **Hardcore** | 21 million tonnes | 81% | NFDC Annual Returns 2005 |
| **Mixed C&D waste** | 1.7 million tonnes | 6.5% | NFDC Annual Returns 2005 |
| **Reclaimed material** | 3.3 million tonnes | 12% | BigRec Survey 1998 |

The hardcore material represents materials such as concrete, aggregates, glass, bricks and blocks. The mixed C&D waste includes materials such as plastics, timber, composites and will originate largely from soft-strip activities (i.e. the removal of interior fixtures and fittings). The reclaimed materials include items such as architectural and ornamental antiques, reclaimed materials (timber beams and flooring, bricks, tiles, paving and stone walling), salvaged materials (iron and steel and timber) and antique bathrooms. It should be noted that an update of the BigRec survey is currently being replicated as part of this project as circumstantial evidence suggests that there has been a fall in the amount of materials being reclaimed (Waste Statistics Team, 2015).

Typical composition of demolition waste is given in Figure 2.6. This is based on pre-demolition audits carried out at BRE (Waste Statistics Team, 2015). It is assumed that all of the hardcore materials are recycled and that the mixed demolition waste is landfilled (based on NFDC data). In terms of applying the principles of the waste hierarchy to demolition arisings, reduction is not applicable unless the decision is taken to reuse/refurbish the building rather than demolish (Waste Statistics Team, 2015). Therefore the two principle waste management routes are reclamation (i.e. reusing products preferably in the same application) and then recycling (i.e. using the material for a product) (Waste Statistics Team, 2015). Further to this statement, there is a need to revise the waste hierarchy, and a revised hierarchy should clarify the steps to be taken at each stage of the construction and demolition project. This would evaluate and minimise the waste generation in all stages and further provide stability in economic and environmental terms.

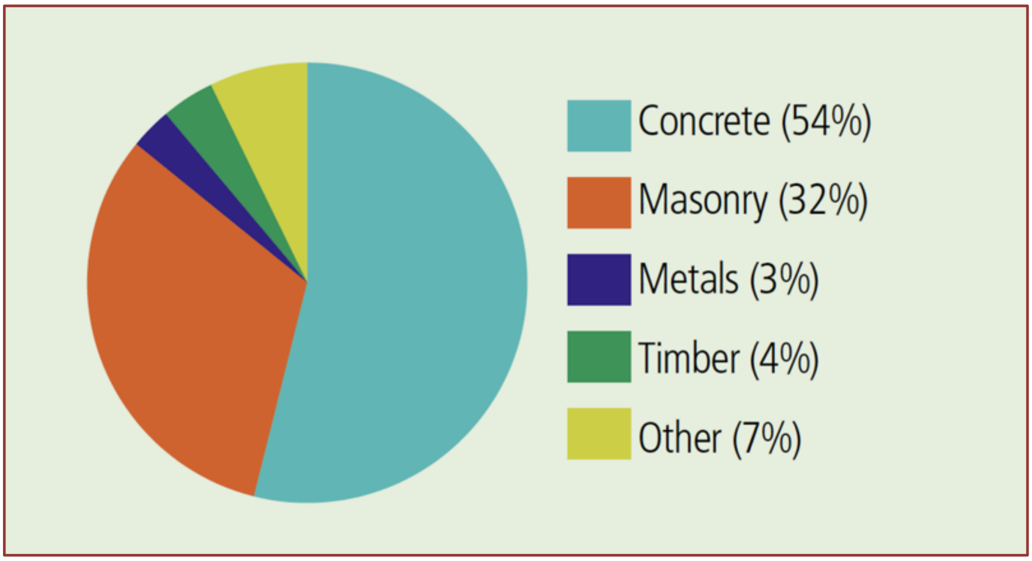


***Figure 2.7 Typical composition of waste (Source: Waste Statistics Team, 2015)***

Clearly, concrete and masonry contributes the maximum amount to waste as compared to other material waste as shown in Figure 2.6 (Waste Statistics Team, 2015). These materials are highly used during the construction of any sort of building, either it is residential or commercial. However, residential construction projects accounts for maximum use of masonry material when compared to commercial. This fact has to be taken into account for the identification of the key decision-making factors, as it constitutes a major difference in both residential and commercial scenarios.

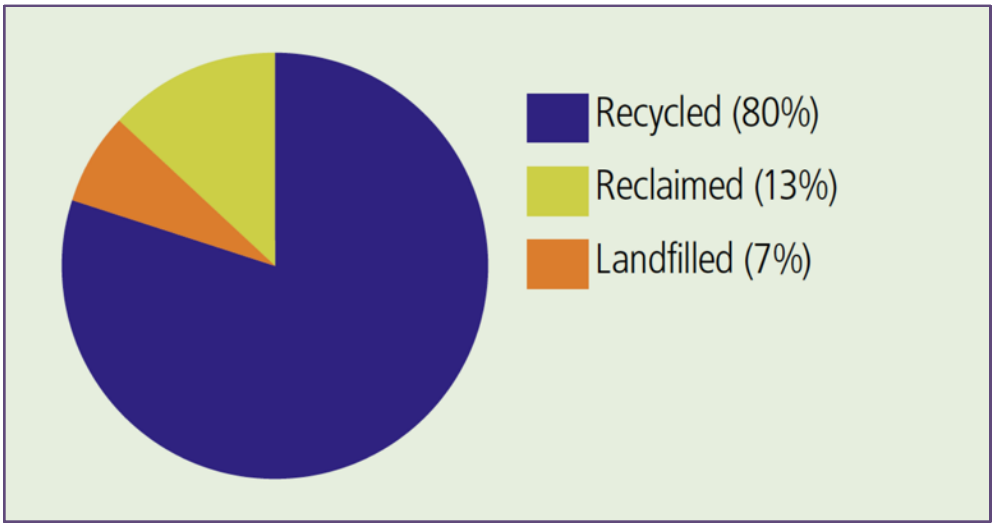


***Figure 2.8 Waste management – current practice (Source: Waste Statistics Team, 2015)***

In terms of the landfill of demolition waste, 32% (0.5 million tonnes) is hazardous waste. 80% of materials recycled (i.e. hardcore) includes the recycling of 53% on site and the remaining 47% off site (Waste Statistics Team, 2015; Waste Statitics Team, 2016). The current recycling rates of 80% is although high (see Figure 2.7), hiding the fact that it is usually low grade recycling, with the potential for high-grade re-use is higher. This has an impact in terms of cost benefits and environmentally favoured project.

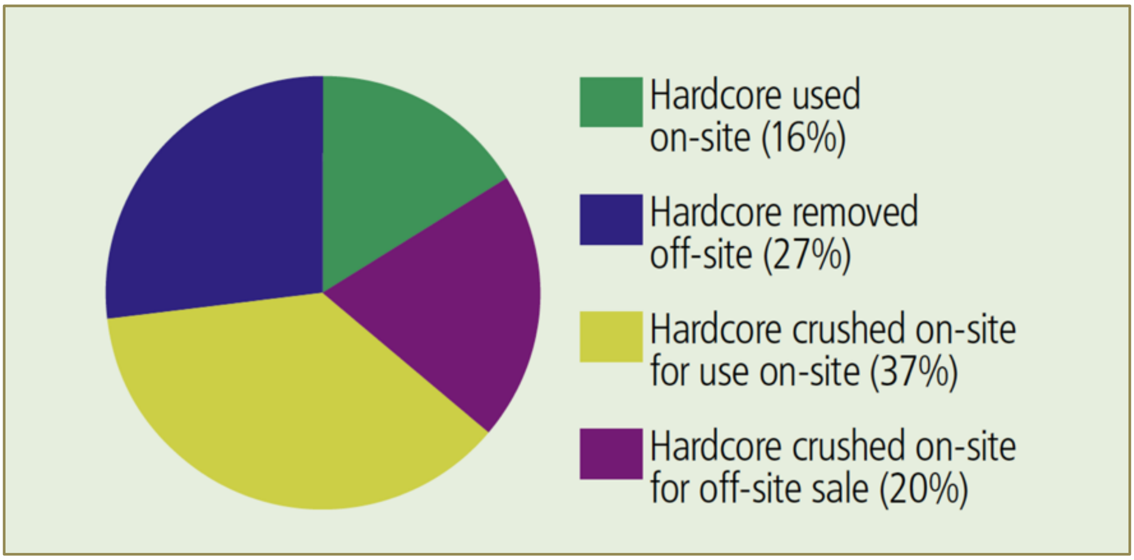


***Figure 2.9 Hardcore recycling rates (Source: Waste Statistics Team, 2015)***

Furthermore, the amount of recycled hardcore waste depends on the condition. The reusable waste was crushed and reused on site and un-usable hardcore waste was removed off-site. This involves transportation or waste collection. A fine strategy for waste reduction on and off-site needs to be implemented, further leading to the identification of the key decision-making factors.

#### 2.6.1.11 Transportation

Emissions of $CO_2$ have been calculated for the distances travelled for the demolition arising; obviously if material is being reused on site, only a tiny fraction of $CO_2$ will be attributed to transportation impacts (DEFRA, 2007). Therefore, assuming the maximum distance for transportation of demolition arising is 20 miles, then the following $CO_2$ emissions from transportation apply, see Table 2.7.

***Table 2.7 $CO_2$ emissions (Source: modified from DEFRA, 2007)***

| $CO_2$ emissions from travelling 20 miles* | | |
|---|---|---|
| **Demolition material** | **Current practice** | **Best practice** |
| Hardcore recycled on site | Saving of 21,000 tonnes | Saving of 18,200 tonnes |
| Hardcore recycled off-site | 18,400 tonnes | 14,560 tonnes |
| Reclaimed material | 6,000 tonnes | 12,740 tonnes |
| Landfilled | 3,100 tonnes | 1,820 tonnes |
| ***Assuming 0.091kg of $CO_2$ for 1 tonne every 1 mile travelled.** | | |

Therefore, currently 21,000 tonnes of $CO_2$ emissions are saved by recycling materials on site through savings in transportation. By currently transporting materials from site this generates 24,400 tonnes of $CO_2$ emissions with an additional 3,100 tonnes created from transporting this waste to landfill (DEFRA, 2007).

For the best practice scenario the amount of $CO_2$ emissions increases – this is because the amount of material salvaged for reuse increases requiring the movement of materials offsite (DEFRA, 2007). However, it should be noted that reclaimed materials can travel much further (between 100 to 7,500 miles) before their environmental benefit is lost against new materials.

#### 2.6.1.12 Costs

The assumed total cost of current and best practice waste management routes from demolition are shown in Table 2.8 below.

***Table 2.8 Assumed total cost of current and best practice waste management routes (Source: modified from DEFRA, 2007)***

| Type of demolition arising | Total value - current practice | Total value – best practice | Data sources |
|---|---|---|---|
| **Reclaimed material** | + £389 million | - £819 million | Based on BigRec Survey data |
| **Hardcore material – recycled on site** | + £35 million | - £30 million | Based on a cost saving of £3/tonne |
| **Hardcore material – recycled off site** | + £20 million | - £16 million | Based on a cost saving of £2/tonne |
| **Landfill – mixed C&D waste** | - £58 million | - £25 million | Based on £50/tonne |
| **Landfill – hazardous waste** | - £50 million | - £50 million | Based on £100/tonne |
| **Total** | + £344 million | + £790 million | |

#### 2.6.1.13 Solution 1 - current practice – demolition waste

Assumption: 26 million tonnes arising (DEFRA, 2007).

13% reclaimed (3.3 million tonnes), 80% recycled (21 million tonnes), 53% recycled on site (11 million tonnes), 47% recycled off site (10 million tonnes), 7% landfilled (1.7 million tonnes), 32% is hazardous waste (500,000 tonnes), so total benefit is £344 million (DEFRA, 2007).

$CO_2$ from transportation is 27,500 tonnes with 21,000 tonnes saved by recycling on-site. The material impact is equivalent to 4.74 million tonnes of $CO_2$ (DEFRA, 2007).

#### 2.6.1.14 Solution 2 - achievable best practice – demolition waste

Assumption: 26 million tonnes arising (DEFRA, 2007).

28% reclaimed (7 million tonnes), 68% recycled (18 million tonnes), 4% landfilled (1 million tonnes), 50% is hazardous waste (500,000 tonnes) (DEFRA, 2007).

- Total benefit is **£790 million;;**
- Reclamation income increasing by **£430 million;**
- Recycling income decreasing by **£9 million.**

Landfill costs decreasing by £38 million $CO_2$ from transportation is 29,120 tonnes an increase of 1620 tonnes with 18,200 tonnes saved by recycling on-site. The material impact is equivalent to 3.8 million tonnes of $CO_2$, a reduction of 0.94 million tonnes (DEFRA, 2007).

These options are based on current practice in terms of the types of buildings being demolished and the techniques used (DEFRA, 2007). The following issues should be noted when implementing a strategy for demolition waste:

- Due to the changes in practices for construction such as the higher use of modern methods of construction, more use of composite materials etc it is likely in the longer term that it will be harder to achieve these levels of reclamation and recycling (DEFRA, 2007);
- There is a requirement for designers, architects and clients to design buildings that aid recovery options at the end of the buildings life. This involves the disassembly and deconstruction of buildings as preferential over demolition[19] and specifying materials and products which can be reclaimed or recycled. Many of the current techniques used for fixing and joining do not currently aid these principles (DEFRA, 2007). This is also important in terms of the amount of hazardous waste which is currently produced which is likely to rise.

Factors affecting the demolition industry and the amount of materials that can be recovered include:

- an increasing move towards more mechanized ways of operating (largely due to health and safety requirements) which means the removal of more 'bulk' material rather than higher value products;
- less time to demolish buildings and therefore realise the true value of demolition arising;
- the interpretation of the waste legislation especially related to the recycling of waste on and off site (DEFRA, 2007).

In terms of reclamation, issues that need to be considered are:

- the markets and associated logistics for increasing the number of products for reclamation;
- the costs of reclaiming materials (i.e. usually requires more time and labour);
- the incentive for using reclaimed.

## 2.7 Design Life of Buildings

BRE has a number of publications relating to the lifetime performance of building materials and products (BRE Digest 429, 1998). This ranges from research and test work carried out on specific materials and components, to an overview of materials, their durability and whole life performance (BRE Digest 420, 1997). The development of whole life performance techniques is dependent on the material performance and lifetime data that is available (Marsh, 1996). This can only be determined by research into the performance of materials, something which BRE has a long experience in carrying out through Government sponsored research and consultancy work. These findings and material data are available from BRE publications.

BRE has carried out a scoping study for the Scottish Building Standards Agency (SBSA) into the possibility of including a statement of 'Design service life' into Regulation 8 of the Scottish Building Standards. This study has looked at possible methodologies for assessing design service life and what the assessment criteria would include. This work was undertaken as a desk-based study, although this has been supplemented by meeting with Building Standards Officers. This provided valuable feedback on how the design service life of buildings could be assessed and how the methodology could be developed. Design service life should be defined as follows:

"the assessment of a structure, both as a complete building and individual components, which predicts its potential lifetime based on levels of design, workmanship, maintenance and the environment."

### 2.7.1 Factors affecting the Durability of Material or Component

The durability of building materials and products is a key element in the building design and lifetime performance. The selection and installation of materials and construction systems will have a direct impact on the durability of the building. In the UK materials and products are often exposed to periodic driving wind and rain and this can affect the performance over the lifetime of the building (Kelly, 2007). These 'service conditions' should be accounted for in the design and specification process and installed correctly subject to manufacturers guidelines (Kelly, 2007).

According to Kelly (2007), there are a large number of environmental and chemical factors which can affect the durability of a material or component during its service life. These include the following:

- Moisture;
- Humidity;
- Temperature;
- Driving wind and rain;
- Chemical pollutants;
- Solar radiation;
- Site conditions.

The durability of a material or component will be affected by some, or a combination of, these factors. Their resistance and, therefore, suitability for use should be based on accepted test methods for determining durability (Kelly, 2007). These tests are described in various UK and European Standards for materials and products used in the construction industry. There is a large number of product standards relating to the full range of construction products, from bricks and blocks to glass and aluminum cladding.

As Building Standards are amended to reflect the need for greater energy efficiency, more and more new products are becoming available within the construction industry. Many of these materials include greater thermal efficiency and/or space saving features, and it is these innovative features that can leave them out-with traditional material 'groupings'. New materials, as well as more established products, should still be assessed in relation to their durability and performance (Kelly, 2007). Guidance to Regulation 8 recommends that fitness of materials is met by using materials, fittings, and components, or parts thereof which comply with any of the following standards:

### 2.7.2 Initiatives and Techniques

Initiatives within the construction industry such as the Egan Report (Egan, 1998) and the Latham Report (Latham, 1994) have set targets for cost savings which are assessed using Whole Life Cost (WLC) techniques. The Egan report states that,

"design needs to encompass whole life costs, including costs of energy consumption and maintenance costs. Sustainability is equally important. Increasingly, clients take the view that construction should be designed and costed as a total package to include costs in use and (through to) final decommissioning."

A whole life costing approach encourages decision making that takes account of durability, future running (Quillin, 2001) that are more compatible with the concept of sustainable construction.

The UK has also led the international development of standardisation within the sector of service life planning. Several trial and demonstration projects have been carried out for various Government agencies and this has led to an increase in the popularity and use of WLC techniques (Kelly, 2007). This included the publication of international standard BS ISO 15686-1 (2000) 'Buildings and constructed assets – Service life planning. This standard was published in five parts (Kelly, 2007). The most relevant part to this research project, Part 3 describes the approach and procedure to be applied to prebriefing, briefing design, construction and, where required, the life care management and disposal of buildings and constructed assets to provide a reasonable assurance that the measures necessary to achieve performance over time will be implemented.

Part 4 of the standard describes the range of data requirements that will allow the service life to be determined, and Part 5 will provide guidance on the assessment of the life cycle costs of a building.

### 2.7.3 Whole Life Cost Techniques

Whole life costs techniques are usually employed at the planning stage as a method of option appraisal and is not often considered after a construction project is underway. It can be used to assess the merits and costs of various elements of the building such as windows, cladding systems, roofing or flooring (Kelly, 2007). The costs of purchasing, installing and maintaining the element can then be estimated over an agreed lifetime.

Recent studies by BRE have developed a concise definition of WLC as (Clift & Bourke, 1999),

“the systematic consideration of all relevant costs and revenues associated with the acquisition and ownership of an asset”.

Within the construction industry this was likely to account for procurement costs such as the following:

- Initial construction or major refurbishment;
- Purchase or leasing;
- Interest;
- Fees.

In addition to this, costs for the continued use or occupancy of the building should also be considered as follows:

- Rent and rates;
- Cleaning and refurbishment;
- Maintenance, repair, replacement and renewal;
- Energy and utilities;
- Dismantling, disposal or demolition;
- Security and management.

Fundamental to the success of the WLC approach is the availability of accurate material data. This data should indicate the service life of the material, its maintenance schedule and future removal, renovation or demolition cost. If this information is not available then some estimation of the cost will be used (Kelly, 2007). This can introduce an error into the WLC calculation which will accumulate if applied to a whole building.

### 2.7.4 Design Life Stages

There is a list of terms which can be used to describe lifetime of buildings, components and materials. In some cases the definition of these terms and how they differ from one another is unclear. Many factors in the construction process can determine whether or not a structure will meet its design service life. There have been numerous examples of durability problems due to poor design detailing, poor workmanship, inadequate cover to vulnerable components and lack of proper maintenance (Kelly, 2007). The actual end of life can be determined by a number of factors including changes of use and economics. Consequently, a number of alternative types of service life have been defined as follows:

***Table 2.9 Design life stages (Source: modified from Kelly, 2007)***

| | |
|---|---|
| **Required (service) life** | The minimum period during which the structure or a specified part of it should perform its design functions (subject to routine servicing and maintenance) to meet the users' requirements. |
| **Design (service) life** | The period of intended use by the designer. |
| **Technical (service) life** | The actual time in service until a defined minimum acceptable state is reached. |
| **Functional (service) life** | The time in service until the structure is obsolete due to changes in functional requirements. |
| **Economic (service) life** | The time in service until replacement is economically more advantageous than continued maintenance in service. |

More importantly, the economic service life is one of the main concerns of the building owner (Kelly, 2007). Managing the building as a resource and ensuring adequate return on the investment made in its purchase and use will be assessed in line with the economic service life predictions (Kelly, 2007).

Individual components of a structure will have different expected service lives. Structural members are generally expected to perform their intended function for at least the service life of a structure whereas it may be acceptable for non-structural components to be repaired or replaced.

When estimating the design service life of a structure or element, it is important to consider what constitutes the end of the service life. It may even be possible that the building becomes obsolete within its service life. There are, therefore, many principles on which the end of the service life of a structure might be based, which could go as far as dilapidation, as in the following examples:

- Deterioration of 'protective' materials or components;
- The point at which corrosion is initiated.

The actual limits of required service life used at the design stage will depend on the nature of the structure and the client's requirements. The required service life may also depend on the type of structure or its elements, its performance (including safety) requirements, and on the maintenance regime that is adopted.

### 2.7.5 Buildings to be Included

The assessment of design service life of buildings could be applied to a variety of buildings from private extensions to dwellings, garages, new-build houses and non-domestic buildings. Each of these constructions need to comply with existing Building Regulations and Standards and could theoretically be assessed under the design service life procedure. For smaller buildings such as extensions and garages, this process may not be economically viable due to the extent of the information required and time taken to complete a design service life assessment.

New buildings that meet the floor area requirements could be assessed using the design service life procedure. Existing buildings that are due to be converted, altered, or extended could also be subject to a design service life assessment, but the collation of information may be more difficult if the design and specification of the original structure is unknown. A design service life assessment can be undertaken for the conversion, alteration or extension work, but the design service life assessor would need to make an informed judgement on the how the design service life of the building will be affected by these works.

### 2.7.6 Durability and Maintenance

As well as the materials aspects of designing for durability, the following issues are also critical in designing durable buildings:

- The impact of the design detailing, especially on the service life of high and medium ‘classed’ structures and elements.
- The ‘buildability’ of the design and good workmanship.

These will have a direct impact on the design service life of the building. Detailing and design are important factors in order to maximise the properties, performance and lifetime of the materials and components to be used in a building. High grade materials and components will not achieve their performance potential if they are fitted incorrectly or not to the manufacturers guidelines. Vulnerable materials are also at risk if design detailing is not carried out correctly. Many insulation materials, for example, will deteriorate rapidly if they are exposed to moisture and UV radiation. Therefore, protection and detailing surrounding these, and similar materials is important.

The issue of ‘buildability’ is equally important. Careful design and detailing would be rendered useless if the intricacies of the design could not be reproduced on site. Careful consideration should always be given to site conditions, the availability of skilled labour and the practical implications of carrying out the work.

Workmanship issues are, of course, important to ensure the design service life of the building is achieved. Minimal accepted levels of workmanship are described in BS 8000 although more detailed instruction may be required for new or innovative materials. If these instructions are not available, or unusual construction methods are required without adequate information being provided, the lifetime of the building may be compromised.

Maintenance schedules are also important when assessing the design service life of buildings. Periodic treatment or repair of elements within the building will help to maintain their performance over its intended lifetime.

Regulation 8 requires that materials, fittings and components should be suitable for their purpose, correctly used or applied, and sufficiently durable, taking account of normal maintenance practices, to meet the requirements of the regulations. Accordingly, it must be assumed that design detailing, workmanship, durability, and maintenance meet a satisfactory minimum standard and therefore these aspects need not be addressed in a design service life assessment for the purposes of any new building regulations requirement.

### 2.7.7 Assessment Procedure

BRE has proposed that the assessment of design service life for the purpose of a building warrant application should be based on a combination of the two approaches, as follows:

- A factoring method as described in BS ISO 15686-1 (2000) ‘Buildings and constructed assets – Service life planning: Part 1 – General principles’.
- Dividing the components of a building under the headings of ‘structural’ and ‘non-structural’ and carrying out an assessment of design service life for each grouping, but with a standardised assumption of satisfactory design detailing, workmanship, durability, and maintenance.

By dividing the building into structural and non-structural elements, their lifetime may be more easily estimated. Structural walls may be made up of masonry, steel or timber frame whose durability and lifetime in most cases would be a minimum of sixty years. The durability and performance of these structures is often well researched and documented. Consequently, information on the potential lifetime of the structural system should be readily available in most cases.

The non-structural elements may be seen as more likely to be replaced or requiring maintenance during their lifetime. These elements would include cladding, windows, internal finishes and services. Many non- structural elements will have a maintenance schedule that could be sourced from the manufacturer. This information could be used as a source of evidence for the likely lifetime of the product if it is maintained correctly.

If the building is divided into structural and non-structural elements, sourcing this information may not be such an onerous task. The method by which the information is presented will also have an impact on the likelihood of it being provided.

#### 2.7.7.1 Assessment Form

A prerequisite of the assessment of design service life is that it should be straightforward and not incur an unrepresentative amount of effort to complete. The assessment form has been developed so that it can be used to evaluate the component parts of a building (Kelly, 2007). These components can be categorised into structural and non-structural elements as follows:

1) **Structural components**
    a. Roofs (including structural components and tiles);
    b. Ground floor;
    c. Other floors;
    d. External walls (structural);
    e. Internal walls (structural);
    f. Foundations.
2) **Non-structural components**
    a. Windows and rooflights;
    b. Doors;
    c. External walls (cladding);
    d. Internal walls (partition);
    e. Services.

An assessment form can then be completed for each component. A suitable form is shown in Appendix A and includes the reduced factoring system. This system uses a nominal value of 1 to show a factor which will neither increase or decrease the lifetime of the material or component. If the factor improves the likely performance, durability and lifetime of the component, this can be factored up to a maximum of 1.2 (Kelly, 2007). If the factor reduces the lifetime of the component it can factored down to a minimum of 0.8 (Kelly, 2007).

The design service life can, therefore, be estimated by multiplying together all of the relevant factors. The reference service life of the element or component should be estimated from an accurate source at all times e.g. manufacturer or certification (Kelly, 2007). This statement holds true for all factors to be assessed and manufacturers should be the primary source of this information (Kelly, 2007). Where information is lacking, other sources may be used such as the HAPM Manual or BPG publication.

The estimated reference service life is, perhaps, the most important factor to accurately determine. This value will have greatest influence on the estimated design service life and effort should be made to source accurate information. Manufacturers literature, research publications and British and European Standards should provide the majority of this data (Kelly, 2007).

#### 2.7.7.2 Factors for Design Life Prediction

Based on the initial literature survey carried out and described in BRE Report 228290.1, a factoring method for assessing the design service life of buildings has been proposed. This approach would adopt a standard service life for components with assumptions made for their quality and their use in a building (Kelly, 2007).

BS ISO 15686-1 uses the following approach to categorising the factors influencing the estimated design service life:

$EDSL = RSLC \times Q_m \times D_l \times W_l \times E_c \times U_c \times M_c$

Where;

- EDSL = estimated design service life;
- RSLC = reference service life;
- $Q_m$ = quality of materials factor;
- $D_l$ = design level factor;
- $W_l$ = work execution level factor;
- $E_c$ = environmental conditions factor;
- $U_c$ = in-use conditions factor;
- $M_c$ = maintenance conditions factor.

The ‘reference service life’ refers to the time that the component or building can be expected to last under normal conditions (Kelly, 2007). ‘Normal’ conditions, in this sense, are related to the building being used to the purpose for which is was designed and not exposed to any extreme loading from the weather or other unnatural events. The reference service life may be derived from modelling, experience, accelerated testing, data from the manufacturer or from product standards. $Q_m$ to $M_c$ represents factors from BS ISO 15686 that can affect the estimated design service life under circumstances where they do not meet the levels specified in manufacturers recommendations or in the Codes and Standards (Kelly, 2007). Appropriate values for these factors need to be judged by the designer and based on the particular circumstances of the project, previous experience and information available on the effects of factors on design service life (e.g. design concept, structural detailing, environment, workmanship and maintenance).

For Building Standards purposes, it may only be practical to assess factors A and D. Regulation 8 has requirements relating to B, design level factor, and C, work execution level factor and it makes assumptions relating to $U_c$,: in-use conditions factor, and $M_c$, maintenance conditions factor (Kelly, 2007).

The reduction of the number of factors would therefore result in an estimated design service life for regulatory purposes, as follows:

Estimated Design Service Life for Regulation (EDSL-R) = reference service life x quality of materials factor ($Q_m$) x environment factor ($E_c$).

The factors that applied will be between 0.8 and 1.2 (Kelly, 2007).

### 2.7.8 Examples of Design Life Assessment

These case studies has been provided as a means of illustrating how the design service life of a building could be assessed. They have been included for information purposes only and is not based on any 'real- life' examples.

#### 2.7.8.1 Private Dwelling (Structural Elements)

The main factors affecting the estimated design service life of a private dwelling will be particular to the structural and non-structural elements. The structural elements are a timber frame system, brick cladding and concrete roof tiles. The non-structural elements are made up of timber windows and doors, plasterboard partition walls and the electrical and plumbing services.

The main factors affecting all of the structural elements will be moisture ingress and movement in the building. These are a feature of the site and its exposure to the weather conditions.

Using the factoring method described in Section 2.7.7.2, the estimated design service life of the timber frame system for regulation purposes can be estimated as follows:

EDSL-R = RSLC x A x D

Where;

- EDSL: estimated design service life;
- RSLC: reference service life–structural component ,not accessible: value 60 years. The factors should vary by no more than 0.2 from 1.0;
- A: quality of materials factor ($Q_m$) – Certified timber: value 1.1;
- D: External exposure – suburban location, elevated and exposed: value 0.9

Therefore, EDSL-R = 60 x 1.1 x 0.9 = 59 years.

Using the factoring method described in Section 2.7.7.2, the estimated design service life of the brick cladding system for regulation purposes can be estimated as follows:

EDSL-R = RSLC x A x D

Where;

- EDSL: estimated design service life;
- RSLC: reference service life – structural component, not accessible: value 60 years. The factors should vary by no more than 0.2 from 1.0;
- A: quality of materials factor ($Q_m$) – Frost resistant bricks: value 1.1;
- D: External exposure – suburban location, elevated and exposed: value 0.9

Therefore, EDSL-R = 60 x 1.1 x 0.9 = 65 years.

Using the factoring method described in Section 2.7.7.2, the estimated design service life of the concrete roof tiling system for regulation purposes can be estimated as follows:

EDSL-R = RSLC x A x D

Where;

- RSLC: reference service life structural component, not accessible: value 50 years;
- The factors should vary by no more than 0.2 from 1.0;
- A: quality of materials factor ($Q_m$) – BBA Certified product: value 1.1;
- D: External exposure – suburban location, elevated and exposed: value 0.9

Therefore, EDSL-R = 50 x 1.1 x 0.9 = 54 years.

#### 2.7.8.2 Private Dwellings (Non-structural Elements)

The main factors affecting the non-structural elements will be the ingress of moisture and water damage. Using the factoring method described in Section 2.7.7.2, the estimated design service life of the timber windows for regulation purposes can be estimated as follows:

EDSL-R = RSLC x A x D

Where;

- EDSL-R: estimated design service life;
- RSLC: reference service life – non-structural component, accessible: value 25 years;
- A: quality of materials factor ($Q_m$) – non-durable redwood, fully machined and pressure treated with a solvent based preservative: value 1;

- D: environmental conditions factor ($Q_m$) – internal environment, low risk; external environment, sheltered from wind, rain and particulates: value 1.1.

Therefore, EDSL-R = 25 x 1.1 x 1.1 = 30 years.

Using the factoring method described in Section 2.7.7.2, the estimated design service life of the internal plasterboard partitions for regulation purposes can be estimated as follows:

EDSL-R = RSLC x A x D

Where;

- EDSL-R: estimated design service life;
- RSLC: reference service life – non-structural component, accessible: value 30 years;
- A: quality of materials factor ($Q_m$) – foil-back plasterboard: value 1;
- D: environmental conditions factor – internal environment, low risk; external environment, sheltered from wind, rain and particulates: value 1.1.

Therefore, EDSL-R = 30 x 1.1 x 1.1 = 36 years.

Using the factoring method described in Section 2.7.7.2 the estimated design service life of the services for regulation purposes can be estimated as follows:

EDSL-R = RSLC x A x D

Where;

- EDSL-R: estimated design service life;
- RSLC: reference service life – non-structural component, accessible: value 30 years;
- A: quality of materials factor ($Q_m$) – wiring and plumbing using quality materials: value 1;
- D: environmental conditions factor – internal environment, low risk; external environment, sheltered from wind, rain and particulates: value 1.1.

Therefore, EDSL-R = 30 x 1.1 x 1.1 = 36 years.

#### 2.7.8.3 Concrete Frames

The main factors affecting the estimated design service life of the reinforced concrete structure are the grading of the material, reinforcement and protection. The environment and exposure to possible corrosive compounds, such as salt spray, will also be important to consider.

Using the factoring method described in Section 2.7.7.2, the estimated design service life for regulation purposes can be estimated as follows:

EDSL-R = RSLC x A x D

Where;

- EDSL: estimated design service life;
- RSLC: reference service life–structural component, not accessible: value 60 years. The factors should vary by no more than 0.2 from 1.0;
- A: quality of materials factor – Portland blast furnace slag cement (to British Standards) with good coverage of reinforcement: value 1.1;
- D: External exposure – inner city location away from coast and significant frost, frame covered by cladding: value 1.2.

Therefore, EDSL-R = 60 x 1.1 x 1.2 = 79 years.

#### 2.7.8.4 Softwood Window

The main factors affecting the estimated design service life of the softwood window are the inherent timber quality and the quality of the timber treatment, together with the quality of maintenance of any coating. The window design and its orientation and position within the building are also important factors to consider.

Using the factoring method described in Section 2.7.7.2, the estimated design service life can be estimated using the factorial approach as follows:

EDSL-R = RSLC x A x D

Where;

- EDSL-R: estimated design service life;
- RSLC: reference service life – non-structural component, accessible: value 25 years;
- A: quality of materials factor – non-durable redwood, fully machined and pressure treated with a solvent based preservative: value 1;
- D: environmental conditions factor – internal environment, low risk; external environment, sheltered from wind, rain and particulates: value 1.1.

Therefore, EDSL-R = 25 x 1.1 x 1.1 = 30 years.

These examples are not given as an indicative guide to reinforced concrete structures or softwood windows. Their purpose is to serve as an illustration of the assessment procedure that can be carried out for structural and non-structural components.

## 2.8 Design for Deconstruction (DfD)

The deconstruction of buildings has gained more and more attraction in recent years. The deconstruction and dismantling of buildings instead of their demolition helps to increase the amount of components to be reused or materials to be recycled. Thus, the share of demolition waste deposited in landfills can be reduced (Crowther, 2001). In Germany and France several research projects have proven that dismantling of buildings also helps to reduce the environmental burden of recycled construction materials by encouraging the production of recycling materials containing less harmful substances (Crowther, 2001). Furthermore, it can be shown, that environment-friendly dismantling and recycling strategies can even be advantageous from an economic point of view.

Design for deconstruction is one of many useful strategies to assist in reducing the environmental burden of our built environment (Crowther, 2001). It has not however been well investigated, or well implemented on a broad scale. With a greater understanding of the issues and their interrelationships it is hoped that design for deconstruction might become an important consideration in any construction project.

According to Crowther (2001), there is a basic lack of understanding or knowledge of design for deconstruction in architecture. The types of knowledge that might be needed can be investigated by asking a number of basic questions:

- Why deconstruct;
- When and where to deconstruct;
- What to deconstruct;
- How to deconstruct.

### 2.8.1 Why Deconstruct

The general need for an improvement in the current rates of materials and component reuse is well accepted. Any response to this must however fit within the broader understanding of sustainable construction. It is not beneficial to design for deconstruction to increase rates of recycling if the overall life cycle environmental costs of such a strategy are actually greater than the potential benefits (Crowther, 2001).

An understanding of this holistic relationship must form part of any understanding of design for deconstruction in order that the benefits are realised. The issues of design for disassembly need to be located within a general model for sustainable construction so that the external consequences of a design for deconstruction strategy might be highlighted and considered.

### 2.8.2 When and Where to Deconstruct

Different parts of buildings have different life expectancies, for economic, service, social, and fashion reasons. An understanding of the life expectancy of parts of a building is an integral part of a strategy of designing for deconstruction. The theory of time related building layers, the idea that a building can be read as a number of distinct layers each with its own different service life, offers some insight into the relationship between life expectancy and deconstruction (Crowther, 2001). Knowing which layer a component is from, and where the layer begins and ends, assists in determining when and where to deconstruct.

### 2.8.3 What to Deconstruct

There are many possibilities for the recycling of materials and components, from complete relocation and reuse, to material recycling or incineration for energy. The question of what to deconstruct can in part be answered by asking what is the intended form of recycling (Crowther, 2001). What is deconstructed for material recycling may be different to what is deconstructed for component relocation. There is therefore a relationship between the hierarchy of recycling options and design for deconstruction.

### 2.8.4 How to Deconstruct

There are several sources of information of how to deconstruct. These include industrial design, architectural technology, buildability, maintenance, and international research into deconstruction. While the question of how to deconstruct buildings has not been well investigated in the past, the above sources of information can be searched for recurring themes (Crowther, 2001). These themes can then be developed as principles for design for deconstruction.

### 2.8.5 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 (Tingley, 2013). When does it become better for the environment to remove the existing buildings and rebuild? 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 (Tingley, 2013). 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 (Tingley, 2013). Work has been done to develop a number of tools to help assess the feasibility of the deconstruction of existing buildings.

### 2.8.6 Recycling Hierarchy and Design for Deconstruction

The relevance of the hierarchy of end-of-life scenarios to the design process is that it is possible to design a product or building to facilitate the more environmentally advantageous scenarios.

Graedel and Allenby made an important contribution to the debate by noting that the end- of-life scenarios that are possible for a product will be determined by the physical characteristics of that product (Crowther, 2001). That is to say that the actual design of the product will determine whether it is possible to achieve the environmentally preferable scenarios of maintenance and reuse, rather than just recycling or disposal (Crowther, 2001). Attempts to address this issue have been through promoting the notion of design for disassembly and in the development of guidelines for design for disassembly in the field of industrial design (Crowther, 2001).

In building design, Guequierre and Kristinsson, like Graedel and Allenby, make the point that there are physical features of the product (building) that will determine which end-of-life scenarios are possible or probable (Crowther, 2001). This notion suggests that it will be possible to design a product (building) in a way that will facilitate or encourage the implementation of the higher (more environmentally preferable) end-of-life options (Crowther, 2001).

#### 2.8.6.1 Conclusions to Recycling Hierarchy

This section has shown how the concept of recycling can be more appropriately represented by a group of end-of-life scenarios;

- building reuse or relocation;
- component reuse or relocation in a new building;
- material reuse in the manufacture of new component;
- material recycling into new materials.

These scenarios can be arranged in a hierarchy, in which reuse is (generally) more environmentally beneficial than recycling or disposal. Environmentally responsible building design should attempt to facilitate the higher level scenarios.

There is a direct relationship between the physical design features of a building and what can be done with the building, or its components, when the end of its service life has been reached. It will therefore be possible, through design for deconstruction, to produce new buildings that can achieve more environmentally beneficial end-of-life scenarios.

### 2.8.7 Principles of Design For Deconstruction

The strategy of design for deconstruction, has not yet become a major issue in the construction industry. There are however various sources of information on design for deconstruction that can be assessed for recurring themes (Crowther, 2001). These themes have been developed into principles to be used by building designers to either develop building designs, or to assess existing designs or buildings, for future disassembly (Crowther, 2001). The sources of information used in this research include:

- Industrial design;
- Architectural technology;
- Buildability;
- Building maintenance;
- Research into deconstruction.

#### 2.8.7.1 Industrial Design

In the fields of industrial and product design, there is already a good understanding of the environmental benefits of recycling and reuse. The concept of Industrial Ecology has to some extent addressed the notion of reduced environmental impact through improved rates of material and component reuse to minimise waste. There are in fact many researchers who have already identified explicit guidelines for design for deconstruction, or design for disassembly, of industrial or manufactured products. Similarly numerous car, computer and household product manufacturers have already implemented the actual practice of design for disassembly (Crowther, 2001).

A study of industrial design practice and research reveals a number of these design for disassembly or deconstruction guidelines that may have application in the construction industry (Crowther, 2001). These guidelines typically cover issues such as material compatibility, connection type, number of connections, handling facilitation, and information management.

#### 2.8.7.2 Architectural Technology

While design for disassembly or deconstruction has not become a major part of mainstream construction practice, there have been a considerable number of unique architectural efforts that have used such a technique. Throughout history there have been many cases of buildings designed for deconstruction, either to allow for material reuse or for whole building relocation. From primitive huts to the Crystal Palace, and from traditional Japanese timber building to the schemes of Archigram and the Metabolists, there are valuable lessons in design for deconstruction (Crowther, 2001).

A survey of these historic examples reveals a number of common technological trends that suggest the possibility of developing guidelines for designing for deconstruction in buildings (Crowther, 2001). These trends can be roughly grouped in to ideas about materials, structural systems, access, connection type, number of components, and appropriate technology.

#### 2.8.7.3 Buildability

If the process of deconstruction is considered as the opposite of the process of construction, there may be some value in the study of making construction easier. If a building is easier to put together, it should be easier to take apart. The notion of buildability, making buildings easier to construct, has received some research attention (Crowther, 2001). This research has resulted in some explicit guidelines for buildability that should also assist in design for deconstruction. These guidelines are primarily concerned with issues of handling, access, and prefabrication (Crowther, 2001).

#### 2.8.7.4 Building Maintenance

The maintenance of buildings often requires the replacement of components or materials. To achieve such replacement it is necessary to deconstruct parts of the building. Research into this facet of building maintenance may therefor offer guidance on how to make such disassembly easier. Investigation of research into replacement maintenance has resulted in some principles of design that make such replacement easier. These principles can be adapted to inform the field of design for deconstruction for reasons other than maintenance (Crowther, 2001).

#### 2.8.7.5 Research into Deconstruction

The International Council for Research and Innovation in Building and Construction (CIB) Task Group 39 on Deconstruction is concerned with research into the disassembly and deconstruction of buildings to achieve higher rates of material and component re-use and recycling. This group has identified a number of research projects dealing primarily with the deconstruction of existing building (Crowther, 2001). From this research, and other related projects, a number of desirable attributes of buildings can be deduced if buildings are to be designed to be easily deconstructed in the future (Guy & McLendon, 2000).

### 2.8.8 Demolition vs Deconstruction Cost

Deconstruction can be more cost effective than demolition when considering the reduction in landfill disposal costs and the revenues from the salvage value. Another opportunity is the savings in the transportation costs. The net income from deconstruction can be increased by carefully salvaging more material with the least damage, so the amount of waste material is reduced while increasing reuse and recycling potential of salvaged materials (Guy & McLendon, 2000).

In many cases, there are problems with the supply chain of salvaged material including storage space, availability, and location of end markets. Therefore, there is a need for establishing secondary material businesses such as used building material stores, recycling companies that divert salvaged waste into secondary materials, and product manufacturers that use secondary feedstock.

According to a cost comparison conducted by Guy and McLendon (2000), which was based on the study of demolition vs. deconstruction of six houses in Florida, the average estimated demolition cost, was approximately $5.25-5.50 per square feet with disposal cost being an average of 40% of the total costs. The average gross or initial deconstruction cost was around $6.20-6.50 per square feet, which was approximately 25% higher average cost than demolition. Disposal costs for deconstruction were on average 15% of the total costs. Asbestos and lead surveys and remediation was an average of $0.97 per square foot for both demolition and deconstruction.

Another study has also shown similar cost benefits of deconstruction although the difference in cost between the two approaches is not consistent. Guy and Gibeau (2003) provided another comparison showing the demolition vs. deconstruction cost to be $5.36 per square feet versus $3.19 per square feet. He argues that even if the realized salvage value is only half of what is estimated to be achieved, the cost comparison will still be in favor of deconstruction: $5.36 for demolition vs. $4.83 for deconstruction.

Deconstruction can be more cost effective than demolition when considering the cost reduction in landfill disposal costs and the revenues from the salvaged material. On average, the initial or gross deconstruction costs are generally higher than gross demolition costs; however, the net cost of deconstruction, after considering the resale and recycling of salvaged materials, is generally lower than demolition (Guy & Gibeau, 2003). It should be noted that the salvage value is highly variable based on the type, condition and value of the salvaged material. Material should be carefully salvaged with minimal damage in order to be reused. Another interesting aspect of deconstruction costs is that many deconstruction operations are run by non-profit organisations. These organizations can factor in a tax-deductible donation benefit to their clients in their deconstruction bids and cost estimates. This is an added benefit to the non-profit approach to deconstruction.

Waste transportation and disposal costs are a significant cost component in demolition projects. The distance to and tipping fees at landfills considerably affect this cost component. In addition, asbestos and lead surveys and remediation is another important cost component to consider. In smaller demolition projects, based on the type of hazardous material, the hazardous material remediation cost is often avoided and the material are disposed in a manner that would not require abatement (Guy & Gibeau, 2003). One such approach is the wet/wet demolition approach where the debris is kept wet from start of the demolition project until they are safely disposed of in landfills. This cost cannot be avoided in the case of deconstruction projects, therefore making this option less cost competitive with demolition in such cases.

## 2.9 Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is a tool used for the quantitative assessment of a material used, energy flows and environmental impacts of products. It is used to assess systematically the impact of each material and process. LCA is a technique for assessing various aspects associated with development of a product and its potential impact throughout a product's life (i.e. cradle to grave) from raw material acquisition, processing, manufacturing, use and finally its disposal (ISO 14040, 1997).

Of all the current models for understanding, assessing, and reducing the environmental consequences of our actions, LCA is perhaps the most useful.

The notion of LCA has been generally accepted within the environmental research community as the only legitimate basis on which to compare alternative materials, components and services and is, therefore, a logical basis on which to formulate building environmental assessment methods (Cole, 1998).

The idea of the life cycle is that all stages in a system (product or service activity) are recognised, from inception to final disposal. A life cycle assessment is made by investigating all the environmental consequences of each stage in the life cycle of the system. Such an assessment can be represented as a two dimensional matrix. Such a matrix offers a good model for the environmental assessment of a system (product, service, building). In order to do more than simply assess the system, to actually understand how the system might be altered to reduce the environmental burden, it is necessary however to add a third dimension (Sharma, et al., 2011). This will be a dimension of strategic solutions, or of principles for sustainable activity. LCA methodological framework comprises of the following four stages:

1. **Goal and scope definition –** establishes the functional unit, system boundaries, and quality criteria for inventory data.
2. **Life cycle inventory analysis –** deals with the collection and synthesis of information on physical material and energy flows in various stages of the products lifecycle (Sharma, et al., 2011).
3. **Life cycle impact assessment –** these environmental impacts of various flows of material and energy are assigned to different environmental impact categories, the characterisation factor is used to calculate the contribution of each of the constituents for different-different environmental indicators (GHG emissions, ozone layer depletion etc.).
4. **Life cycle interpretation –** deals with the interpretation of results from both the life cycle inventory analysis and life cycle impact assessment. It includes the identification of significant issues and the evaluation of results (Sharma, et al., 2011).

### 2.9.1 LCA of Residential Buildings

Adalberth, et al. (2001) performed LCA on four multi-family buildings built in the year 1996 at Sweden. The functional unit was considered as usable floor area ($m^2$) and the lifetime of building was assumed to be 50 years. The main aim was to study different phases of life-cycle of all four buildings and to find out which phase has the highest environmental impact, and were there any differences in environmental impact due to the choice of building construction and framework. The environmental impact was evaluated with an LCA tool developed at Danish Building Research Institute (DBRI) (Peterson, 1997). In this study, the environmental impacts referred to GWP, AP (Acidification Potential), EP (Eutrophication Potential) and human toxicity. Different phases of a building considered were: manufacturing, transport, erection, occupation, renovation, demolition and removal phase. Value of energy consumption was calculated to be 6400 kWh/m2.50yrs. The occupation phase alone accounts for about 70–90% of total environmental impact caused by a building, so it is important to choose such constructions and installations options which have less environmental impact during its occupation phase.

Arpke & Hutzler (2005) used the LCA and LCC (life-cycle cost analysis) techniques to study the use of water in multi-occupant buildings. The selected locations for this study were Boulder, Colombia; Houghton, Michigan; Ames, Iowa and Newark, New Jersey located in US. In this analysis Building for Environment and Economic sustainability (BEES) (Lippiatt, 2000) tool Version 3.0 has been used and it is applicable for both LCA and LCC. This tool was used to study a 25 year operational life cycle for plumbing fixtures and water-consuming appliances for four different multi-occupant buildings: an apartment, a college dormitory, a motel and an office building. The efficient fixtures and appliances should be used rather than conventional fixtures and appliances; and the use of natural gas rather than electricity for water heating should be done because $80,000 have been saved if natural gas is used to heat water as an alternate for electricity (Sharma, et al., 2011).

Norman, et al., 2006 compared high and low populated buildings for their energy use and GHG emissions. It illustrates that the choice of functional unit is highly relevant for full understanding of urban density effects and choose two functional units; living area (per $m^2$ basis) and number of lives in a house (per capita basis). Both the conditions were selected for Toronto (Canada) (Sharma, et al., 2011). The EIO-LCA (Economic Input–Output based LCA) was used to estimate the environmental impacts of material manufacturing required for construction of infrastructure. EIO-LCA is a tool developed by researchers at Carnegie Mellon University (Myer & Chaffee, 1997). For building operations nationally averaged public datasets were utilized and detailed location-specific data for the Greater Toronto area were used for public and private transportation. Energy use and GHG emission estimates for per person-kilometre for different transportation models were taken from previously submitted report by Kennedy (Kennedy, 2002; Sharma, et al., 2011). This study shows that embodied energy and GHG emissions resulting from material production across the supply chain were approximately 1.5 times higher for low-density case study than the high-density case study on per capita basis; and the high-density development scenario becomes 1.25 times more energy and GHG emissions intensive than low-density if considered for unit living area basis. Also the EIO-LCA analysis performed in this study disclosed the fact that the most important construction materials contributing to embodied energy and GHGs for both density cases were brick, windows, drywall and structural concrete used in the buildings (Sharma, et al., 2011). These four materials in combined account for 60–70% of the total embodied energy and production related GHG impacts for both low and high-density case studies.

Guggemos & Horvath, 2005 compared environmental effects of steel and concrete framed buildings using LCA. Two five-storey buildings with floor area of $4400m^2$ were considered which were located in the Midwestern US and were expected to be used for 50 years. In this study two methods, process based LCA and EIO-LCA, were used to evaluate life-cycle environmental effects (LCEE) of each building through different phases: material manufacturing, construction, use, maintenance and demolition phase. The results showed that concrete structural-frame had more associate energy use and emissions due to longer installation process (Sharma, et al., 2011).

Blengini, 2009 performed LCA of building which was demolished in the year 2004 by controlled blasting. The adopted functional unit used in the current case-study was 1$m^2$ net floor area, over a period of one year. This residential building was situated at Turin (Italy). In this study demolition phase and its recycling potential were studied. The life cycle impact assessment (LCIA) phase was initially focused on the characterisation and six energy and environmental indicators were considered, GER (Gross Energy Requirement), GWP, ODP (Ozone Depletion Potential), AP, EP and POCP (Photochemical Ozone Creation Potential). SimaPro 6.0 (The Netherlands: Pre Consultants BV, 2004) and Boustead Model 5 (Boustead, 2004) were used as supporting tools in order to implement the LCA model and carried out the results (Sharma, et al., 2011). The results demonstrated that building waste recycling is not only economically feasible and profitable but also sustainable from the energetic and environmental point of view.

### 2.9.2 LCA of Commercial Buildings

Junnila & Horvath, 2003 studied the significant environmental aspects of a new high-end office building with a life span of over 50 years. In this study functional unit is considered as 1 kW h/$m^2$/year and location of study was at Southern Finland (Northern Europe). The LCA performed here had three main phases – inventory analysis for quantifying emissions and wastes, impact assessment for evaluating the potential environmental effects from the inventory of emissions and wastes, and interpretation for defining the most significant aspects. In this study life cycle of a building was divided into five main phases; building materials manufacturing, construction process, use of the building, maintenance, and demolition (Sharma, et al., 2011). The result shows that the most of the impacts are associated with electricity use and building materials manufacturing. Particularly, electricity used in lighting, HVAC systems, heat conduction through the structures, manufacturing maintenance of steel, concrete and paint, and office waste management were identified as the most significant aspects. GHG emissions were estimated to be 48,000 ton $CO_{2eq}/m^2$.50yr.

Richman, et al., 2009 performed LCA for cold storage buildings in North America. They considered RSI value (R = insulating value) as a functional unit. As energy loss is proportional to 1/R. The models were simulated as if they were located in the cities of Tamp, Florida and Milwaukee, Wisconsin (US). This research basically examined the estimated average roof insulation requirement in modern cold storage buildings. Both environmental and economic aspects were considered (Sharma, et al., 2011). This study shows that there is a need to improve the level of insulation; depending upon the climatic conditions i.e. RSI-8.45 to RSI-9.86 insulation should be used in cold climates and RSI-9.86 to RSI-11.27 insulation should be used in warm climates (Sharma, et al., 2011).

Scheuer, et al., (2003) performed LCA on a 7300m$^2$ six-storey building whose projected life was 75 years at SWH (Sam Wyly Hall). The building is located on the University of Michigan Campus, Ann Arbor, Michigan, US. LCA had been performed in accordance with EPA (Environmental Protection Agency), SETAC (Society for Environmental Toxicity And Chemistry), and ISO standards for LCA (Vigon, et al., 1993; SETAC, 1993; ISO, ISO 14041, 1997). Most of the data was taken from the DEAM™ database (Ecobilan, 2001) and other material production data was taken from two databases by Swiss Agency for the Environment, Forests and Landscape (SAEFL, 1998), SimaPro software (PRe, 2000) and from Franklin Associates Reports (Franklin Associates, 1990). Primary energy consumption, GWP, ODP, NP (Nitrification Potential), AP, and solid waste generation were the impact categories considered in the life cycle environmental impacts from SWH (Sharma, et al., 2011). Computer modelling was done in order to determine the primary energy consumption for heating, cooling, ventilation, lighting and water consumption. The primary energy intensity over the buildings, life cycle was calculated to be 316 GJ/m$^2$ . HVAC and electricity alone accounts for 94.4% of life cycle primary energy consumption. An inventory analysis of three different phases: Material placement, Operations and Demolition phase was done (Sharma, et al., 2011). Results showed that the optimisation of operations phase performance should be primary emphasis for design, as in all measures, operations phase alone accounted for more than 83% of total environmental burdens (Sharma, et al., 2011).

Kofoworola & Gheewala, (2008) conducted an LCA for an office building in Thailand. The building used in this study is a 38 storey building in the central business district of Bangkok and its service life was estimated to be 50 years. The functional unit for this study was considered as 60,000m$^2$ gross floor area of building. This study covered whole life cycle including material production, consumption, construction, occupation, maintenance, demolition and disposal. Inventory data was simulated in an LCA model and environmental impacts for each phase were computed. Main three impact categories considered were; GWP, AP and photo-oxidant potential (POP). Two LCA methodologies were used in the study, i.e. a process-based LCA and the EIO-LCA (Horvath, 2006; Bullard III & Herendeen, 1975; Guinee, 2002; Heijungs & Suh, 2013; Suh & Huppes, 2005; Sharma, et al., 2011), (de Haes, et al., 2008). The results shows that steel and concrete were the most significant materials, both in terms of quantities used and also for their associate environmental impacts at the manufacturing stage. Also the life cycle environmental impacts of commercial buildings are dominated by the operation stage, which accounts 52% of total global warming, 66% of total acidification and 71% of total photo-oxidant formation potential respectively.

Arena & De Rosa, (2003) considered a school building and performed an LCA to compare different building technologies which have been applied in a rural school building for obtaining thermal comfort with minimum fossil energy consumption. This school building is situated in Lavalle, a small town in Northern Mendoza (Argentina). Life span of building was considered to be 50 years. A simplified LCA methodology was used and only construction and operational phases were considered. Environmental impacts which were considered in this study are; GWP, EP, ARP (Acid Rain Potential), PSP (Photo-Smog Potential), resource consumption and TP (Toxicity Potential). For all calculations regarding inventory, impact assessment and normalization phases the SBID (Society of British Interior Design) database was used (Petersen, 1999). The annual energy savings and global energy savings (for 50 years) were calculated and showed that the annual energy savings during use phase were 5307.5 MJ/year, and global energy savings for 50 years life span were 265374.5 MJ/year. This study showed that almost all the environmental aspects investigated were improved when conservative technologies were implemented.

### 2.9.3 Adopted Model for Sustainable Construction

Returning to the two-dimensional model of life cycle assessment, it is now possible to add the third dimension of principles of sustainable architecture. Such a combination has already been investigated by (Kibert, 1994). By combining the two axes of time (Phase) and impact categories (Resources), with the axis of principles, a simple conceptual model is produced. This model then can be graphically represented as three radiating axes (see Figure 2.9).

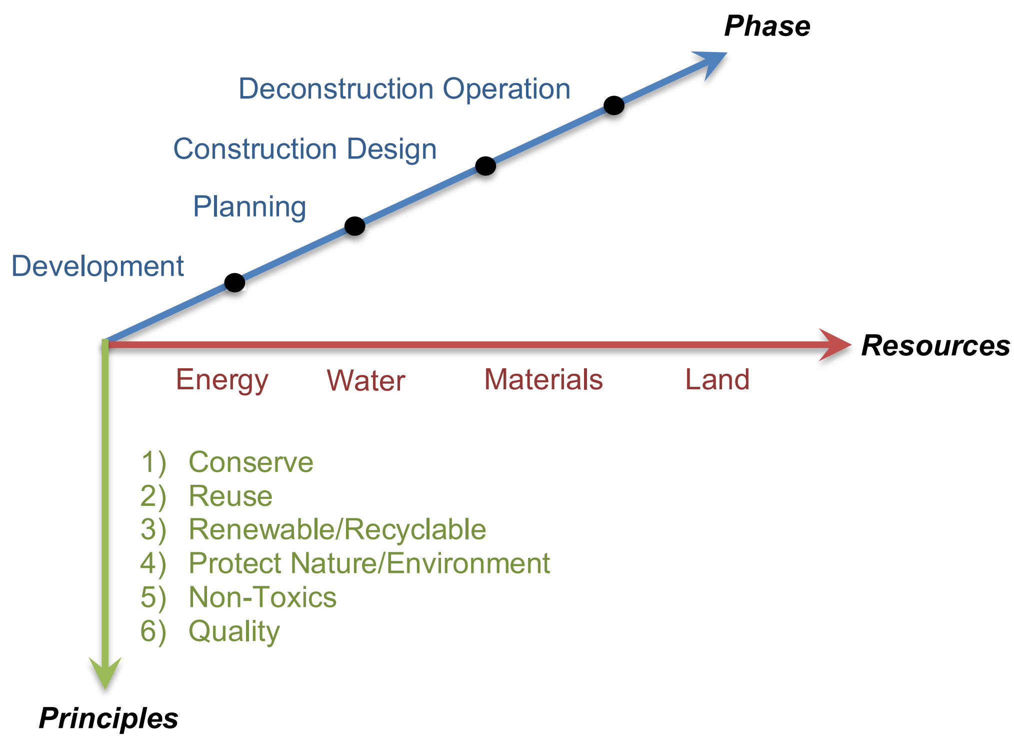


***Figure 2.10 A conceptual model for sustainable construction (Source: modified from Crowther, 2001)***

Using this model, it is possible to place a particular issue within the broader context of sustainable architecture. In this way it is possible to highlight where the issue of design for deconstruction sits within the broader context of sustainable construction. Design for deconstruction deals with the design of a building, for the reuse (in preference to recycling or disposal), of materials. While it might be considered that design for deconstruction is intended to deal with the deconstruction stage of the life cycle, it is a strategy that must be implemented at the design stage, as such it deals with design issues that will have later ramification at the deconstruction stage (Crowther, 2001). It might also be considered that design for deconstruction is an issue relating to the recyclable nature of a building. However, design for deconstruction is an attempt to raise materials and components up the recycling hierarchy, away from recycling, and up to a more environmentally preferable point of reuse. For these reasons design for disassembly is primarily, but not exclusively, an issue of design for the reuse of materials.

In comparing the proposed end-of-life scenarios of the industrial designers with the architects, it can be seen that the subtle differences between product re-use, remanufacture, and repair may not be as relevant to the construction of the built environment as to product manufacturing (see Table 2.10). If the building is considered as a product, then the vagaries of the sub-assemblies may be beyond the direct control and concern of the product (building) designer. It is appropriate then to combine product remanufacture and product repair, since both are concerned with the production of 'new' products. In this way it is possible to consider the technical results of the scenarios as a way of defining them.

***Table 2.10 Levels of Hierarchy of End-of-life Scenarios – Recycling ( modified from Crowther, 2001)***

| **Ref.** | **Young (1998)** | **Ayres & Ayres (1996)** | **Graedel & Allenby (1995)** | **Magrab (1997)** | **Fletcher (2000)** | **Guequi-erre (1999)** | **Kibert & Chini (2000)** | **(Crowther, 2001)** |
|---|---|---|---|---|---|---|---|---|
| Most desirable ↑ | | | | | System level | Repair product | | Reuse building |
| | Reuse | Reuse | | Reuse | Product level | Repair product | Reuse of product | Reuse product |
| | Maintain | Repair | Maintain | Remanu-facture | Product level | Repair product | Reuse of material | Reprocess material |
| **End-of-Life Scenarios** | Remanu-facture | Remanu-facture | Recycle compon-ent | | Product level | Recycle material | | Reprocess material |
| | Recycle | Recycle | Recycle material | Recycle | Material level | | Recycle | Recycle material |
| | | | | | | | Compost | |
| | | | | Burning | | Burning | Burning | |
| ↓ Least desirable | | | | Landfill | | Landfill | Landfill | |

There are four (differently scaled) possible technical results, which have been previously proposed by Crowther (2001):

- the reuse of a whole building;
- the production of a new building;
- the production of new components;
- the production of new materials.

These would relate to the four end-of-life scenarios of:

- building reuse or relocation;
- component reuse or relocation in a new building;
- material reuse in the manufacture of new component;
- material recycling into new materials.

If the strategies of recycling as used in industrial ecology were applied to the built environment, the life cycle stage of demolition could be replaced with a stage of deconstruction. The typical once-through life cycle of materials in the built environment could then be altered to accommodate the possible end-of-life scenarios and produce a range of alternative life cycles (see Figure 2.10).

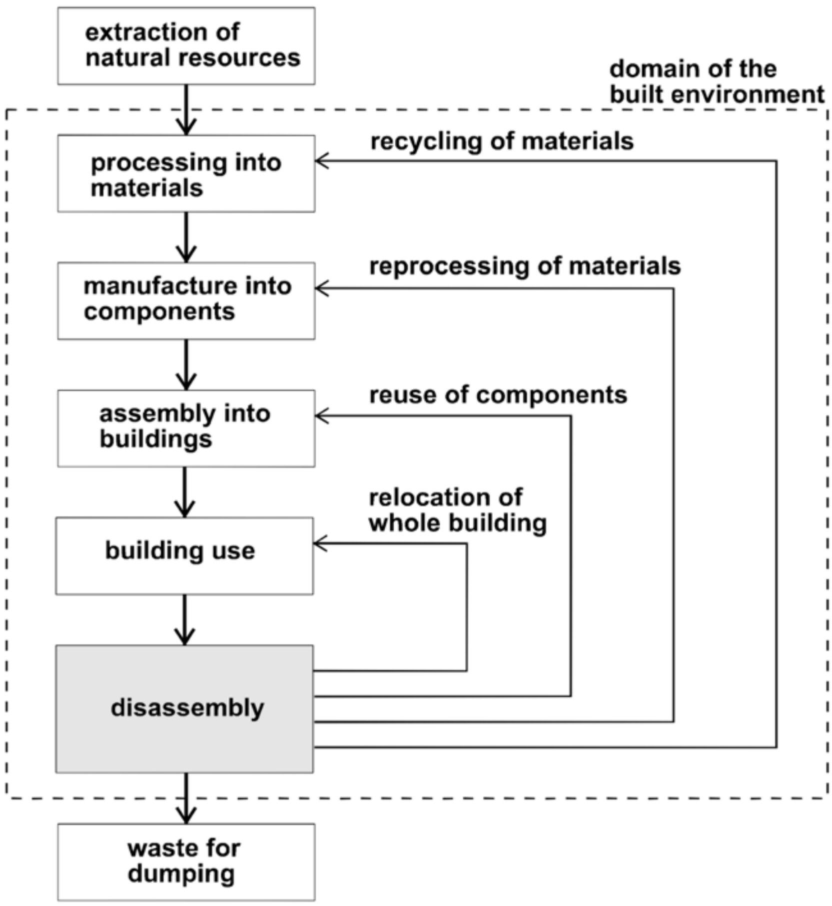


***Figure 2.11 Possible End-of-life Scenarios for the Built Environment (source: Crowther, 2001)***

### 2.9.4 Limitations of LCA Studies as Decision-making Support Tools

It is generally recognised that all the three streams of methods of life cycle studies can be used to evaluate and compare the environmental impacts of building designs. However, there are some drawbacks which are common to the three streams and impair their usefulness as decision making support tools. Broadly speaking, drawbacks can be classified into four major categories according to their boundary scoping, methodology framework, data inventories, and practices (Chau, et al., 2015). Table below shows a summary of limitations for each category for using life cycle studies as decision making support tools.

***Table 2.11 A summary of limitations of LCA studies as decision-making support tools (Source: modified from Chau, et al., 2015)***

| ***Category*** | ***Limitations*** |
|---|---|
| ***Boundary scoping*** | Only focuses on environmental impacts.<br>Some environmental qualities such as indoor air quality are not included.<br>Economic and social dimensions of sustainability are not included.<br>Environmental impacts are assumed to be constant over time.<br>Geographic site specific factors are not included. |
| ***Methodology framework*** | Different tools may include different types of impact categories.<br>Different studies may adopt different normalization factor, grouping or weighting methods.<br>Different studies may have different assumptions on building configurations, climate conditions, etc.<br>Assumptions in studies may lead to uncertainties. |
| ***Data inventories*** | Materials/products from different manufactures cannot be compared.<br>A lack of inventories for new innovative materials.<br>Availability and uncertainty of inventory data can affect results. |
| ***Practices*** | The lack of benchmarks in LCA results.<br>Life cycle evaluations of buildings are more complicated than conventional products.<br>Reluctance to move design timeline.<br>A lack of chain management responsibilities. |

#### 2.9.4.1 Boundary scoping

- As the assessment itself only focuses on environmental impacts, it does not cater for any quality, energetic, structural nor aesthetic requirements (Buyle, et al., 2012).

- Even the focus is often limited to the search for environmental optima, some environmental qualities are still not included in LCA studies. Generally, conventional LCA does not take into account the building related functions in a user perspective, for example building indoor air and thermal comfort were not included (Erlandsson & Borg, 2003; Hauschild, et al., 2009) such that it overlooks important indoor environmental problems such as human health (Jönsson, 2000), occupational health or well-being effect (Verbeeck & Hens, 2010) in building assessment. Failing to include this may result in product or process optimizations at the expense of occupants' or workers' health (Hellweg, et al., 2009) and well-being.
- LCA cannot be fully utilised for catering for sustainability assessments which embrace the environmental, economic and social dimensions. For example it does not consider financial feasibility or life cycle cost, even though some tools like BEES do incorporate the financial considerations into decision making by allowing users to input their own relative importance weightings distinguishing between financial and environmental considerations. Almost all these tools do not take social considerations into account.
- Most LCA studies do not cover time as an important aspect in their analysis by assuming the impacts are constant over time (Erlandsson & Borg, 2003; Jeswani, et al., 2010).
- Most LCA studies do not consider site specificity or differences in geographical site locations (Crawley & Aho, 2010). Factors such as human population density and ecological properties of the environment are generally not included in LCA studies (Guinée, et al., 1996; Heijungs, et al., 1992). It was even found that the life cycle impacts of buildings in southern European countries were smaller than those in middle and north European countries on average. Climatic conditions are one of the reasons accounting for differences in these results (Nemry & Uihlein, 2008). As building development is a site specific process, several local impacts, e.g. building's effect on surrounding microclimate and solar access for adjacent buildings may need to be considered in LCA (Kohler & Moffatt, 2003).

#### 2.9.4.2 Methodology framework

Some drawbacks are inherited by the flexibility in the methodology choices being provided within the LCA framework in complying with the details of each individual step. For example:

- The number and type of impact categories used for categorising the environmental impacts are up to the discretion of users even though it gives user flexibility to decide what consideration that should be accounted for (Erlandsson & Borg, 2003). As a result, different impact categories were used in different LCA software tools. For instance, water extraction is included in ENVEST LCA software but not included in ATHENA.

- Different studies may use different normalisation factors, grouping methods or weighting factors given normalisation, grouping and weighting are optional steps in LCA studies. In consequence, the findings derived from different studies may not be fully comparable and differences may occur for different products.
- Different studies may use different specific properties like layout, climate, comfort requirements, local regulations, etc.
- LCA is merely a model and simplification of reality, so assumptions made will generate uncertainties on different levels: model, scenario and parameter uncertainties. For instance, different studies use different lifespan assumptions (Ibn-Mohammed, et al., 2013; Méquignon, et al., 2013). Parameter uncertainty can be enhanced by data gaps, resulting in less accurate data to be used.

#### 2.9.4.3 Data inventories

Some drawbacks are attributed by the characteristics of data inventories and are listed as follows:

- All the methods developed so far are not primarily targeted at comparing propriety products or products from different manufacturers as the databases employed for these methods are mostly derived from industry-average data (Catarina , 2000; Heinonen & Junnila, 2011; Prusinski, 2006).
- There is always a lack of inventory data for some new innovative materials e.g. phase-change materials, which renders comparisons against conventional materials difficult.
- The availability and quality (precision, completeness, age, geographical and technological properties, representativeness, transparency and uncertainty analysis) of data greatly influence the results of an Life Cycle study (Menzies, et al., 2007).

#### 2.9.4.4 Practices

- Difficulties encountered in carrying out a full LCA of a building as LCA was mainly developed for designing low environmental impact products. Buildings are more complicated than a single conventional product as they have a comparatively long life, they undergo changes often, they have multiple functions, they contain many different components, they are normally unique (Bribián, et al., 2009). The evaluation of buildings also involves many site specific or site-dependent data covering spatial difference (Erlandsson & Borg, 2003).

- The lack of benchmarks may even render regulators difficult to make the LCA mandatory for assessing building designs as they will open to great challenges in courts.
- There is always a reluctance to move design time lines to accommodate the extra time needed for an LCA even though the design may offer clear financial, environmental and even social benefits (Hes, 2007).
- Lack of chain management responsibility can be a basic barrier of LCA and top level management may not have the commitment to LCA (Clark & Leeuw , 1999).

## 2.10 Building Information Modeling (BIM)

This section aims to briefly discuss and highlight the revolutionising impacts of Building Information Modeling (BIM) within the C&D industry. The primary purpose is to determine the importance of BIM within this industry and figure out how the proposed decision-making framework can be successfully integrated into BIM. However, not all the C&D companies have fully adopted BIM. As the purpose of this research is to identify the key decision-making factors in a bid to make a decision of whether to rebuild or re-use, integration of BIM during this process could be helpful in the decision-making of existing building that requires rework and design life estimation for new developments.

### 2.10.1 Background

BIM has evolved from computer-aid design (CAD) research. However, there is still no single, widely- accepted definition for BIM. BIM is defined in different terms from model and design data to construction management. From a three dimensional (3D) perspective, BIM is defined as a conceptual approach to building design and construction that encompasses 3D parametric modelling of building for design and detailing and computer-intelligible exchange of building information between design, construction and other disciplines (Sacks, et al., 2010). BIM is a technology, based on computer-aid design (CAD) that enables better information sharing among construction project stakeholders throughout the project lifecycle. The National Building Information Model Standard Project Committee (NBIMSPC) defines BIM as “a digital representation of physical and functional characteristics of a facility”. Its adoption is a major evolution in the ways in which information on construction projects is generated, shared and managed. BIM brings the potential for widespread efficiencies in project delivery. From a design and project data management standpoint, BIM is a set of interacting policies, processes and technologies that generate a methodology to manage building design and project data in digital format across all life-cycle stages (Penttilä, 2006). In terms of construction management, BIM is an intelligent simulation of architecture to achieve an integrated project delivery (Eastman, et al., 2011). BIM enables the project team to visualise 3D view of a design concept while sharing knowledge and information about a project, forming a reliable basis for decision-making during the project life-cycle. Therefore, in literature, there is general consensus that BIM is a useful tool to identify causes and origins of waste at early stages of a project to effectively identify, evaluate and reduce construction waste generation. However, not many significant researches have been conducted around the globe to identify the current use of BIM and its potential to reduce construction waste, which is also the focus of this research. However, the only difference that this research has from all other researches is the BIM integrated decision-making framework that would let the designers or the contractors to decide the scope of the building before the start of the construction process.

Most of the developed countries have already adopted the BIM integration as the basic requirement for any proposed design to be submitted for approval from the local borough. Singapore is one of the leading example of this. The benefits of design and execution of a project through BIM are listed in the Figure 2.11 below:

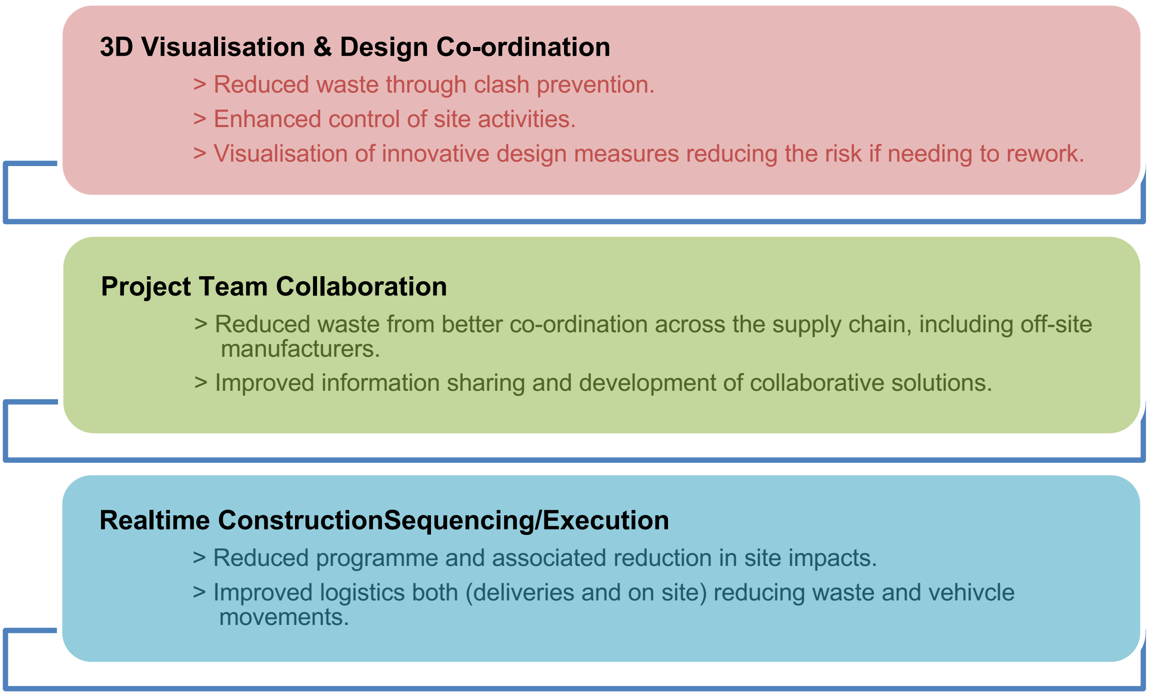


***Figure 2.12 BIM project design and execution benefits (Source: The Author)***

The benefits accruable from BIM have stimulated several nations to set a deadline for its adoption. For example, the UK government has stipulated that from April 2016, all procurement in public sector work must adopt BIM approach. This deadline has forced most companies in the UK to integrate BIM into their activities in order to sustain their competitive advantage. Due to the rise in BIM adoption, the implementation of BIM has experienced diverse innovation especially for building design, cost estimation, 3D coordination, facility maintenance, building performance analysis, etc. In addition, there is progressive improvement on the capabilities of BIM and its integration with technologies such as RFID, GIS, big data, Internet of Things (IoT), and others (Bilal et al., 2016a). Despite the benefits accruable from the use of BIM and the steep rise in the adoption of BIM, the use of BIM for end-of-life scenarios is often neglected (Akinade et al., 2015). This is because most BIM implementations focus on the planning to the maintenance stages of the building and only few works have been done on BIM for end-of-life scenarios.

BIM provides a comprehensive database of project dimensions, specifications and technical information. This presents early opportunities to conduct rapid, analyses of proposed designs offering immediate feedback on proposed alternatives. Such calculations enable the realistic assessment of a project's performance, identifying areas that present potential opportunities to improve resource efficiency which are then fed-back into the design process as a series of actions.

**Material quantity -** Rapid quantification and analysis of design options facilitates the selection of those that meet project requirements with the lowest material demands. Through early analysis, teams can identify more efficient building components to achieve, for example, lightweight structures.

**Material wastage -** The quantity data held within BIM models support more accurate estimations of wastage quantities thereby helping to identify core waste streams and implement effective waste management strategies. BIM data can be combined with waste performance benchmarks to identify priority opportunities to reduce waste generation.

**Embodied carbon -** BIM can be used to conduct sophisticated environmental analyses of project material to estimate the embodied and operational carbon impact of design options.

### 2.10.2 Potential of BIM in Construction Waste Minimisation

WRAP (WRAP, 2013) and O'Reilly (O'Reilly, 2012) argued that CWM could be supported and enhanced through the use of BIM, particularly during the design stages. An increasing body of literature suggested the importance of investigating the impact of adopting information communication-related techniques and tools, such as BIM, to assist in minimising construction waste during building design and construction (Whyte, 2012). Few studies have attempted to investigate the use of BIM to address construction waste generation. These include BIM-enhanced coordination; structural reinforcement of rebar waste reduction (Porwal & Hewage, 2012); material resource efficiency (Whyte, 2012);

demolition waste management (Cheng & Ma, 2013); and on-site waste management improvement.

Additionally, WRAP (WRAP, 2013) developed guidelines in improving and achieving resource efficiency through the implementation of BIM, attempting to align BIM with lifecycle stages of building projects, from concept to handover. However, these guidelines focused on energy efficiency and carbon reduction and gave little consideration to CWM.

There is a lack of decision making tools for CWM during design in the literature (Osmani, 2013). Moreover, the literature revealed that there are no BIM-related tools to support waste minimisation throughout building design stages. This emphasises the need for a comprehensive investigation to explore the potential of BIM to reduce construction waste in building design, which indeed will require a decision-making power based on the key factors in order to address the issue.

### 2.10.3 BIM-Related Software Applications

A wide range of BIM software applications are currently available for various project performance purposes. A vast majority of BIM related packages focused on design and pre-construction stages. There is a consensus in literature that BIM applications in their current use are vastly superior to 2D and 3D CAD-based tools, which do not maintain comprehensive integrity when changes are made. On the other hand, it is widely acknowledged that associating BIM with the development and use of 3D virtual building modeling techniques and technologies can yield very productive results (Liu, et al., 2011). This research project uses Revit (BIM) software package for assessing the life cycle assessment (LCA) of the BIM CAD model.

BIM applications in construction projects are being used for economic assessments (cost estimating and income forecasting) of project substantive feasibility in the preparation stages (Liu, et al., 2011). However, there is a lack of BIM tools to help satisfy the client’s business requirement; identify potential solutions for feasibility studies; and outline project feasibility requirements.

Furthermore, BIM applications are predominantly used for decision-making, and lean or sustainable building construction and performance analysis, such as energy and water analysis are used in pre-construction stages (Liu, et al., 2011).

### 2.10.4 Potential of BIM in Life Cycle Costing

Life Cycle Analysis (LCA) and Life Cycle Costing (LCC) are among the most-used methodologies by the international community to assess the environmental and economic impacts of a product (Santos, Costa, Silvestre, & Pyl, 2019). Whereas LCA is used as an assessment methodology that quantifies the environmental impacts of a building's life cycle, LCC is an economic evaluation methodology that predicts the full life cycle cost of a project, including the acquisition, design, construction, operation, maintenance, and disposal phase costs.

There are three main approaches for BIM integration with LCA and LCC. The first two resort to multiple software for both analyses or export the bill of quantities from a BIM model and use it with external databases. Wang, et al. (2011) were among the first ones to use the first approach. The authors explored the BIM-LCA potential to evaluate the environmental impact of a building. Ultimately, the authors identified the most sustainable solutions (e.g. materials and building orientation) by using Ecotect.

Studies that use the second approach are more recent, mostly owing to the advances in the BIM technology and the market demand for more automatic analysis (Santos, Costa, Silvestre, & Pyl, 2019). In another study, the authors used an integrated three-module framework (BIM, LCA, and a certification and cost module) to obtain the environmental impact of a building (Jrade & Jalaei, 2013; Santos, Costa, Silvestre, & Pyl, 2019). The BIM model was used to generate and export a quantity take-off that connects with an external database developed by the authors, and contains environmental data (from Athena Impact estimator tool), cost data, and potential leadership in energy and environmental design (LEED) points for building components. The authors also highlighted that designers will not be able to quantify the environmental impacts of materials to support the decisions needed to design sustainable buildings due to the following reasons: (1) a lack of information about the sustainable materials that are stored in the database, (2) a lack of interoperability between the design and analysis tools that enable full life cycle assessments (LCAs) of buildings (Jrade & Jalaei, 2013).

Despite of the significant development of the field of BIM integration with LCA/LCC, current studies and approaches still have a few limitations. The limitations of the first approach are more obvious, as interoperability issues arise among the different programs, license costs, and time spent in each program, and from the propensity for human error (Santos, Costa, Silvestre, & Pyl, 2019). Although more advantageous, the second approach is dependent on the flexibility of the database itself (i.e. the possibility to include/edit information). The type of LCA data (specific, average, or generic) has a great impact on how representative the results can be. This means that not only should the analysis take into consideration the materials' quantity, but also their type (brand), as products from different manufacturers can have very distinct environmental and economic impacts (Santos, Costa, Silvestre, & Pyl, 2019). Another limitation is that all LCA and LCC data is not stored in the BIM model, which should serve as a centralised data repository.

### 2.10.5 Potential of BIM in Whole Life Costing

Several BIM software solutions have been developed with the aim of calculating Whole Life Cost (WLC), but none of them offers a complete solution (Zanni, Sharpe, Lammers, Arnold, & Pickard, 2019). One reason for this is that data exists in varying formats with different owners. Thus, there is the need to bring together different approaches into a standardized framework that utilizes the existing technological enablers by establishing links between them. More importantly, it is essential to specify information requirements and exchange procedures (Zanni, Sharpe, Lammers, Arnold, & Pickard, 2019). It has been argued that the most common barrier to achieving design intent is the absence of comprehensive information during design and construction stages, leading to poor decision-making, which impacts on performance and WLC.

Zanni et al. (2019) demonstrated how cost information related to maintenance and actual performance of completed buildings can be incorporated during design processes in order to make decisions that are critical for the timely assessment of WLC. It was proposed by Zanni et al. (2019) that BIM can provide a more integrated and rigorous vehicle for assessing viability of BTR schemes, while maintaining high performance standards for quality, thus offering a competitive approach through improved customer service.

Furthermore, Building Information Modelling (BIM) has the potential to facilitate a more comprehensive and accurate design approach from the early stages. A detailed and accurate model can allow designers and clients to understand the wider impacts of design changes, and to track this information through construction stages. However, dependencies between design decisions and WLC have yet to be understood (Zanni, et al., 2019). The concepts of WLC and its implementation into BIM has been valuable in terms of cost savings at early design stages of the project. However, with further research on this subject of Whole Life Costing (WLC), many more and new techniques and plug-in tools are expected to be introduced.

## 2.11 Highways and Pavements

Highway pavements are one of the sources of waste materials as road pavements need to be refurbished or recycled at the end of their design life, which is normally 40 years for both flexible and rigid pavements (Ali, 2016).

It is a normal practice to recycle the bound layer of an old pavement and use them as subbase for new roads. But sometimes, these bound layers material can be mixed with fresh materials and fresh binders and laid on the same road in what is called cold in-place recycling and hot in-place recycling or off-site recycling (Ali, 2016). Recycled materials from demolished buildings and other structures can also be used in the foundation layers of the new roads.

Maintenance and repair of flexible pavements can take a number of basic forms and still other variants on those basic themes. This section is intended as an overview of the techniques that are more typically used in highway repairs. The surveyor/highway inspection team will detect a recurring theme – the more early and often pavement preservation and maintenance techniques are applied, the lower the life cycle costs for a given pavement section will be and roadway users will be happier because of it. These brief descriptions are intended only to raise awareness for those not immersed in the transportation field; a plethora of information is available from Internet sites for Federal Highway Administration, state departments of transportation, research universities, and professional organisations that are specialised in these transportation areas.

### 2.11.1 Flexible Pavement

A typical flexible pavement consists of a bituminous surface course or surface layer over base course and sub-base course (see Figure 2.12). The surface course may consist of one or more bituminous or hot mix asphalt (HMA) layers. These pavements have negligible flexure strength and hence undergo deformation under the action of loads (Mahajan, 2020). The structural capacity of flexible pavements is attained by the combined action of the different layers of the pavement. The load from trucks is directly applied on the wearing course, and it gets dispersed (in the form of a truncated cone) with depth in the base, sub base, and subgrade courses, and then ultimately to the ground. Since the stress induced by traffic loading is highest at the top, the surface layer has maximum stiffness (measured by resilient modulus) and contributes the most to pavement strength.

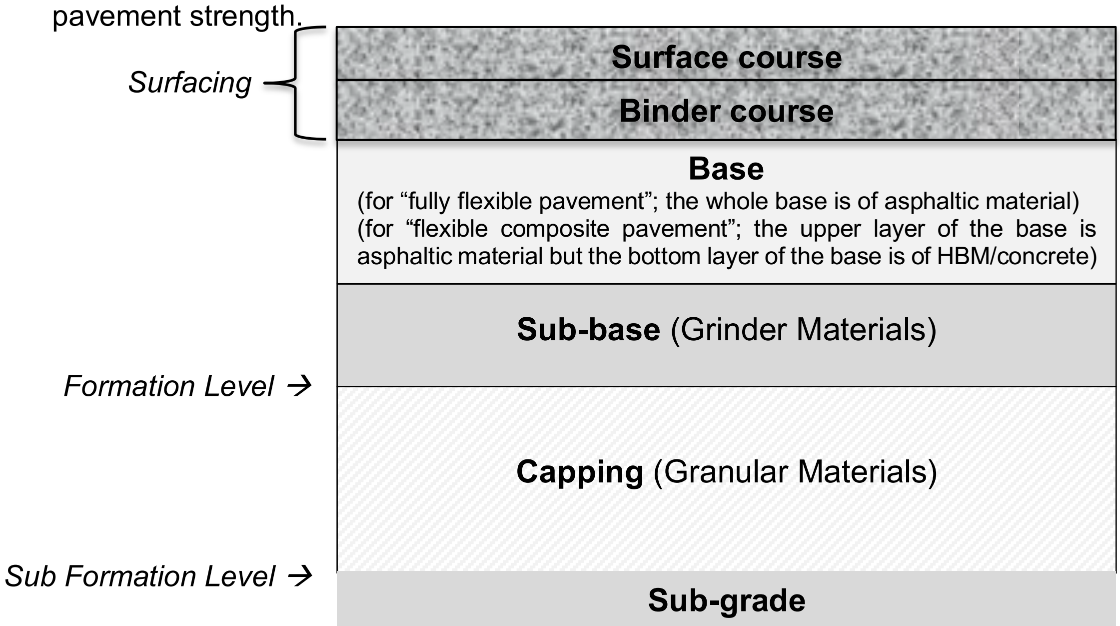


***Figure 2.13 Cross-section of flexible pavement (Source: modified from Ali, 2016)***

The layers below have lesser stiffness but are equally important in the pavement composition. The subgrade layer is responsible for transferring the load from the above layers to the ground (Mathew, 2015). Flexible pavements are designed in such a way that the load that reaches the subgrade does not exceed the bearing capacity of the subgrade soil. Consequently, the thicknesses of the layers above the subgrade vary depending upon strength of soil affecting the cost of a pavement to be constructed.

#### 2.11.1.1 Maintenance and rehabilitation of flexible pavements

The maintenance and rehabilitation of flexible pavements involves a range of activities which may be categorised as:

- routine maintenance;
- periodic maintenance;
- rehabilitation.

**Routine maintenance –** is concerned with minor activities required to slow down or prevent deterioration of a road pavement. It tends to be preventive as well as corrective and includes such activities as (Mahajan, 2020):

- crack-sealing;
- pothole repair;
- minor correction of surface texture deficiencies;
- minor shape correction.

**Periodic maintenance –** primarily involves preservation of the asset using thin surfacing to restore texture or ride quality, protect the surface against entry of moisture, or prevent deterioration through raveling and weathering.

**Rehabilitation –** includes major work carried out to restore structural service levels. As such, the treatments are corrective in nature and include:

- non-structural overlays;
- structural asphalt overlays;
- reconstruction or recycling of pavement materials, etc.

#### 2.11.1.2 Pavement failures

In the case of most structures, failure hardly needs defining – it happens suddenly, it is very obvious, and it marks the end of the structure's useful life (Mathew, 2015).

Consider a suspended concrete slab. Simply support this at each end and then apply an increasing load at the centre (Mathew, 2015). Eventually the concrete snaps and we have a "catastrophic" failure.

Whilst some pavement failures happen suddenly, in most situations a pavement gradually deteriorates. Perhaps a more typical example is a barge board on a house. If the board is left unpainted, gradually the paint deteriorates and cracks to the extent that it has to be scraped back and repainted. If the board is further left unattended, the board will eventually rot away and will be difficult and expensive to replace, in that some other components will also have to be removed and replaced.

The term "pavement failure" is used when the deterioration of a section of pavement reduces its serviceability and/or future usefulness, such that appropriate remedial action is necessary. Most primary failures result from weakness at one of three points in a pavement. The flexible pavement fails in two modes:

1. **Deformation –** This is the predominant mode of failure of flexible pavement. It is a structural failure and is mainly due to the subgrade rutting (deformation), which will cause all the pavement layers to deform.
2. **Fatigue cracking –** This is the second mode of failure of flexible pavement, which normally takes place due to fatigue cracking that starts at the bottom of the bound/base layer as a result of tensile forces acting at that location.

However, some layers of the pavement may fail due to various reasons including severe defects, traffic and temperature loading, hydraulics and chemical attacks, ageing and environmental effects. Examples of these are listed below:

**a) Surface Failures –** Potholes, ageing, etc., which are generally shown by sharp edges or firm pavement without general distortion.

**b) Base Failures –** Insufficient strength caused by bad design, overloading, or material change due to moisture or weathering. This failure is characterised by plastic deformation of the pavement. In advanced stages it may also be accompanied by crocodile cracking, followed by leaching of fine materials as deterioration increases.

**c) Bond Failures –** Normally occur between bitumen bound layers, between bound layers or between a bitumen bound layer and the base course.

#### 2.11.1.3 Identification of defects and treatments

Below are some of the most common and experienced types of failures that are found in flexible pavements:

- **Alligator cracking –** Alligator cracking is a load associated structural failure. The failure can be due to weakness in the surface, base or sub grade; a surface or base that is too thin; poor drainage or the combination of all three. It often starts in the wheel path as longitudinal cracking and ends up as alligator cracking after severe distress.

*Figure 2.14 Alligator cracking (Source: Mathew, 2015)*

- **Treatment:** Because a structural failure is taking place, the only possible solution to alligator cracking is to perform a full-depth patch.
- **Block cracking –** Block cracks look like large interconnected rectangles (roughly). Block cracking is not load-associated, but generally caused by shrinkage of the asphalt pavement due to an inability of asphalt binder to expand and contract with temperature cycles. This can be because the mix was mixed and placed too dry; Fine aggregate mix with low penetration asphalt & absorptive aggregates; poor choice of asphalt binder in the mix design; or aging dried out asphalt.

*Figure 2.15 Block cracking (Source: Mathew, 2015)*

- **Treatment:** Less severe cracks can be sealed to prevent moisture from entering into the sub grade. More severe cracks should be fixed by removing the cracked pavement layer and replacing it with an overlay.

- **Edge cracks –** Edge Cracks travel along the inside edge of a pavement surface within one or two feet. The most common cause for this type of crack is poor drainage conditions and lack of support at the pavement edge. As a result underlying base materials settle and become weakened. Heavy vegetation along the pavement edge and heavy traffic can also be the instigator of edge cracking.

***Figure 2.16 Edge cracks (Source: Mathew, 2015)***

- **Treatment:** The initial treatment to this defect is to remove any existing vegetation close to the edge of the pavement and fix any drainage problems. Crack seal/fill the cracks to prevent further deterioration or remove and reconstruct to full depth fixing any support issues.

- **Potholes –** Small, bowl-shaped depressions in the pavement surface that penetrate all the way through the asphalt layer down to the base course. They generally have sharp edges and vertical sides near the top of the hole. Potholes are the result of moisture infiltration and usually the end result of untreated alligator cracking (Neal, 2013). As alligator cracking becomes severe, the interconnected cracks create small chunks of pavement, which can be dislodged as vehicles drive over them. The remaining hole after the pavement chunk is dislodged is called a pothole.

*Figure 2.17 Potholes (Source: Neal, 2013)*

- **Treatment:** Full depth replacement patch.
- **Rutting –** Ruts in asphalt pavements are channelised depressions in the wheel-tracks. Rutting results from consolidation or lateral movement of any of the pavement layers or the subgrade under traffic. It is caused by insufficient pavement thickness; lack of compaction of the asphalt, stone base or soil; weak asphalt mixes; or moisture infiltration (Neal, 2013).

*Figure 2.18 Rutting (Source: Neal, 2013)*

- **Treatment:** If rutting is minor or if it has stabilised, the depressions can be filled and overlaid. If the deformations are severe, the rutted area should be removed and replaced with suitable material.
- **Shoving –** Shoving is the formation of ripples across a pavement. This characteristic shape is why this type of distress is sometimes called wash-boarding. Shoving occurs at locations having severe horizontal stresses, such as intersections. It is typically caused by: excess asphalt; too much fine aggregate; rounded aggregate; too soft an asphalt; or a weak granular base.

*Figure 2.19 Shoving (Source: Neal, 2013)*

- **Treatment:** Partial or full depth patch.

### 2.11.2 Pavement Recycling

Recycling or reuse of pavement material is a very simple but powerful concept. Recycling of existing pavement materials leads to new pavement materials that considerable saving material, money, and energy (Costel & Plescan, 2015). At the same time, recycling of existing material also helps to solve disposal problems. Because of the reuse of existing material, pavement geometrics and thickness can also be maintained during construction (Federal Highway Administration, 1997). In some cases, traffic description is less than that for other rehabilitation techniques. The specific benefits of recycling can be summarised as follows:

- reduced costs of construction;
- conservation of aggregate and binders;
- preservation of the existing pavement geometrics;
- preservation of the environment;
- conservation of energy;
- less user delay.

#### 2.11.2.1 Recycling as a rehabilitation alternative

Recycling is only one of the several rehabilitation alternatives available for asphalt pavements. The choice of rehabilitation alternative depends on observed pavement distress, laboratory and field evaluation of existing material, and design parameters (Costel & Plescan, 2015). Also, maintenance of geometrics and original thickness of pavements, especially in underpasses, influence the choice of rehabilitation method. However, recycling has some unique advantages which are not available with other types of rehabilitation techniques (Costel & Plescan, 2015). For example, recycling can result in savings, help in conservation of natural resources, and can maintain pavement geometrics as well as thickness.

According to Costel and Plescan (2015), studies have indicated that if a highway is maintained at an acceptable level of service, it will ultimately cost less in a longer run and will not need to be demolished and rebuild from the subgrade soil. Different recycling methods are now available to address specific pavement distress and structural needs. All pavements deteriorate over time due to traffic and environmental factors and thus rehabilitation is needed in order to maintain the pavement at an accepted level.

#### 2.11.2.2 Approved methods for flexible pavement recycling

The need to minimise use of scarce primary resources is becoming ever more urgent in most industries as humanity relentlessly exhausts this planet's ability to satisfy its demands and carelessly discards waste to the detriment of the environment. The roads industry is no exception to this. In the UK, for example, roads consume some 25% of all materials extracted from the ground (Thom & Dawson, 2019) and, while most of these sources are not in immediate danger of becoming exhausted, the impact on the environment is substantial.

Furthermore, the cost of road materials delivered to a construction site comprises two parts: The cost of the raw material at the quarry or gravel pit; and transport costs, both financial and environmental, which are frequently the higher of the two. Locally-available materials are obviously to be preferred. To this must be added the fact that if in situ recycling can be achieved, there are substantial time savings, beneficial for both the road authority and the user. Thus, the drivers are strong, both economic and environmental, in support of recycling and/or the use of locally-available materials.

Following are the methods for pavement recycling:

a) **Hot mix asphalt recycling –** It is the process in which reclaimed asphalt pavement materials are combined with new materials, sometimes along with a recycling agent, to produce hot mix asphalt (HMA) mixtures. Both batch and drum type hot mix plants are used to produce recycled mix. The reclaimed asphalt pavement material can be obtained by milling or ripping and crushing operation. The mix placement and compaction equipment and procedures are the same as for regular HMA (Wells, 2018).

*Figure 2.20 Hot mix asphalt recycling (Source: Wells, 2018)*

b) **Hot in-place recycling –** This consists of a method in which the existing pavement is heated and softened, and then scarified/milled to a specified depth.


*Figure 2.21 Hot in-place recycling (Source: Davis, 2018)*

c) **Cold in-place recycling –** This involves reuse of the existing pavement material without the application of heat. Except for any recycling agent, no transportation of materials is usually required, and aggregate can be added, therefore hauling cost is very low. Normally, an asphalt emulsion is added as a recycling agent or binder (Construction Equipment Guide, 2014).


***Figure 2.22 Cold in-place recycling (Source: Construction Equipment Guide, 2014)***

d) **Full depth recycling –** This has been defined as a recycling method where all of the asphalt pavement section and a predetermined amount of underlying base material are treated to produce a stabilised base course. It is basically a cold mix recycling process in which different types of additives such as asphalt emulsions and chemical agents such as calcium chloride, cement, fly ash, and lime, are added to obtain an improved base (Mallick & Veeraragavan, 2017).

***Figure 2.23 Full depth recycling (Source: Mallick & Veeraragavan, 2017)***

### 2.11.3 Rigid Pavement

Rigid pavements are named so because of the high flexural rigidity of the concrete slab and hence the pavement structure deflects very little under loading due to the high modulus of elasticity of their surface course. The concrete slab is capable of distributing the traffic load into a large area with small depth which minimises the need for a number of layers to help reduce the stress. The most common type of rigid pavement consists of dowel bars and tie bars. Dowel bars are short steel bars that provide a mechanical connection between slabs without restricting horizontal joint movement. Tie bars on the other hand, are either deformed steel bars or connectors used to hold the faces of abutting slabs in contact. Although they may provide some minimal amount of load transfer, they are not designed to act as load transfer devices and are simply used to 'tie' the two concrete slabs together.

Rigid pavements have a relatively long service life if they are properly designed, constructed and maintained. These pavements can serve up to its design service life and even beyond if timely repairs and rehabilitation are undertaken (Seehra, 2019). All types of pavements deteriorate with time, however, the rate of deterioration is comparatively much slower in rigid pavements than in flexible pavements. There are three types of rigid pavements:

1. Fully rigid pavement.

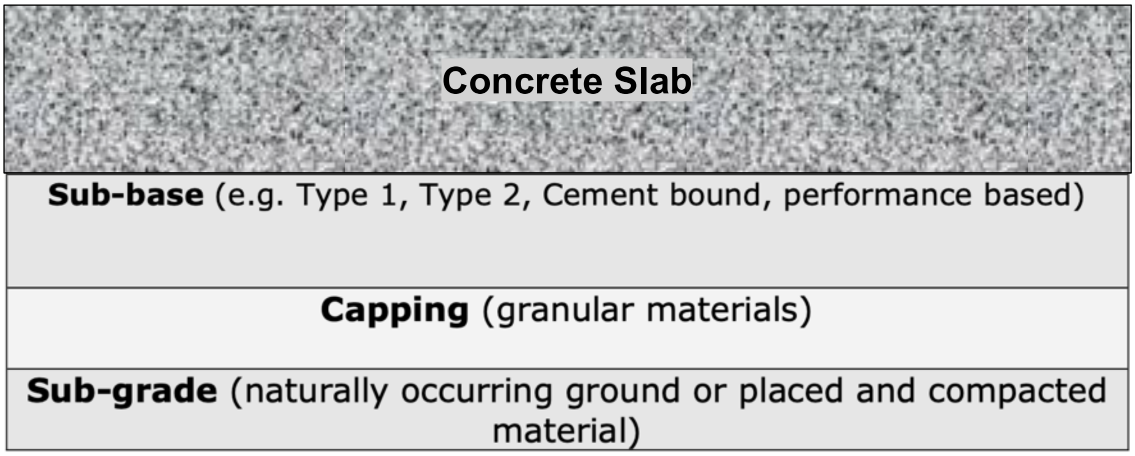


***Figure 2.24 Cross-section of rigid pavement (Source: Ali, 2016)***

2. Continuously reinforced concrete base (CRCB) rigid pavement.

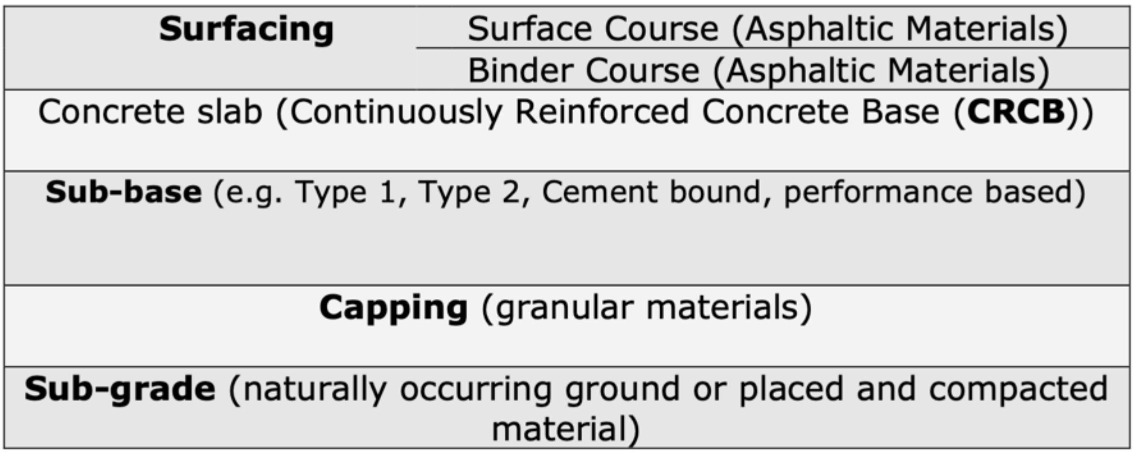


***Figure 2.25 Cross-section of CRCB rigid pavement (Source: Ali, 2016)***

3. Continuously reinforced concrete pavement.

| |
|---|
| **Surfacing** (Thin Surfacing Course System (TSCS)) |
| Concrete slab (Continuously Reinforced Concrete Pavement (**CRCP**)) |
| **Sub-base** (e.g. Type 1, Type 2, Cement bound, performance based) |
| **Capping** (granular materials) |
| **Sub-grade** (naturally occurring ground or placed and compacted material) |

***Figure 2.26 Cross-section of CRCP rigid pavement (Source: Ali, 2016)***

#### 2.11.3.1 Maintenance and rehabilitation of rigid pavements

Rigid Pavement Maintenance is more than just a collective set of specific pavement maintenance techniques. It is a way of thinking and the guiding force behind an agency's financial planning and proper asset management (Mahajan, 2020). Pavement management must be tailored to each road agency's system to meet the need of various pavement distresses in the most cost-effective manner (Seehra, 2019). This involves using a variety of treatments and pavement repairs to extend the rigid pavement's life.

Most of the pavement designs involve two or more performance periods. A pavement is constructed at an initial serviceability level and is rehabilitated to an acceptable level at some time during its design life (Seehra, 2019). This process of rehabilitation may be repeated several times depending on the condition of the existing rigid pavement, from time to time (Mahajan, 2020).

**Routine maintenance –** It is concerned with minor activities required to slow down or prevent deterioration. It tends to be preventive as well as corrective and includes such activities as:

- crack-sealing;
- minor correction of surface texture deficiencies;
- minor shape correction.

#### 2.11.3.2 Modes of failure of rigid pavements

Rigid pavement usually fails in two main modes:

i. **Fatigue cracking –** This is the predominant mode of failure of rigid pavement when the concrete slab cracks due to excessive traffic and temperature loading and lack of support from the foundation layers.
ii. **Differential settlement or erosion –** This may happen when the subbase materials are eroded due to presence of water and the deflection of the slab. It may also happen due to differential settlement in the foundation.

#### 2.11.3.3 Rigid pavement defects, identifications and treatments

Below are some of the most common and experienced types of failures that are found in rigid pavements:

- **Joint cracks –** These are cracks in an asphalt overlay of a rigid pavement (i.e., asphalt over concrete). They occur directly over the underlying rigid pavement joints (Neal, 2013). Joint reflection cracking does not include reflection cracks that occur away from an underlying joint or from any other type of base (e.g., cement or lime stabilised).

***Figure 2.27 Joint cracks (Source: Neal, 2013)***

- **Treatment:** For less severe cracks, crack sealing will prevent the further entry of moisture into the subgrade. If the cracks are more severe the removal of the cracked pavement layer followed by an overlay may be required.
- **Longitudinal cracks –** Longitudinal cracks are cracks that are approximately parallel to the centerline of the roadway. Such cracks are generally straight, but in some instances they may be curved. In severe cases, the pavement may also be faulted on one side of the crack.

***Figure 2.28 Longitudinal cracks (Source: Jung, et al., 2008)***

- **Treatment:** Crack sealing prevents water intrusion into the cracks and the development of secondary deterioration, so all cracks should be sealed on a routine basis. If the cracks are narrow and inactive, sealing may be all that is required. Another repair method for this type of defect is a full depth repair. This treatment reinstates the structural integrity of the pavement (Jung, et al., 2008). This repair is feasible for active longitudinal cracks and for repairing localised structural problems.

- **Spalling –** Crack spalling is the loss of concrete around an existing transverse crack. The depth of the spall is frequently around 1 inch. and typically extends 6 to 12 inches. from the existing crack (Jung, et al., 2008). Spalling may occur along the whole length or only a portion of the length of the crack and may occur on either side of a crack. Spalling is a problem in several areas of England and Wales, causing substantial reduction in the ride quality of the pavement, and can cause accelerated structural failure of the slab.

***Figure 2.29 Spalling (Source: Jung, et al., 2008)***

- **Treatment:** Full depth repair reinstates the structural integrity of the pavement. This repair is feasible for deep spalling, which is greater than 1/3 the thickness of the slab (Jung, et al., 2008).

## 2.12 Summary of the Chapter

In summary, it has been concluded that current practices on the utilisation and reduction of waste needs to be accelerated, as this is a vast subject with many core elements that have inter relation with each other. A solution to all these ongoing issues is to have a well-informed decision based criteria/factors that should led to the decision of whether to refurbish/re-use or rebuild/recycle. This criteria should be applicable in all scenarios related to construction and demolition (C&D). Having discussed about the current codes of British Standards (BS), the key factors should work in close relativity and compliance in accordance with the relevant BS Standards, that include BS 15686-1 (BS ISO 15686-1, 2000), BS 15686-2 (BS ISO 15686-2, 2001) and BS 7543 (British Standard BS 7543, 2003). In terms of waste production during the construction, demolition and maintenance of highways, this could be used in buildings where applicable and vice versa. However, a suitable and appropriate methodology is required to bridge this gap between the highways and buildings waste, as there are many other aspects to consider too in both sectors that would require close compatibility with each other. A detailed framework has been proposed in Chapter Five, which illustrates a bridge between these two sectors, having some similar factors as of key decision-making criteria for rebuild or re-use. Following the investigation of the project related case studies, below are the considerations for the key factors that have been found to have the potential for the decision-making on whether to refurbish/re-use or rebuild/recycle. Further evaluations are discussed in Chapter Four and Five. Taking account of all the data and statistics that are reported in this chapter, following initial factors have been found so far to have the potential for reducing waste:

### 2.12.1 Building Re-use

The first factor is that of relocation or reuse of an entire building. This may occur where a building is needed for a limited time period but can later be reused elsewhere for the same or similar purpose. A good example of this is the Crystal Palace of 1851. This modular exhibition building designed by Joseph Paxton was based on a simple system of prefabricated structural and cladding units that could be easily joined together. These factory produced elements allowed for the quick assembly and disassembly of the building, and its eventual relocation and reuse after the exhibition (Peters, 1996).

### 2.12.2 Component Re-use

The second factor is the re-use of components in a new building or elsewhere on the same building. This may include components such as cladding element or internal fit-out elements that are of a standard design. The cladding of this building consists of panels that are interchangeable and can be easily moved by just two people. This allows the buildings cladding to be altered to suit changes in the internal use of the building. It is also possible for these components to be used on other buildings of the same design (Bryden, 1993). This factor saves on resources, waste disposal, and energy use during material processing as well as energy use during component manufacture and transport.

### 2.12.3 Material Re-use

The third factor, that of reprocessing of materials into new components, will involve materials or products still in good condition being used in the manufacture of new building components. A good example of this is the re-milling of timber. In most parts of the world that use timber as a building materials there is a strong vernacular tradition of constructing buildings so that members may be removed and reused or re-processed into smaller members. Even till today, the re-use of timber has been in the same way. As well as the waste disposal advantages of the recycling scenario, this reprocessing also reduces the energy required for material processing.

### 2.12.4 Material Recycling

The final factor, recycling of resources to make new materials, will involve used materials being used as a substitute for natural resources in the production of manufactured materials. One of the most common current examples of this is the crushing of reinforced concrete to make aggregate that is used for road base. While this scenario does reduce the solid waste stream, other environmental issues may actually not be so positive. While the natural resource use and waste disposal problems are alleviated, the total energy use, and the resultant pollution, may actually be greater than if new resources were used.

# Chapter 3. **Methodology**

## 3.1 Chapter Overview

In this chapter, epistemological assumptions underpinning the whole study as well as the methodological approaches adopted in undertaking the study are presented. The chapter explicates various interrelated elements of the study in a manner that portrays their sequence. Possible strategies and methods to the study were identified and evaluated, and justifications for preferring one approach to others were made. The chapter addresses three major elements which are theoretical assumptions underpinning the study, strategy of enquiry and the research design.

The methodological and epistemological assumptions, which cover the research philosophy and research strategies, are addressed in the first two sections. The strengths and weaknesses of each philosophical school of thoughts were evaluated, with respect to the focus of the study to theorise the study within suitable worldview and epistemological perspectives. This was then followed by a critical evaluation of research strategies, otherwise known as research methodologies, to determine which and which congruent with the focus of the study. Suitability of the research strategies for this study was analysed and justified in favour and against each of them preceded selection and explanation of appropriate methodological viewpoint.

Further in the chapter, different research design approaches, in terms of qualitative, quantitative and mixed method designs, were presented in a bid to develop an appropriate design for the study. After a critical analysis, a qualitative method of data collection and analysis is deemed suitable for the study. After this, discussion of the following is presented: rationale for research approach, description of research sample, details of the research design, data collection and analysis methods, ethical considerations, and issues of data validity and reliability. On adopting and justifying the need for exploratory sequential mixed design method, a brief summary concludes the chapter.

## 3.2 Research Paradigms

A paradigm consists of the following components: ontology, epistemology, methodology, and methods (Scotland, 2012). Each component is explained, and then the relationships between them are explored. Research paradigms or theoretical perspective is an important phenomenon that shapes the way research is formulated and implemented (Mackenzie and Knipe, 2006). Kuhn, (1962) defines paradigm as the assumptions and intellectual structure that underlie research and development in a field of enquiry. Just like structural elements to buildings, paradigm determines the integrity of a research activity (Fellows and Liu, 2008). Although scholars separated research methods from paradigms, it still holds that modes of data collection, data analysis, the relationship between researchers and the researched, among others, are largely influenced by the research paradigms (Crotty, 1998; Creswell, 2009). As such, it is important that matters of paradigms are resolved at the inception of a research project. By doing this, the expected relationship would be established between the researchers and the participants, with an appropriate mode selected for data sampling, data collection and data analysis. According to Guba (1990), research paradigm encompasses matter of ontology, epistemology and methodology. This section evaluates various aspects of research paradigms in a bid to view the study with right lenses. It addresses matters of ontology, epistemology, research philosophy as well as the logic of reasoning.

### 3.2.1 Ontological Assumption of the Study

Ontologies are the foundation on which knowledge-intensive problem solvers depend. Ontologies encapsulate domain concepts, tasks, problem-solving knowledge, and methods (Ugwu, et al., 2005). After nearly a decade in which statistical techniques made “ontology” a bad word in various computational communities, there are encouraging signs that the pendulum is swinging back (Hovy, 2005). But ontologies will be most readily accepted by their traditional critics only if at least two conditions are met: good methodologies for building and evaluating them are developed, and ontologies prove their utility in real applications (Hovy, 2005).

Crotty (1998) described ontology as the study of being, while Blaikie (2007) provides a more encompassing explanation, suggesting that ontological claims are ‘claims and assumptions that are made about the nature of social reality, claims about what exists, what it looks like, what units make it up and how these units interact with each other'. He further emphasised that ‘ontological assumptions are concerned with what we believe constitutes social reality'. It is a science of being, that reflects how an individual interprets what constitute a fact, and it essentially addresses whether an entity is perceived as being real or relative.

Generally, researchers in the field of ontology and knowledge engineering often begin an ontology creation effort by asking the question “what is the ontology of X?” where X is some type of entity or process in a domain of interest. Such a probing question often leads to two broad levels of ontology. The first level identifies the basic conceptualisations that are required to talk about X. The second level identifies the different types of basic concepts in X, and relates the resulting typology to any additional constraints identified in the first level (Ugwu, et al., 2005). For example, in the steel structures domain, the first level ontology would include things like columns, beams, rafters, bracings, purlins, roof, foundation, etc., while the second level would include things like: simply supported beams, fixed beams, pinned columns, fixed columns, etc.

The second level can be incrementally improved as knowledge of the domain improves and more object types are identified. Ontologies can also be task-dependent. This means that while it is essential that things that exist in the domain be independent of the uses to which the knowledge will be put, at the same time tasks that the ontology is being written for drive the level of details to be identified in the domain (Ugwu, et al., 2005). Thus, an ontology for constructability assessment would be constructed to incorporate objects that relate to constructability issues, which are perceived as significant constructability factors (such as foundations and column bases, connections and bolts, etc.). Ugwu, et al. (2005) generated framework (abstract layer) for ontology design and classification (see Figure 3.1).

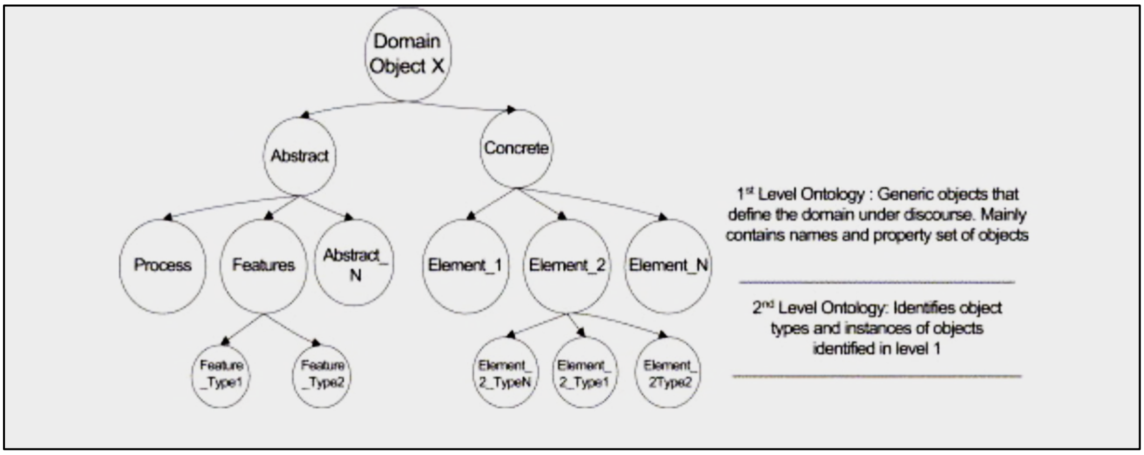


***Figure 3.1 Framework for ontology design and classification (Source: Ugwu, et al., 2005)***

Meanwhile, different approaches are being used in design, procurement and construction processes towards mitigating waste generation. However, the use of these approaches (as highlight in Figure 3.1) has achieved less in reducing construction waste (Ugwu, et al., 2005). It is however believed that there is that procedural approach that could reduce waste intensiveness of the construction industry. This means that to tackle waste at a holistic level; there is a need to unravel those procedural approaches and protocol for achieving low waste projects. This tends to an assumption there is an existing approach capable of achieving waste-effective projects. Relating the above analogy from ontological perspectives, it could be argued that reality in this perspective could not be multiple, notwithstanding the possibility of perceiving the optimum approach in a different way. Based on these, relative ontology, which assumes that there is no absolute validity (Ugwu, et al., 2005), could not underpin a study that seeks to unravel what is believed to be an optimum approach to waste management. Conversely, a suitable ontological belief underpinning the study is that of realists, which claim that there is only single mind- independent reality (Guba and Lincoln, 2005). According to this ontological perspective, the aim of a research is to disentangle the reality which, in the scenario of this study, is an optimum approach capable of minimising construction and demolition waste at design, procurement and construction stages of every project by identifying the key decision-making factors that aid the decision on whether to refurbish/re-use or demolish/recycle. Thus, to identify the key decision-making factors, there is a need for value free ontology rather than value loaded assumption, which is otherwise based on speculation instead of factual evidence.

### 3.2.2 Epistemological Requirements of the Study

While seeking to understand, predict, explain or control a phenomenon, there are two basic ways of knowing; these are objective and subjective approaches (Collis & Hussey, 2013). The objective approach is defined as, the researcher should be independent and able to study the research entity without being influenced or influencing other individuals. As such, the researcher uses pre-defined research instrument, such as questionnaires and structured interview among others, for data collection. Contrarily, subjective research involves understanding and construction of meaning through interaction between the researcher and subjects of study (Collis & Hussey, 2013).

Considering the focus of the study, the two ways of knowing are capable of enriching the outcome of the study. Subjective approach becomes more valuable at the inception of the study, to gain an in-depth understanding of various waste causative and preventive measures through inter-subjective interaction with the industry professional. The overall purpose of the subjective approach at this stage is to ensure that research instrument at the later stage is as exhaustive as possible. This approach would be used at the early stage of the study, when there is little knowledge of the concept under investigation, as the approach is deemed more suitable in a situation where an important phenomenon has been poorly or wrongly conceptualised (Van Manen, 1990; Jasper, 1994). This would, therefore, help in unravelling comprehensive list of measures and factors, which could be further tested through a more objective approach.

While seeking to ensure a generalisable result, there is a need for research sample to be representative of the research population (Creswell, 2009). Ability to arrive at a generalizable result would enhance the value of the study. However, in order to reach out to a representative population, which requires a large number of participants, a cost and time-effective measure is to make use of pre-designed research instrument (Creswell, 2009). While using this, a researcher becomes an objective participant in the study. Owing to this necessity, this research project requires subjective and objective epistemologies at its intensive and extensive stages respectively. As the subjective approach would assist in obtaining a comprehensive list of waste mitigating measures, a more objective approach would assist in testing the practicability of those measures, towards proposing the key identified decision-making factors to be considered for refurbish or rebuild scenarios.

### 3.2.3 Philosophical Approach to the Study

A review of extant literature shows that paradigms have been explained and exemplified from one another through three basic measures, which are the purpose of enquiry, ontological belief and epistemological perspectives. Based on these distinctive features, each of the research paradigms has its area of suitability, which is determined by what researchers seek to unravel. Irrespective of one's position, justification of researchers' choice of underpinning paradigms gives credibility to their studies (Crotty, 1998).As such, research paradigms are to be considered at the inception of research projects in order to provide a basis for subsequent choice of research methods and research design.

Research paradigms describe pattern of beliefs and assumptions regulating inquiry in a discipline, by providing the framework within which investigation is accomplished (Weaver & Olson, 2006). It provides lenses for viewing and interpreting issues and holds principles and vocabularies governing research approaches. Hinshaw (1996) claims that paradigms are developed by communities of scholar having shared beliefs and presuppositions about what constitutes reality as well as pattern and mode of knowledge acquisition and construction. Adherence to a paradigm connotes that knowledge acquisition, direction of theory development and suitability of research approach and knowledge acquisition procedure are delimited by the paradigm. Thus, each paradigm defines how knowledge is acquired, processed and developed within its tenet.

Different models have been used to categorise existing paradigms in social and natural science. While Burell and Morgan (1979) categorised research paradigms into radical humanism, radical structuralism, interpretivism and functionalism, Guba and Lincoln (1994) categorised paradigms into positivism, post-positivism, critical theory and constructivism. Using similar model as Guba and Lincoln, Crotty (1998) described constructivism as "interpretivism" and included postmodernism and feminism while categorising what was termed as theoretical perspectives. Based on works of Habermas, critical theory is another popularly known philosophical approach to research (Alvesson and Willmott, 2012). According to Krauss (2005) post-positivism as described by Guba and Lincoln (1994), Neopost-positivism described by Manicas and Secord (1982) and what Healy and Perry (2000) described as realism is what is also referred to as critical realism by Hunt (1994). Summing up on these different classifications, positivism, interpretivism, critical theory, postmodernism, and critical realism are evaluated for their relevance to this study.

Based on the nature of this research topic, the adoption of philosophical approach was more viable and useful, which includes various scenarios and possibilities depending on different situations and considerations for existing and new buildings. Considering the fact that various scenarios need to be considered during the development of the decision-making frameworks in the research project, such as for new buildings, different factors have to be considered for the decision-making on whether to refurbish or rebuild at the end of the design life. Similarly, different approach has to be considered when deciding whether to refurbish or rebuild an existing building.

Moreover, commercial and residential buildings have different types and different operating licenses, which further led this into a philosophical approach with critical realism to be adopted towards the development of the decision-making strategy/framework such as case studies and contributing factors to waste generation. The case studies in Chapter 4 of this research project includes the investigation of the waste arisings from different semi-commercial construction sites, where an approach was taken to calculate the total amount of waste and the individual waste quantities of each material type. And further to calculating the quantities of waste, each material waste that is commonly used within the industry was taken into consideration to evaluate the available options for its re-use and recycle. After the evaluation of case studies in Chapter 4, another approach was adopted to create different sets of frameworks based on different scenarios for existing and newly developed buildings that includes the possible key factors to be considered for the decision-making of whether to refurbish or rebuild. Having known the options of re-use of material waste, a waste matrix diagram with the philosophy to identify and highlight the type of waste in its respective category was created in Chapter 4, this also indicates the purpose of adoption of critical realism within the philosophical approach towards this research project. The matrix diagrams for waste categories along with the possible key factors from the developed frameworks contributes towards the identification of the key decision-making factor. Further to this has been explained in detail in Chapter 4.

With the adopted philosophical approach in this research project, the highlighted case studies and discussed scenarios with the possibilities of waste generation were mainly addressed to identify the key factors that contributes the decision-making of existing and newly developed buildings.

### 3.3 Research Methodology

As discussed previously in this chapter, several techniques and approaches were adopted in collecting and analysing data in order to fulfil the aim and objectives of this study. This section first highlights the overview of the methodological approach that has primarily been followed during this research project, and this approach is classified into a flowchart in Figure 3.2. It shows the first version of step-by-step procedures and research analyses followed towards the development of the framework, which further lead to the identification of the key decision-making factors. The key factors were then applied in Revit/BIM plug-in tool, Tally during the process of life cycle assessment (LCA) of the building model. A sample of the questionnaire used in the expert opinion survey is available in Appendix D. Methodological approaches used in achieving each of the study's objectives are briefly explained in the following sub-sections.

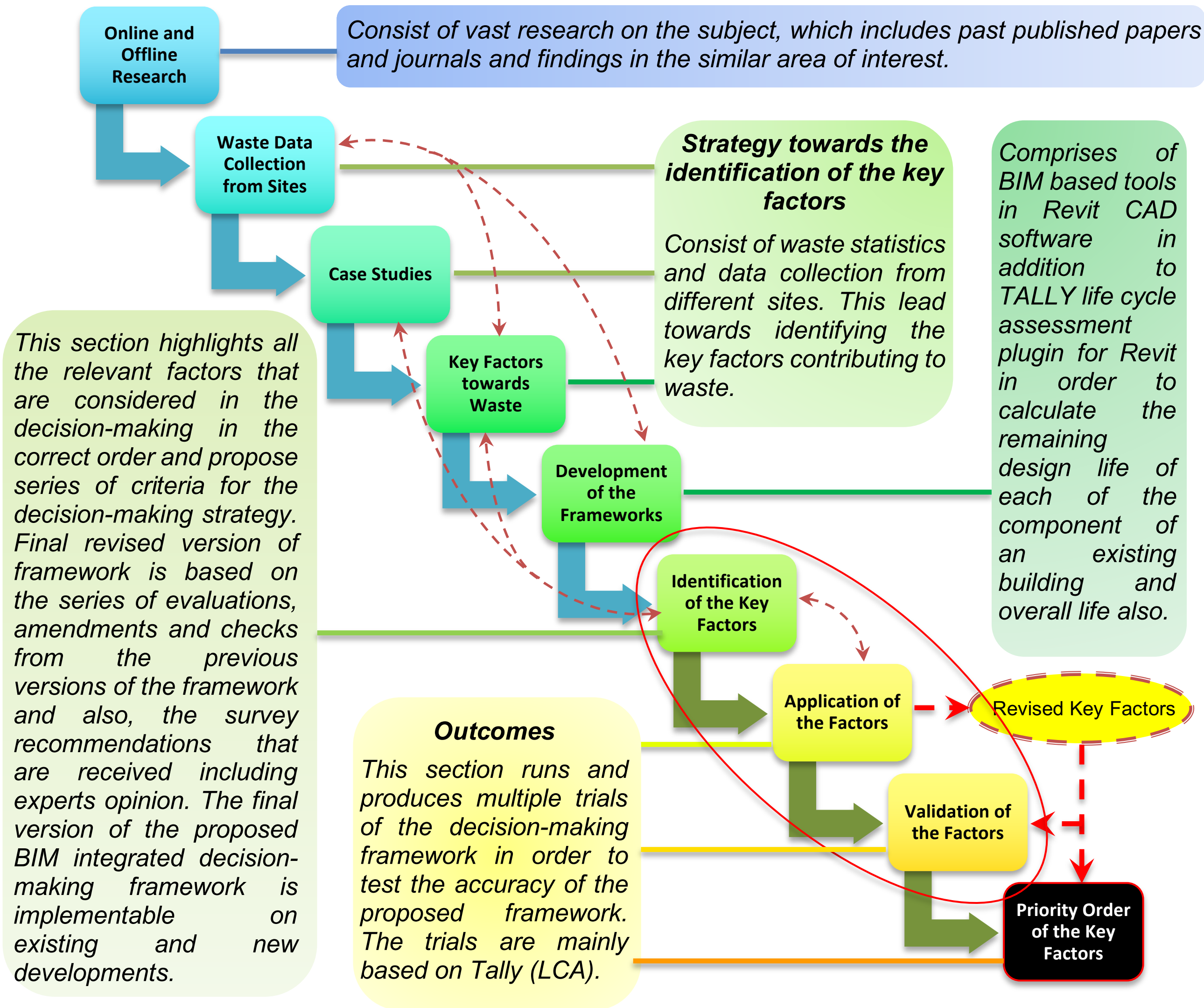


***Figure 3.2 Adopted methodology for this research project (Source: The Author)***

The section of the adopted methodology (as shown in Figure 3.2) for this research project has various sub-sections for further evaluation of each of the primary steps, which includes the literature review, framework development and the key identified factors along with their application and validation. The literature review consists of the background research, offline and online research. The background research mainly consists of the waste policies, a review of past research on the subject, waste hierarchy and BIM (see Figure 3.3 below).

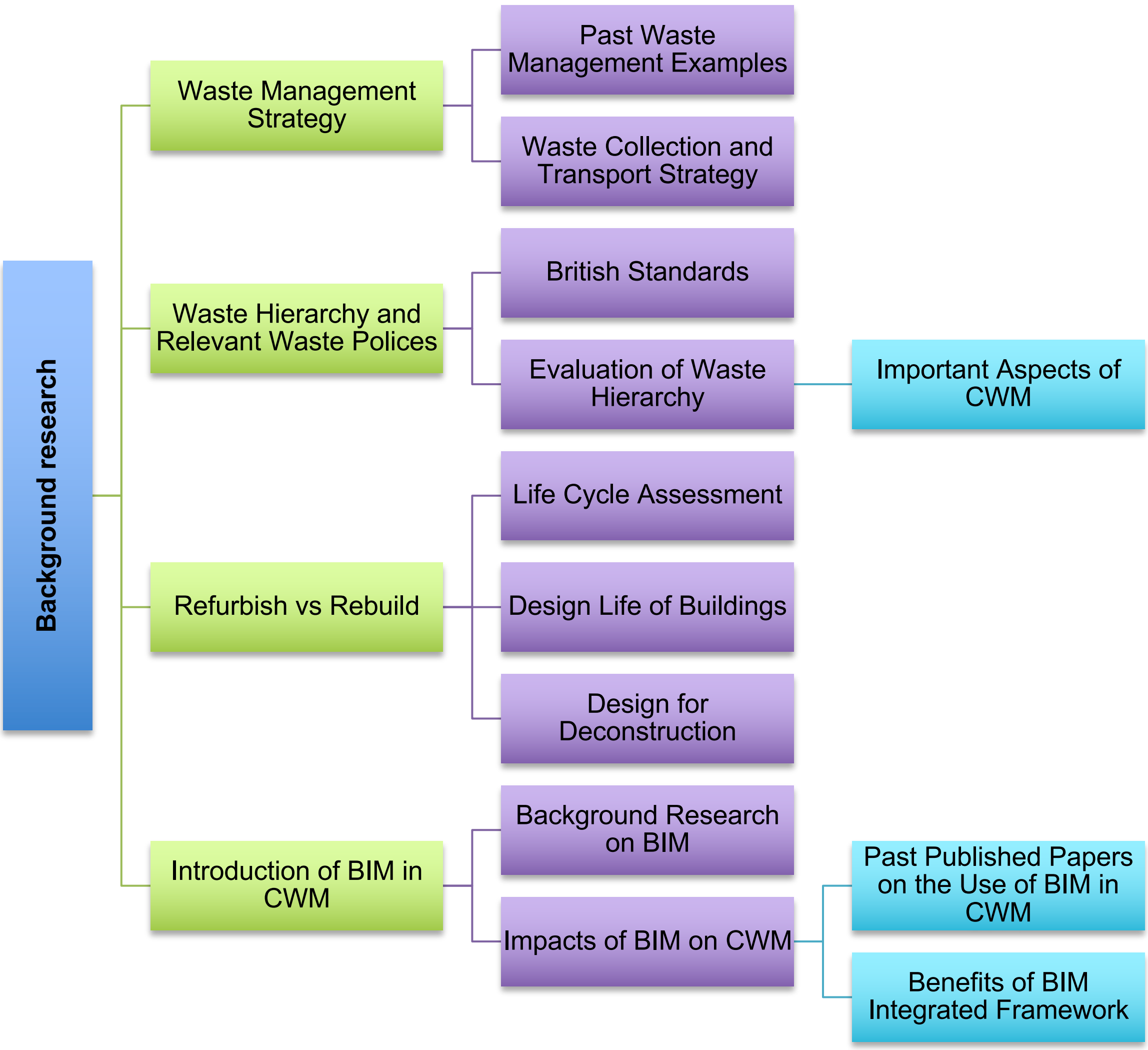


***Figure 3.3 Adopted background research strategy (Source: The Author)***

Following the background research on the subject, gaps were identified within the waste management process, which were then detailed and further explained within the same chapter, this led to a need of the decision-making strategy that should primarily support the reduction of waste from the construction project. This was intended to highlight and identify the waste causing issues within the industry in order to promote the idea of the decision-making strategy. Not only that, but this proposed strategy should also be applicable on all sizes of construction and demolition projects.

With regards to the expert opinion survey questionnaire, determining the sample, or the group of people participating in the survey, is one of the most crucial steps of conducting it. A variety of methodologic approaches exist for conducting research. Selection of a research approach depends on a number of factors, including the purpose of the research, the type of research questions to be answered, and the availability of resources.

Survey research is a useful and legitimate approach to research that has clear benefits in helping to describe and explore variables and constructs of interest. Similarly, like every research, survey research has the potential for a variety of sources of error, but several strategies exist to reduce the potential for error (Julie, 2015).

The contents of the survey questionnaire were described and thorough justification was provided to each participant before they were asked to complete the questionnaire. Their input regarding the sequence of questions and their relevance to the topic was also taken into account in order to improve the quality of the survey questionnaire by maintaining its relevance to the topic. It is helpful to the reader when authors describe the contents of the survey questionnaire so that the reader can interpret and evaluate the potential for errors of validity (e.g., items or instruments that do not measure what they are intended to measure) and reliability (e.g., items or instruments that do not measure a construct consistently).

Survey research is defined as "the collection of information from a sample of individuals through their responses to questions" (Julie, 2015). This type of research allows for a variety of methods to recruit participants, collect data, and utilise various methods of instrumentation (Julie, 2015). Survey research can use quantitative research strategies (e.g., using questionnaires with numerically rated items), qualitative research strategies (e.g., using open-ended questions), or both strategies (i.e., mixed methods).

The survey questionnaire is tailor-made to fit the research project. The questionnaire was distributed online and offline. Where possible, the survey questionnaires were handed in paper form to the experts. However, due to the travel and commute inconvenience, most of the questionnaires were delivered in an electronic format via email.

The goal of sampling strategy in this survey questionnaire was to obtain a sufficient sample that is representative of the population of interest. Therefore, only relevant experts from the industry were asked to participate in this research and provide their valuable opinion mainly with regards to the decision of whether to refurbish/re-use or demolish/rebuild. It is therefore necessary to correctly identify the population of interest.

The Offline research consist of site surveys, questionnaires (based on experts' opinions) and waste data collection from various sites (see Figure 3.4). The online research comprises of the data collected through websites, journals, conferences proceedings and other electronic forms. Vast range of online data and statistics are available, however the collected data within this research project was evaluated numerous times and only the most relevant ones have been selected and referenced. This highlights the epistemological approach towards this study. The online and offline data does play an important role in identifying the main factors that contributes to the decision-making of whether to refurbish or rebuild. Together with the addition of the proposed framework and the implementation of the BIM tools and strategy, the key identified factors were identified.

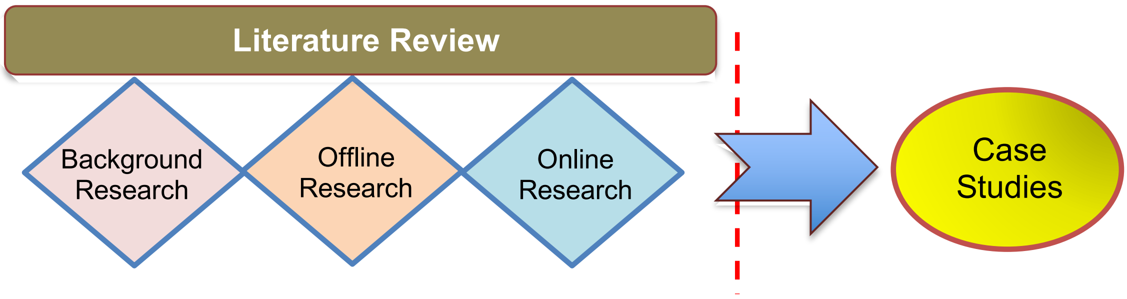


***Figure 3.4 A case for case studies (Source: The Author)***

Primarily, the online and offline research facilitated in identifying the initial key factors to reduce waste. Further to this identification and having considered the gathered research data in the literature review, it had been considered to be necessary to analyse this data use further to perform a case study (see Figure 3.4) on the causes of waste generation. For this purpose, a waste data was collected from the three semi-commercial high-rise building construction sites in London, UK. The key objective of this case study was to identify the main factors that contribute towards waste generation and then implement, use and arrange these factors (where needed) for the development of the decision-making framework. Second case study in Chapter four was performed to assess the capability of Tally (LCA) tool, which has been used for the purpose of application of the key identified factors that aid the decision of whether to refurbish or rebuild. A simplified process towards the identification of the key identified factors is illustrated in Figure 3.5.

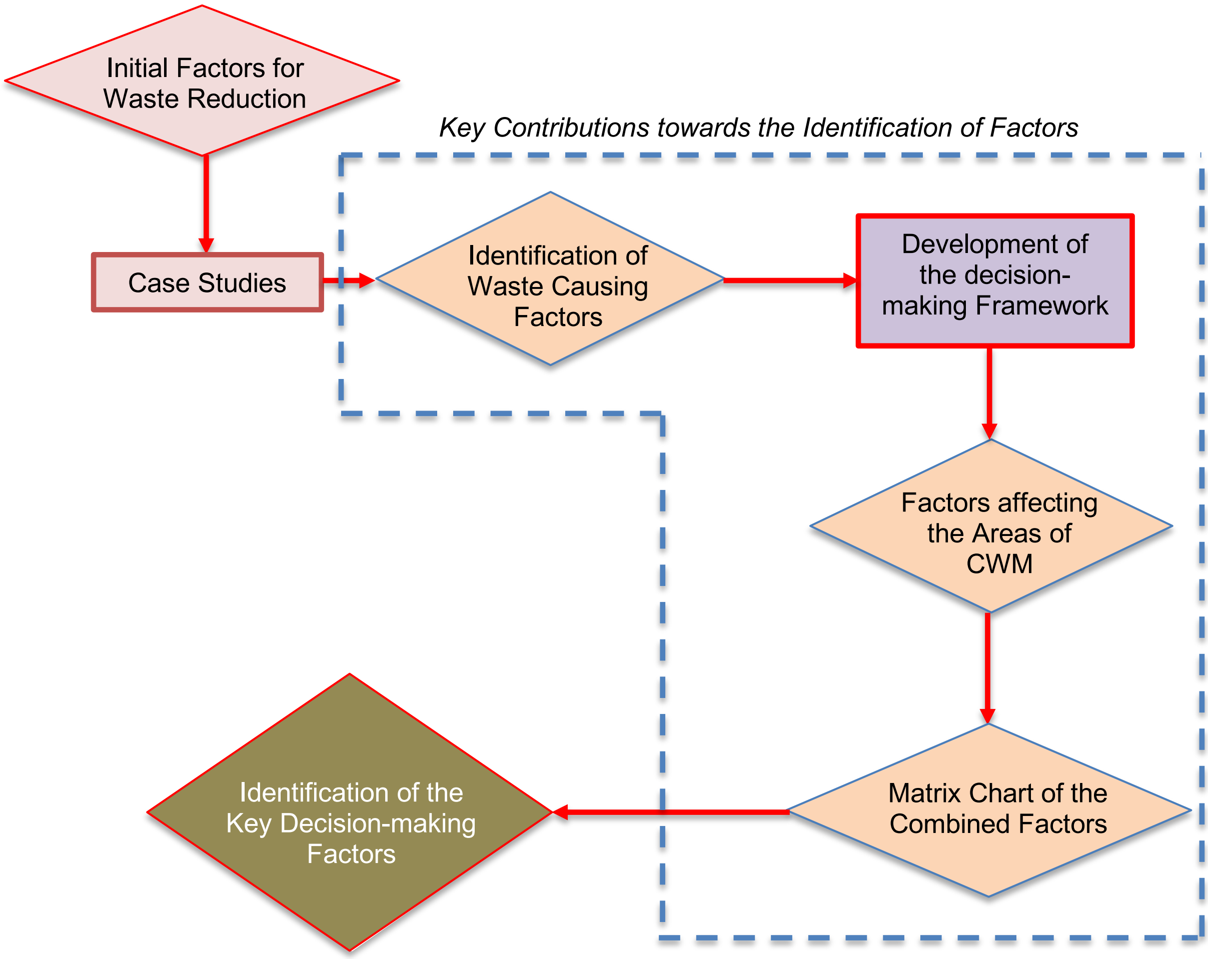


***Figure 3.5 Adopted methodology for the identification of key decision-making factors (Source: The Author)***

As shown in Figure 3.5, the factors that principally played an imperative role in the identification of the key decision-making factors are; overall waste causing factors, factors affecting the areas of construction waste management and a combined matrix chart of these two factors. These three main steps identified the weak spots in their respective area, which led the author to make a counter strategy in order to reverse this process, and that was made possible by taking some guidelines from previously published papers and journals on each of the mentioned areas of the construction industry and also by taking account of the relevant British Standards (BS) code of practice.

Following the identification of key decision-making factors, the application process was done by importing CAD models of existing and new buildings from Revit to Tally with the intention to perform the life cycle assessment (LCA) for each of the models. Further details on the application are discussed in section 3.4 and 3.5 of this chapter.

Talking about the offline research strategy as shown in Figure 3.3, a detailed flowchart has been produced (see Figure 3.6) that reflects all the key research and data collections as a foundation for the need to identify and develop the decision-making framework and an strategical approach towards the identification of the key decision-making factors.

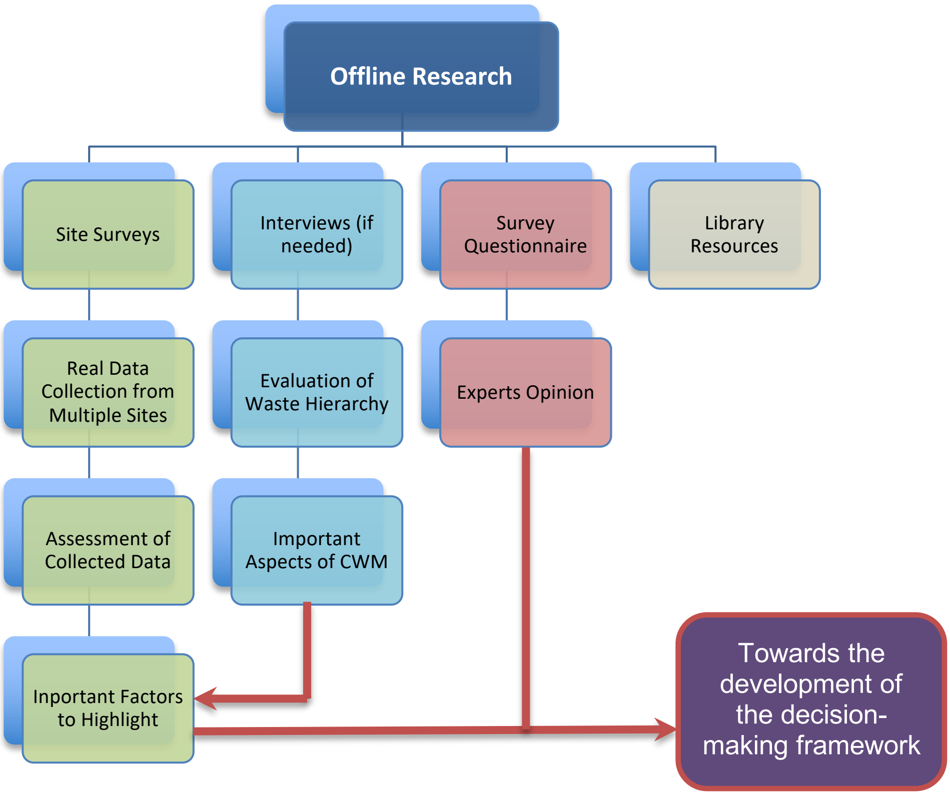


***Figure 3.6 Adopted strategy for offline research (Source: The Author)***

Based on the data collected through offline research, such as waste data from multiple sites and questionnaire based on experts opinions regarding the current waste strategy and feedback on the respective areas of construction waste management (CWM), further revisions were made to the decision-making framework. These revisions were made based on the reviews and opinions from the experts, as they will be mainly utilising the proposed framework and the key identified factors for decision-making, so the concept of imagination was to have a user-friendly and easily understandable framework and the application process for the key identified factors for decision-making. Most of the experts in this research who participated in the questionnaire, are either designers, planners, architects, managers, BIM specialists or contractors. A thorough discussion and analyses on the results of the experts opinion survey have been provided in Chapter five of this research project.

As discussed previously, based on the waste data collection from the construction sites, a case study was conducted and the collected data was then assessed with the aim calculate the approximate amount of waste along with some highlighted figures (see detailed case study in Chapter 4). This led to the development of the decision-making framework (see Figure 3.5).

All in all, the offline data is equally important as online data for the development of the decision-making framework, which further lead towards the identification of the key decision-making factors that aid the decision of whether to refurbish or rebuild an existing building that reaches the end of design life (EODL) or a newly designed building for its future prospects and decision on the basis of its condition and other relevant factors.

As mentioned, the application of the key factors involved the implementation of Revit/BIM software, where a CAD model of existing and new buildings were imported in order to perform the life cycle assessment on these models in Tally. The performed LCA on Revit models highlighted relevance to some of the key identified factors in terms of environmental and economic impact. Further details on the LCA of the Revit models have been provided in Chapter 5. However, the methodology adopted for the utilisation of BIM packages and models has been illustrated in Figure 3.7 below.

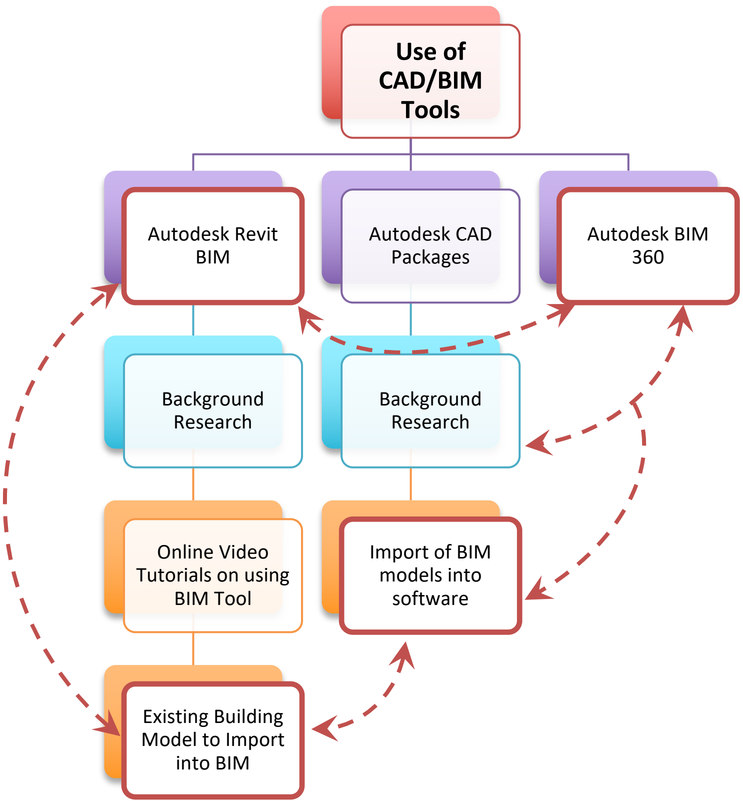


***Figure 3.7 Strategic approach for the use of BIM Tools (Source: The Author)***

The utilisaiton of Revit/BIM tool for this research project is considered to be one of the prime and necessary approach towards achieving the desired results in terms of the application of key identified factors, as this correlates to one of the fundamental objectives of this study, which is the integration of BIM into the key identified factors and to let the factors be utilised by the experts and professionals within the C&D industry. Having BIM integrated factors and frameworks would allow all the relevant stakeholders to work effectively and collaboratively towards the minimum waste design or the decision-making of any existing building or newly built design. For this purpose, understanding of the use of a BIM tool was necessary and hence the methodology was adopted to learn the relevant BIM tool and implement it at the necessary stage in this research study (see Figure 3.7).

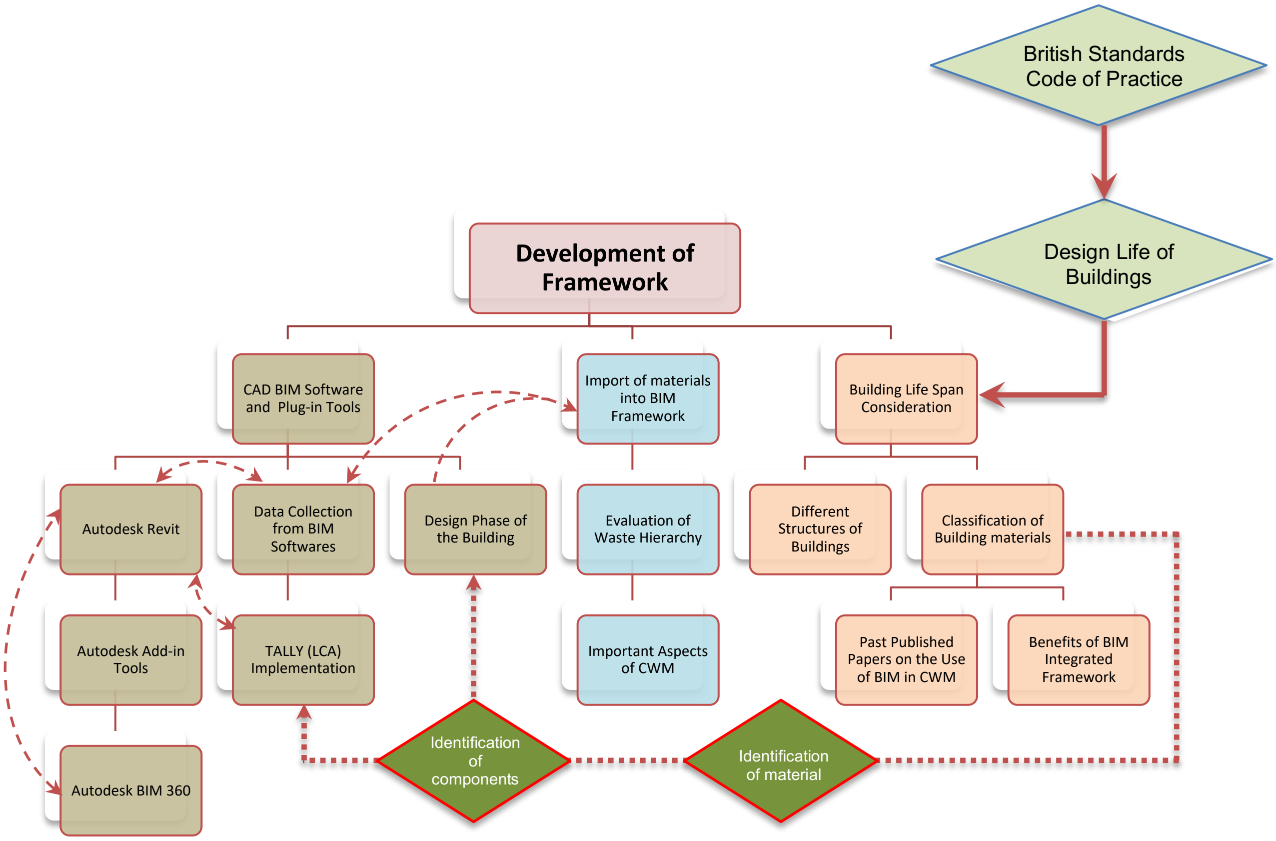


***Figure 3.8 Adopted methodology for the development of the decision-making framework (Source: The Author)***

Different sets of frameworks were used, assessed and amended in order to identify the primary factors that support in decision-making of whether to refurbish or rebuild. Figure 3.8 illustrates the approach used to develop these frameworks. This includes online and offline research, implementation of BIM model, building considerations, material and component data and, LCA tool.

The final sets of the decision-making framework for existing and new buildings were developed by taking account of the previously developed frameworks within Chapter 5 of this research project. The highlighted methodology in Figure 3.8 for the development of these frameworks was adopted for the purpose of the identification of the key decision-making factors, which is why the BIM implications and relevant British Standards codes of practice have been taken into account during the framework development process. This shows the direct relationship between the frameworks and the key identified decision-making factors.

## 3.4 Approach on Deciding the Highway Pavement Condition and Suitable Means to Refurbish or Recycle

Depending on the pavement types (flexible or rigid pavement) and their corresponding modes of failure ("deformation" and "fatigue cracking" for flexible pavement, and "fatigue cracking" and "erosion and differential settlement" of rigid pavement), the conditions of the pavement are identified as sound, critical and failed condition, and the most suitable action would be taken including monitoring, repair or recycling.

The details of how these are decided, and how to repair or recycle is applied in practice are explained in Chapter 4 and the corresponding conclusions are reported in Chapter 7.

## 3.5 Applications of Revit/BIM Software

For the purpose of assessing a 3D model of a building, Revit/BIM CAD software was used. This section discusses how the Revit/BIM software has been used along with its useful and relevant tools within this research project. It also highlights and explains the key functions of this package that were used to import and assess the 3D model in accordance with the required needs The application of Revit/BIM CAD software and its uses within this research project has been explained and illustrated in detail in Appendix D.

## 3.6 Methodological Approach for Tally LCA

Tally, an Autodesk Revit application/plugin that allows designers to quantify the environmental impact of building materials for whole building analysis as well as comparative analyses of design options (Tally TM, 2014). While working on a Revit model, one can define relationships between BIM elements and construction materials from the Tally database. Through this process, variety of output reports can be generated that asks a ranges of design related questions. The result is Life Cycle Assessment (LCA) on demand, and an important layer of decision-making information within the same timeframe, pace, and environment that building designs are generated (Tally TM, 2014). This package is therefore found to have the potential is identifying the relative key factors that can be useful in the decision-making process.

# Chapter 4. **Case Studies and Development of Framework**

## 4.1 Chapter Overview

This chapter mainly consist of two sections; the first section includes the case studies conducted by the author. These case studies are based on waste data collected from multiple residential and commercial construction sites. The purpose of collecting waste statistics from these sites is to calculate the amount of waste generated and then evaluate the cost of some of the main material types. The calculated cost of the material indicates the estimated economic loss for each site, which could be reduced or eliminated by proper planning and well informed decision-making strategy. Here, the planning highlights the design strategy, waste management strategy, material procurement and handling, site management and on-time waste collection etc., having strict policy on these measures would lead to minimum waste. More importantly, a well-informed decision signifies the importance of the waste causing factors that leads to decision-making, thus the identification and mapping of the waste causing factors is the ultimate goal of the conducted case studies.

The second section of this chapter includes the development of different sets framework that leads to the identification of the decision-making factors. The validation process of the decision-making factors has been conducted in Chapter five. This section is a continuation of the first section, where the waste causing factors from section one were used to develop the hierarchies of the proposed decision-making frameworks in section two. The development of the framework is primarily based on the severity of each identified waste causing factor, however there are several other key factors considered during the framework development that are listed within section two along with the justification that also includes some examples from the past case studies where similar factors were used.

## 4.2 Analyses of Construction Waste – Case Study of Three Buildings

In order to determine the contributing factors towards waste generation, a case study was conducted, where the relevant waste data was collected from three semi-commercial construction sites based in East London. The data was then analysed by assessing the site waste management, material procurement, material management, material usage and wastage, in addition to the average amount of waste transported and the volume of re-used materials.

The findings of this case study helps with the better understanding of the major factors that can reduce the construction waste within the forecasted targets and contribute towards achieving sustainability in construction waste management. These factors also help in arranging and finalising the final version of the decision-making framework and the primary factors that help in the decision-making of whether to refurbish or rebuild.

### 4.2.1 Introduction

Several researchers are working towards the improvisation of waste management system and different sets of frameworks are being proposed almost every year in order to control waste generation, yet there has been no major breakthrough so far. Some strategies that have been proposed, do work to some extent, such as, Site Waste Management Plan (SWMP). However, this plan is only implementable on site, when the project has moved from the design to the construction phase. This indicates that there is a need to identify and reduce the possibility of waste generation during the design phase. Moreover, Ofori & Ekanayake, (2000) indicated that wastes usually occur during design, operational, procurement and material handling. The majority of these consume time and effort without adding value for the client thus resulting in losses of material, delay times and execution of unnecessary work. Waste has a direct impact on the productivity, material loss and completion time of projects, resulting in a significant loss of revenue. The physical waste from construction contributes a significant part of landfill, and studies show that 13-26% of landfill is construction waste, which emphasises on the need for a systematic and more efficient waste minimisation method to control the volume of generated wastes at different levels (Bossink & Brouwers, 1996).

As this case study seeks to identify the factors that contribute towards the generation of waste, this information will help researchers to identify some of the main causes of waste generation and how to tackle and plan them ahead of the construction phase.

### 4.2.2 Background Research

In construction, waste is generated throughout project phases, irrespective of the size of the project, the value of the contract and its duration, and the variety of building type (Enshassi, 1996). Wastes are generated right from foundation up to the finishing works, and emanate from sources such as wooden materials, concrete, gravels, aggregate, masonry, metals, plastic, plumbing and electrical fixtures, glass, and material handling (Napier, 2012). Approximately 5 to 10% of the construction materials will eventually end up as waste. Cheung, et al., (1993) through their study found that waste generated typically represents 10–20% of the total weight of building materials delivered to a building site. Meanwhile, Bossink & Brouwers, (1996) found that the level of waste at construction sites, for instance in the Brazilian construction industry, is 20–30% of the total weight of materials on site.

***Table 4.1 Typical building materials and reason for their wastage (Source: Hung & Kamaludin, 2017)***

| Material | Factors contributing to waste | Reason of waste generation |
|---|---|---|
| **Plasterboard / gypsum** | Cutting | Use of products whose size does not fit. |
| | Ordering more than the required quantity. | Required quantity of products unknown due to imperfect planning. |
| | Unexpected damp due to moisture in the atmosphere. | material stored in the wrong place or not protected properly. |
| **Timber** | Cutting | Use of products whose size does not fit. |
| **Concrete** | Ordering more than the required quantity. | Required quantity of products unknown due to imperfect planning. |
| | Loss during transportation. | Settlement of concrete on long transportation time. |
| | Scraping off | Method to lay the foundations of a building. |
| **Insulation** | Ordering more than the required quantity. | Required quantity of products unknown due to imperfect planning; Or required quantity not properly calculated during the planning phase. |
| | Left over pieces after installation. | |
| **Brick/block** | Cutting | Use of products whose size does not fit. |
| | Damaged during transportation. | Unpacked supply. |
| **Tiles** | Sawing consequently on the design of the surface. | Attention not paid to sizes of the used products in design; types and sizes of the different products do not fit. |
| | Damaged during transportation. | Negligent handling by the supplier. |
| **Reinforcement** | Cutting | Use of steel bars that does not fit. |

In the Netherlands, the amount of waste for each building material lies between 1% and 10% of the amount purchased, depending on the type of material. In the UK, a research indicated that at least 10% of all raw materials delivered to most sites are wasted through damage, loss and over-ordering (Guthrie, et al., 1998). Meanwhile, a study conducted in Palestine revealed that 5–11% of the purchased materials were not used well and ended up as waste (Enshassi, 1996).

### 4.2.3 Data Collection

The data collected from the three semi-commercial construction sites consisted of various types of material waste. The selection of these sites for the analyses was based on their location, size, type and nature. The sites are located in East London and the surrounding development consists of residential houses, flats and some commercial buildings, which make these sites to be of important value to be added into the construction waste analyses. The material waste movement to and from the site also indicates the social factor in this scenario, which affected the locals and nearby transport routes. As all the three buildings were semi-commercial, therefore there was a variety of material waste with different re-use options. The collected material waste data has been listed in the Table 4.2 which also highlights the possibility of putting these waste materials to alternative uses.

The Table 4.2 lists the percentage of materials wasted, approximately calculated from the waste data gathered from three construction sites. According to the site waste management and logistics team, there were 88 skips (14 cubic-yard skip on average) delivered and collected from these three sites (Ali, et al., 2018b). Out of these 88 skips, 34 were collected from one site, 31 from the second and 23 from the third. Considering the fact that a single 14 cubic-yard skip takes up to 14 tonnes of waste, the total maximum load of these wastes sums up at 1,232 tonnes. This in itself indicates the magnitude of wasted material that could have been reused through proper planning and use of better strategy prior to the commencement of the construction phase.

***Table 4.2 Waste data collection and* measures for reuse, recycle and reduce *(Source: Tam, 2011)***

| Collected waste data | | Waste % | Possibility of utilising the collected waste | | |
|---|---|---|---|---|---|
| **Material** | Sub-Type | | Reuse | Recycle | Reduction |
| **Plasterboard / Gypsum** | Fire proof board | 21% | Reusing gypsum for other purposes such as filling. | Gypsum waste can be recycled continuously to make the same product. | NIL |
| | Acoustic board | | | | |
| | Moisture board | | | | |
| | Normal/non fire proof board | | | | |
| **Insulation** | Thermal insulation | 9% | Insulation can be re-used for filling gaps between the cavity walls or for ceiling voids. | NIL | NIL |
| | Acoustic insulation | | | | |
| | Celotex floor insulation board | | | | |
| **Bricks** | Miscellaneous | 8% | Can be re-used for landfill on the existing site, if required. | Damaged bricks can be recycled to make aggregate for use as general fill or highway sub-base. | Use of cladding, if possible. |
| **Timbers** | OSB boards | 15% | Timber products, such as formwork, joists and deck boards, can be reused for several times. | Timber can be recycled to local and export recyclers. | Using other materials to substitute such as pre-fabricated building components, drywall partition and standard wooden panels. |
| | Joists | | | | |
| | Cls studs | | | | |
| | Deck boards | | | | |
| **Cardboards** | Packaging | 7% | Re-use cardboard material, such as packaging. | Encourage manufacturers to recycle their original packaging materials. | Use of environment friendly paper, in which the composition processes will |

| | | | | | |
|---|---|---|---|---|---|
| | Floor covers | | | | have less emission of pollutant or products and materials with reduced packaging. |
| | Delivery boxes | | | | |
| **Electrical wires** | Miscellaneous | 4% | NIL | Copper and rubber coating on the wire can be recycled for many other purposes. | NIL |
| **Plastic** | Plastic wrapping | 4% | Reusing plastic for other purposes, such as material protection. | Used plastic can be recycle to local and export recyclers. | Using other materials to substitute plastic. |
| **PVC conduits and waste pipes** | Electrical and plumbing pipes | 5% | Can be re-used for small works. | PVC is recyclable. | NIL |
| **Concrete** | Type C40, C30 etc. | 4% | Reuse concrete waste as temporary work. | Concrete can be recycled as aggregate for concrete production. | Accurately calculate and order quantity of concrete; Use of prefabricated building components; Or alternative construction methods. |
| | Solid, precast and reinforced etc. | | | | |
| | Screed | | | | |
| **Glass** | Miscellaneous | 4% | Glass can be re-used for several purposes. | Glass waste can be recycled as aggregate for concrete production. | Using other materials, in substitute glass; Or alternative construction methods. |
| **Iron pieces / Reinforcements** | Beams | 3% | Can be re-used and cut into size for smaller structural works. | There are various steel / iron recycling yards where these can be sent | NIL |
| | Columns | | | | |
| | Bolts | | | | |
| | Connection plates | | | | |
| | Reinforced bars | | | | |
| **Paint boxes** | Miscellaneous | 8% | Can be re-used for filling and pouring liquid material, if undamaged. | These are recyclable, as mentioned at the bottom surface | NIL |
| **Ducts** | HVAC works | 8% | Can be re-used if not too old and has a remaining design life as specified by manufacturer. | Ducting mostly consists of galvanised, stainless steel or aluminium, that can be recycled. | NIL |

The percentage of waste is Figure 4.2 is calculated from the amount of each waste recorded during the construction on these construction sites (Ali, et al., 2018b).

### 4.2.4 Waste Calculation

In order to calculate the approximate amount of waste recorded from the 3 semi-commercial construction sites, the data recorded for calculation is as follows:

- Total skips recorded on 3 sites = 88;

- Size of each skip on average = 14 yards;
- Load capacity of each skip = 14 tonnes.

Total waste (Σw)= 88 x 14 = 1,232 tonnes (Equation 4.1)

The calculated total waste of 1,232 tonnes is an approximate estimation based on the assumption that each skip was loaded to full capacity of waste, out of which, most of the waste consists of left over material. This is indicating that the planning and procurement of material needs to be more efficient and calculated (Ali, et al., 2018b). Further, in order to specify, which is the most common type of material that ends up into waste in most of the construction sites, a graph in Figure 4.1 below is indicating the generated waste from most of the common material.

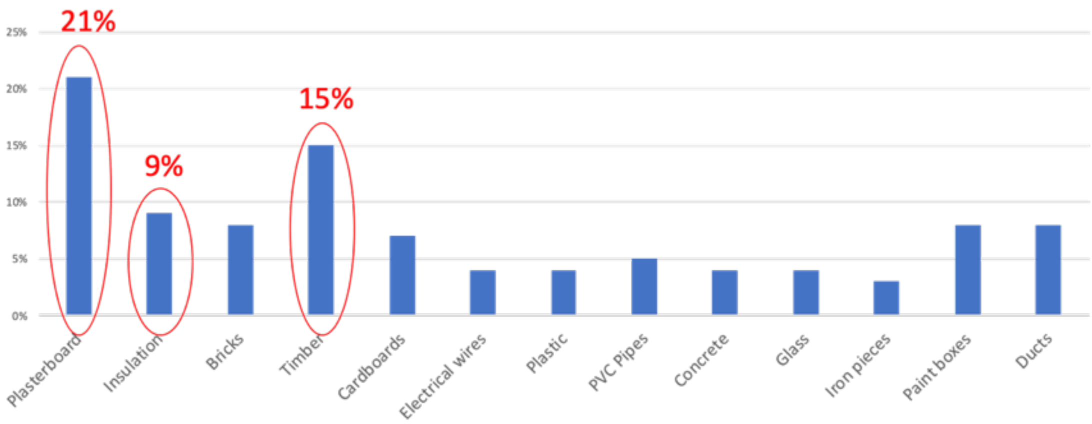


***Figure 4.1 Percentage of waste material weight by category (Source: Ali, et al., 2018)***

#### 4.2.4.1 Estimated amount and cost of plasterboard waste

As indicated in the Figure 4.1, the waste generated through gypsum/plasterboard has the highest percentage among all other material, therefore it is crucial to estimate the total waste generated though this material (Ali, et al., 2018b).

Calculation for total waste generated through plasterboard = 1,232 x (21/100)

Estimated plasterboard waste = 258.72 = 259 tonnes

Average plasterboard data (for cost calculation):

- Dimensions: 2400mm (W) x 1200mm (L) x 12.5mm (thickness);
- Weight = 24kg;
- Recorded plasterboard waste = 259 tonnes = 259,000kg;
- Average price of a plasterboard = £8.

No. of plasterboards/gypsum boards wasted = 259000/24 = 10,791.66

Total cost of plasterboard waste = 10791.66 x 8 = £86,328

Generally, the plasterboard comes in different types and each type has different price range. The prices also vary from company to company. However, in this scenario, the least price for the plasterboard has been considered, so eventually, the actual plasterboard waste cost would be higher than the calculated one.

#### 4.2.4.2 Estimated amount and cost of timber waste

Calculation for total waste generated through timber = 1,232 x (15/100)

Estimated timber waste = 184.8 = 185 tonnes

Average timber data (for cost calculation):

- Dimensions: Varies by type (cls stud considered in this case = 2400mm x 89mm x 38mm);
- Weight = 9kg;
- Recorded timber waste = 185 tonnes = 185,000kg;
- Average price considered for timber in this case = £3 (minimum price considered).

No. of timbers wasted = 185000/9 = 20,555.55

Total cost of wasted timbers = 20555.55 x 3 = £61,666

Again, in this case, the minimum cost of timber has been taken into account for timber waste calculation. The actual waste cost will be higher than the calculated one.

#### 4.2.4.3 Estimated amount of insulation waste

Calculation for total waste generated through insulation = 1,232 x (9/100)

Estimated insulation waste = 110.88 = 111 tonnes

### 4.2.5 Possibilities of Utilising the Material Waste

#### 4.2.5.1 Plasterboard / Gypsum (21%)

- Can be re-used for covering and filling small patched in the walls, if undamaged;
- Can be recycled to make the same product.

#### 4.2.5.2 Timber (15%)

- Can be re-used for several purposes such as stud work for internal wall partitions etc;
- Can be re-used to build floor frame in residential apartments for ventilation purposes;
- Can be recycled to local or export recyclers.

#### 4.2.5.3 Insulation (8%)

- Can be re-used for filling gaps between the cavity walls or for ceiling voids;
- Can be re-used for filling the pitched roof void (depending on the type of insulation).

### 4.2.6 Mapping of the Waste Causing Factors

Upon reviewing the material waste data collected in Table 4.2, certain aspects of the project cycle were found where improvement was possible. In order to highlight the causes of waste generation, a mapping of the waste causing factors has been generated where these areas are classified into phases and categories (see Table 4.3). Details of the causes of waste are indicated in the Table. Some of these causes were past published papers on waste causes that have been gathered and thoroughly investigated in order to get to the primary cause of waste (Ali, et al., 2018b).

In order to simplify the data, each cause of waste is listed to its respective group, as this will give a preliminary idea of what past researchers had discovered in this sector. This mapping evaluation can identify the severity of each factor based on the frequency of the factors identified by past researchers around the world. There are 10 scholarly research papers selected for this study and 54 factors behind construction waste generation were found in the study. These factors are grouped into 8 sub categories of the 3 primary construction project phases (Ali, et al., 2018b). Table 4.3 shows the mapping of the waste contributing factors taken from some past published papers.

***Table 4.3 Mapping of waste causing factors (Source: modified from Nagapan, et al., 2011)***

| **Design Phase** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Group** | Cause of Waste | References | | | | | | | | | |
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Design | Design errors | x | | x | | x | x | | x | | x |
| | Lack of co-ordination | | | | | x | | x | | | |
| | Lack of information | | | | x | x | x | x | x | x | |
| | Frequent design changes | x | | x | x | x | x | x | x | x | x |
| | Poor design quality | | | | | | | | x | x | |
| | Inexperience designer | | | | x | | | | | | x |
| | Lacking of waste efficient design | | | | | | | | x | x | x |
| | Complex drawings | x | | | x | x | | | | | |
| **Pre-Construction Phase** | | | | | | | | | | | |
| | Cause of Waste | References | | | | | | | | | |
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Planning | Un-realistic project schedule | | | x | x | | | x | | x | x |
| | Discrepancies in the Bill of Quantities | | x | x | x | | | | | | x |
| | Discrepancies in material procurement schedule | | | x | x | | | | | | x |
| **Construction Phase** | | | | | | | | | | | |
| | Cause of Waste | References | | | | | | | | | |
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Management | Poor site management | | | x | x | | | x | | | |
| | Poor planning | x | x | | x | x | | | x | x | x |
| | Poor resource management | | | x | x | | | x | x | x | |
| | Poor supervision | | | | | | | | x | x | |
| | Inappropriate construction methods | | | | | | x | | | x | x |
| | Lack of co-ordination | | | | | x | | x | x | x | |
| | Scarcity of equipment | | | | | x | | | x | x | |
| | Lack of resources | x | | | | | | x | x | | |
| | Waiting periods | | | | | | x | x | | | |
| | Rework error | | | | | x | | x | | | |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Communication problems | | | x | | | | | | | |
| | Lack of environmental awareness | | | | | | | | | | x |
| | Lack of effective waste management plans | | | | | x | | x | | | x |
| | Non availability of equipment | | | | | | | | | x | |
| | Outdated equipment | | | | | | | x | x | x | |
| Handling | Poor material handling | x | | x | x | x | | x | x | x | |
| | Wrong material storage | x | | x | x | | | x | x | x | x |
| | Material damage during transportation | | | | x | | | x | | | x |
| | Poor quality of material | | | | | | | | x | x | x |
| | Equipment failure | | | x | x | | | | | | x |
| | Delay during delivery | | | | | x | | | x | x | |
| Worker | Workers' mistakes | | | x | x | x | | x | | | x |
| | Incompetent worker | | | | | x | | | x | x | |
| | Un-ethical work attitude of workers | | | | x | | | x | | | |
| | Damage caused by workers | | | | x | x | | | | | x |
| | Insufficient training for workers | | | | | | | x | | | |
| | Lack of experience | | | | | | | | x | x | |
| | Shortage of skilled workers | | | | | x | | | x | | |
| | Inappropriate use of materials | | | | | | | | x | x | x |
| | Poor workmanship | x | | | | | | | | | |
| Site Condition | Leftover materials on site | x | | x | | | | | | | x |
| | Poor site condition | | | | | | | | x | x | |
| | Waste resulting from packaging | x | | | | | | | | | x |
| Procurement | Ordering errors | x | | x | x | x | | | x | | x |
| | Error in shipping | | | x | | | | | | | |
| | Mistakes in quantity surveys | | | | x | x | | | | | |
| | Ignorance of specifications | | | | | | | x | | | |
| | Waiting for replacement | | | | | x | | | | | |
| Other Factors | Effect of weather | x | x | x | x | x | x | | x | x | x |
| | Accidents | x | | x | x | x | | | | | x |
| | damages caused by third parties | | | | | | | | x | x | |
| | Festivities | | | | | | | | | | x |
| | Unpredictable local conditions | | | | | x | | | | | |

### 4.2.7 Discussion and Analysis

Considering the amount of waste data collected and the findings from Table 4.3, the study suggests that numerous improvements are required throughout the project lifecycle, from the design to the completion phases, in order to reduce the maximum possibility of waste (Ali, et al., 2018b). There is a need for maximum co-ordination among all relevant stakeholders involved in the design, planning and construction processes, and meetings should be held at regular intervals to address the issues concerning waste. At least waste minimisation can be achieved through the normal practices of building work, such as reducing concrete by using prefabricated components; reusing steel formwork; and recycling steel for generating income (Shen & Tam, 2002). Although the reuse, recycling and waste reduction of construction materials have been promoted for several years, environmental awareness is still not satisfactory, likewise the support of different layers of management. The primary problem of inefficient and ineffective practices of reuse, recycle and reduction of construction waste is lack of understanding of how to treat construction wastes (Ali, et al., 2018b). Based on the discussions with construction practitioners, several measures of reusing, recycling and reducing construction materials are suggested in Table 4.2.

Further, it has been observed that a huge amount of waste can be predicted during the design phase of the project. Hence, the designers can play an important role by coming up with efficient designs where minimum waste is entailed (Ali, et al., 2018b). This is especially possible if the designers and engineers collaborate with each other during the design phase. They can use their expertise effectively to minimise waste during the evolution of the design by giving their opinions on the relevant areas of the design.

### 4.2.8 Proposed Revisions to Waste Hierarchy

The findings of this case study shows serious discrepancies within the design and management team, that mainly occurs due to lack of co-ordination, which in most cases, lead to design errors, frequent design changes, in-efficient material procurement, poor material handling, poor application of construction methods on site and delayed delivery of the project (Ali, et al., 2018b). These inconsistencies need to be addressed and adequately resolved.

However, in either of the above scenarios, the waste needs to be reduced. Looking at the current waste hierarchy, it defines the procedure to be followed in order to reduce the waste, however, it does not identify that when and at what stage, each criteria of the waste hierarchy needs to be implemented?

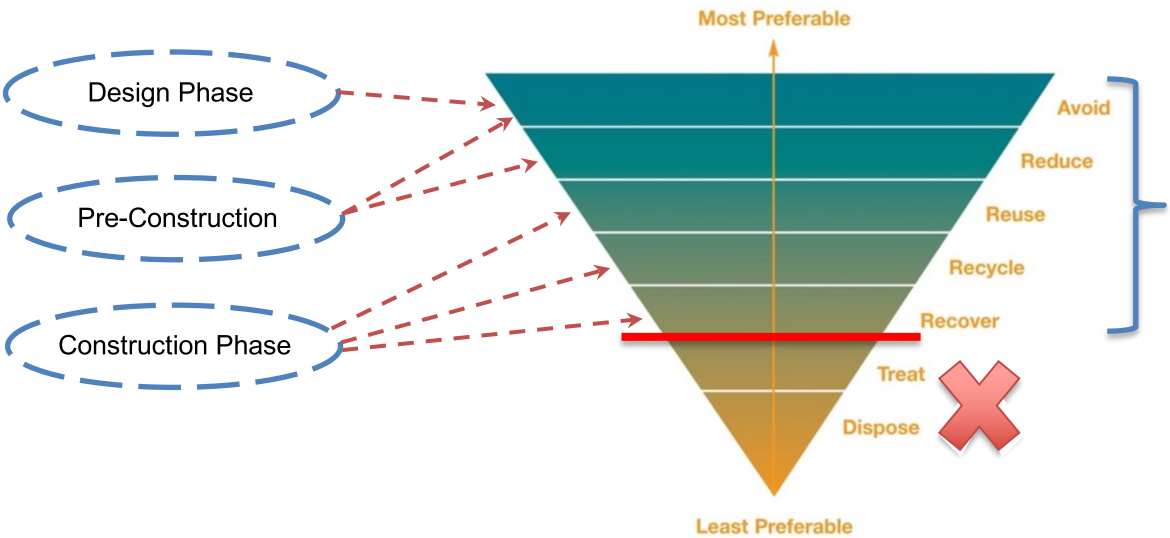


***Figure 4.2 Proposed revision for waste management hierarchy (Source: Ali, et al., 2018)***

For clear and step by step procedure of the waste hierarchy, it has been classified into 3 steps (see Figure 4.2) namely:

1) **Design phase –** During this phase, there is a best possibility of eliminating the predicted waste, this can be possible if the designer co-ordinates with the

engineer while designing the project (Ali, et al., 2018b). This way, the engineer will provide his input at regular intervals in order to specify the areas where the possibility of waste can be avoided or reduced at least.

2) **Pre-Construction Phase –** It can be right to assume that once the design has been finalised, the maximum amount of waste has been finalised too. So, at this stage, there should be focus toward reducing the waste. This can be done by ordering the right amount of material and avoid wasting the material as much as possible (Ali, et al., 2018b). Here the construction planner, procurement staff and waste logistics team needs to actively play their role in order to achieve the minimum waste generation.

3) **Construction Phase –** Once the material is already on site, the waste cannot be avoided or reduce. There will be waste but now the site team has to play their role and reuse the leftover material as much as possible (Ali, et al., 2018b). Furthermore, there will be a need to make sure that even the leftover material (only the one, which is in good condition) is properly stored into the designated place for material in order to reuse it when needed. If the material is not in reusable condition, then the option to recycle or recover shall be considered (Ali, et al., 2018b).

### 4.2.9 Recommendations

Through the present study, which is based on a literature review, the wastage level for different materials commonly used in construction have been identified, as well as the common causes of waste. It is expected that these findings can contribute to improved estimation of waste generation in a construction project from design to completion phase, thereby enhancing the knowledge-based decision-making in developing appropriate strategy for construction waste management to reduce the waste generation to a minimum (Ali, et al., 2018b).

The reported study, which takes the form of a review of the findings of research on three construction projects, relies on professionals' perception during the construction operation, which represents a subjective assessment. Nevertheless, the presented level of construction material wastage can provide interested parties or stakeholders, such as local authorities, policy makers, government, as well as the contractors and practitioners with a basis to consider in order to make more informed and sustainable decisions for reducing waste in construction.

Moreover, construction waste is one of the major contributors to environmental pollution; and this pollution generation from construction activities seems to be uncontrollable (Ali, et al., 2018b). Therefore, the most commonly used and encouraged practice of reusing, recycling and reducing construction materials need further revisions with a decision-making strategy or a guideline as highlighted briefly in the Figure 4.2.

As the findings of this case study helps in identifying the main factors that causes the generation of waste, these factors have been thoroughly investigated further and evaluated within this research study and then rearranged within the BIM integrated decision-making framework with an improvised strategical approach, from which the key decision-making factors have been identified that would aid the decision of whether to refurbish or reuse an existing building that reaches the End of Design Life (EODL).

## 4.3 Review of a Previous Tally Case Study – Whole-Building Life Cycle Assessment of Refurbishment and New Construction

This case study is performed by Hasik, et al. (2019) to assess the life cycle assessment of an existing building in Tally with the scope of refurbishment and redevelopment scenarios and their comparisons. The findings from the review of this case study aids in idetifying the missing considerations in Tally assessment and the recommended steps to overcome and fill these gaps in the LCA of buildings trailed in Chapter five for the purpose of application of the key identified decision-making factors.

### 4.3.1 Background of this Case Study

As discussed in Chapter 2, the life cycle advantages of refurbishments are clear in terms of environmental and economic impact, but there is a lack of uniform guidelines for LCA practitioners on how to conduct LCA on refurbishment projects and how to perform a comparative assessment between refurbished buildings and comparable newly constructed buildings (Ramesh, et al., 2010) and furthermore, the decision to refurbish or rebuild should not only be based on the LCA findings as this is the primary stance of this research project. This inhibits the effectiveness of using LCA to quantify the environmental benefits of refurbishment and to understand the scale of refurbishment benefits in practice (Jackson, 2005; Hasik, et al., 2019). Defining clear guidelines applicable to refurbishments can make it easier for practitioners to conduct such assessments and defining a scope more aligned with whole-building LCA for new construction can make comparisons across projects easier and consistent. According to Hasik, et al. (2019), aligning scopes can also be important for comparisons to any future building LCA benchmarks similar to the Commercial Buildings Energy Consumption Survey (CBECS) and Department of Energy Reference Buildings (DERB) used for benchmarking energy models. Retrofit typically means refurbishment or addition of features for the improvement of performance in a particular area such as, energy efficiency or structural integrity (Designing Buildings Ltd, 2016). Refurbishment and renovation both represents "modification and improvement to an existing building in order to bring it up to an acceptable/required state or condition" (EN, EN 15978, 2011;

Hasik, et al., 2019). The International Organisation for Standardisation (ISO) 21931 (ISO, 2010) and European Standards (EN) 15978 (EN, EN 15978, 2011) both uses the term refurbishment, while the term renovation is more predominant and frequently used in the United States (USGBC, 2014). Additionally, adaptive re-use, a term used in this case study, is a form of building refurbishment with the element of transforming a building of particular use to a different use, which is particularly known as the 'change of use' in the UK. The examples include; transforming a factory into an office building or transforming a hospital into an educational institute.

The ISO 21931 and EN 15978 standards cover refurbishment but provide a limited description of its scope and implementation that normally results in multiple possible interpretations and errors in the data input for LCA. EN 15978 defines the refurbishment sub-stage as part of the use stage (shown in Figure 4.3 as module B5), which includes any major technical or functional changes to a building that are not part of regular use and maintenance, or predictable repair and replacement. According to the standard, the boundary description of module B5 should include the following (see Figure 4.3):

- Production of new components of the building (modules A1-A3);
- Transport of new components (including the production of materials lost during transport (modules A4);
- Construction and waste management as part of the refurbishment process (including the production of materials lost during the refurbishment (module A5);
- End-of-life of the substituted building components (modules C1-C4).

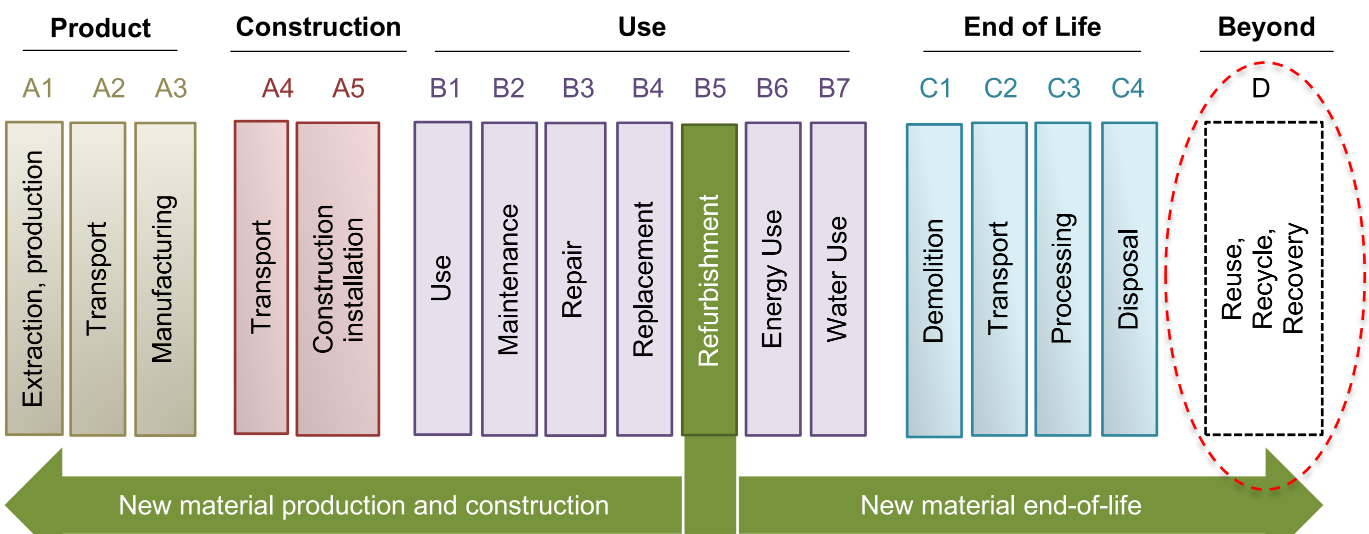


***Figure 4.3 Building lifecycle stages and modules (Source: modified from EN, EN 15978, 2011)***

The EN 15978:2011 standard lacks clarity on what constitutes the "waste management of the refurbishment process" and "end-of-life of substituted building components". It is not specified if the waste management of refurbishment processes should include only the waste from the production and installation of newly added components or if it should also include the waste resulting from the demolition of existing components (Hasik, et al., 2019). Nor is it specified if the end-of-life of the substituted building components should include only the EOL (Module C) of the newly added components or also the EOL (Module C) of the demolished components as shown in Figure 4.3. This shows the lack of clarity within the modules of the life cycle stages for LCA. This clearly indicates that the framework or method followed to perform the LCA of buildings need to be revised with the addition of waste resulting from the demolished components of the building and other considerations.

To avoid uncertainties in this case study, there is a need to define the life cycle stages within the life cycle of building refurbishment projects and also the modules though which these stages are categorised and assessed (see Figure 4.3). Following are the described modules of the life cycle stages as shown in Figure 4.3:

- **Existing Product and Construction Stage:** The initial product and construction stage (Module A) of the building considered for refurbishment/renovation;
- **Existing Use Stage:** Use stage (Module B) of the building intended for refurbishment that occurs prior to the refurbishment;
- **Existing EOL Stage:** End of life stages (Modules C/D) related to partial building demolition during the refurbishment process;
- **Re-used Use Stage:** Use stage (Module B) within the boundary of the refurbished building related to the use, repair, maintenance, and re- placement of retained or reused components after refurbishment occurs;
- **Re-used EOL Stage:** EOL stages (Modules C/D) within the boundary of the refurbished building related to the demolition and disposal of retained or re-used components after refurbishment occurs;
- **New Product & Construction stage:** Product and construction stage (Module A) of the newly added components during the refurbishment process;
- **New Use Stage:** Use stage (Module B) within the boundary of the refurbished building related to the use, repair, maintenance, and replacement of the newly added components after refurbishment occurs;
- **New EOL Stage:** EOL stages (Modules C/D) within the boundary of the refurbished building related to the demolition and disposal of the newly added components at the end of the building life.

Previous LCA studies of refurbishment and retrofit projects have often chosen varying boundaries and scopes depending on the studies' goals. For example, there are many studies that have used LCA to understand trade-offs in implementing operational energy efficiency improvements to existing buildings (Ardente, et al., 2011), these are considered energy retrofits. These studies particularly assess the environmental impacts and embodied energy of the additional components added to existing buildings (e.g. added insulation, doors and more efficient windows, etc.) and compare them to the reductions in impacts and energy use as a result of the operational energy efficiency improvements. According to Hasik, et al. (2019), these studies typically ignore any components that are not related to the energy retrofit based on the assumption that they remain unchanged and therefore have identical impacts. This approach allows investigators to determine the payback time of energy improvements from an embodied energy and environmental impact perspective (Vilches, et al., 2017). Full-building life cycle assessments studying differences between the environmental impacts of renovation and new construction comprehensively are less common and typically do not follow the same clear-cut approach (Hasik, et al., 2019).

Furthermore, Vilches, et al. (2017) recently reviewed literature on the varying definitions, boundaries, scopes, and analysed building types in LCA studies of building refurbishment. The authors concluded the existing product and construction stage (A) and the existing use stage (B) are typically excluded, except where the existing components are reused (i.e. Re-used Use Stage – B, as shown in Fig. 4.4). The New Product and Construction (A), New Use (B), and New EOL (C) stages are typically included. Vilches, et al., 2017 also identified the option to further extend the boundary for the Existing End-of-Life (EOL) Stage (C) (i.e. waste management of selective demolition), and for the re-used EOL Stage (C) (i.e. waste management of retained existing components at the end of their useful design life). An example of this proposed map with life cycle stages is illustrated in Figure 4.4.

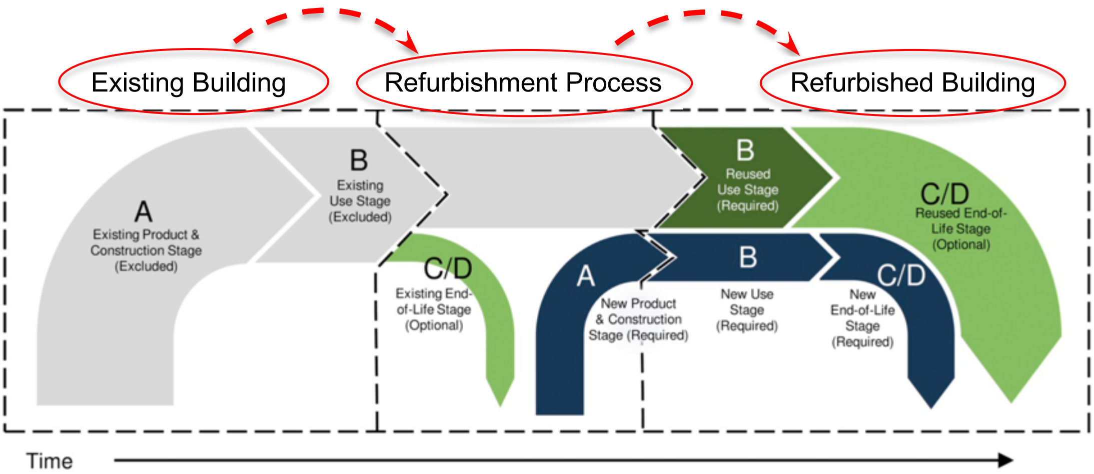


***Figure 4.4 Refurbishment LCA stage and boundary diagram (Source: modified from Hasik, et al., 2019)***

A closer look at the three seminal studies comparing the whole-building embodied impacts of refurbishments with new construction scenarios indicate many different boundary selections for the comparisons (Hasik, et al., 2019) and relationships between the core elements of each boundary selection. Frey, et al. (2011) assessed seven building types across four different locations with a focus on understanding the embodied environmental impact benefits of refurbishment/re-use against new construction or rebuilding. This study used an “avoided burden” approach for the comparison, which treats embodied impacts in existing buildings as a “sunk cost” from the past, eliminating the need for new materials in the present (Hasik, et al., 2019). This means that in both the refurbishment and new construction scenarios, the full life cycle of only new components were included and any of the re-used components in the refurbishment scenario were excluded. The study also included the selective demolition in the refurbishment/re-use scenario and the full demolition in the new construction scenario (i.e., Existing EOL stage in both scenarios). This approach was adopted to capture the refurbishments' lower demand for new materials and the lower burden associated with the disposal of the existing buildings waste during the refurbishment process. A diagram in the Figure 4.5 showing the study's comparison of the refurbishment/renovation and new construction/rebuilding scenario.

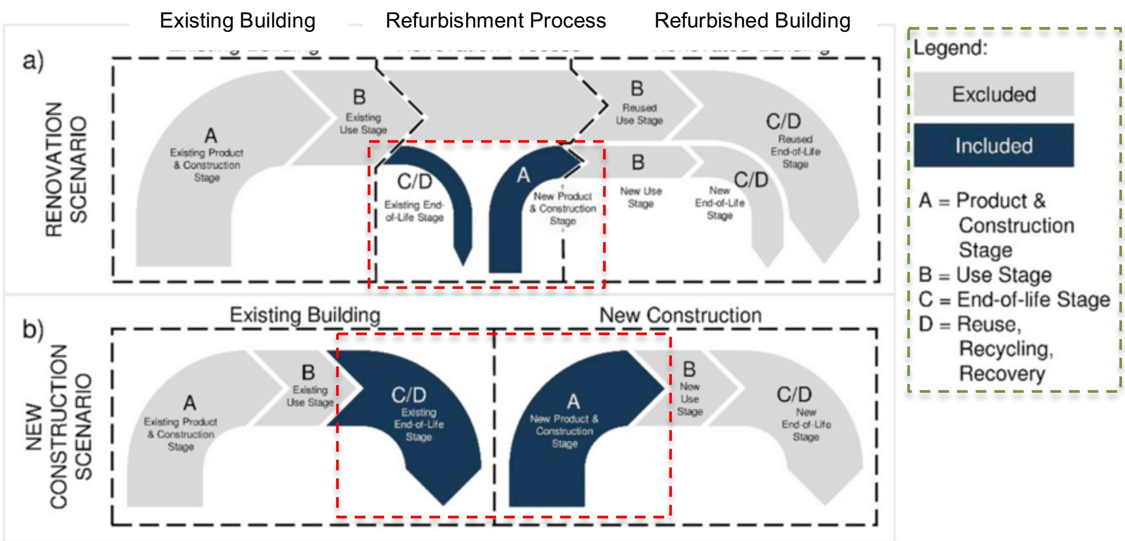


***Figure 4.5 Comparison of (a) refurbishment vs. (b) new construction scope based on the Frey et al. study (Source: modified from Hasik, et al., 2019)***

In another case study, a similar approach was adopted by Rønning, et al. (2009), which aimed at understanding the burdens or benefits of refurbishing a building for the Norwegian Bank headquarters, except this study excluded the future end-of-life disposal of both the refurbishment and new construction scenarios (i.e., the new EOL and re-used EOL stages), as shown in Fig. 4.6. The study included the existing building's demolition (i.e., the existing EOL stage) in both scenarios, be it partial or full demolition. This is also the only known comparative LCA study that included the ‘re-used use stage’ maintenance and replacement (B) in the refurbishment situation in order to capture the additional maintenance and replacement needed for the re-used components of the building. This highlights the significance of the building components to be considered for both scenarios, especially in refurbishment/re-use scenario as the material properties and data sheet contains the information that would aid in determining the remaining design life and also the environmental and economic impact in both scenarios. The specified stages (A-D) of the building's life cycle in this case study have been considered as the major impact categories in the overall decision-making process by the authors.

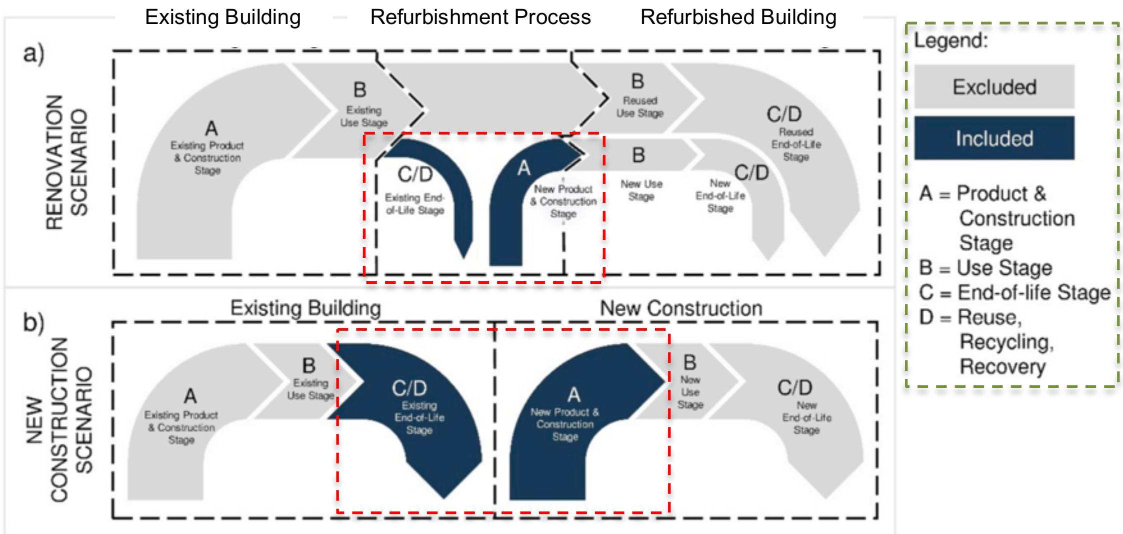


***Figure 4.6 Comparison of (a) refurbishment vs. (b) new construction scope based on the Rønning study (Source: modified from Hasik, et al., 2019)***

Moreover, researchers from the Athena Sustainable Materials Institute (ASMI) conducted a study comparing refurbishment against new construction impacts for a building at the University of British Columbia (Sianchuk, et al., 2011; Hasik, et al., 2019). The investigators took a similar approach to Rønning, et al. (2009), except they further reduced the study boundary to include only the existing building partial or full demolition (i.e., Existing EOL stage in both refurbishment and new construction scenarios) and the new building's new product and construction stage (A); excluding the new and re-used use stages (B) and the new and re-used EOL stages (C) of the new building (see Figure 4.7). The investigators took this approach because they were interested only in the impacts related to the refurbishment process, and not the whole life cycle.

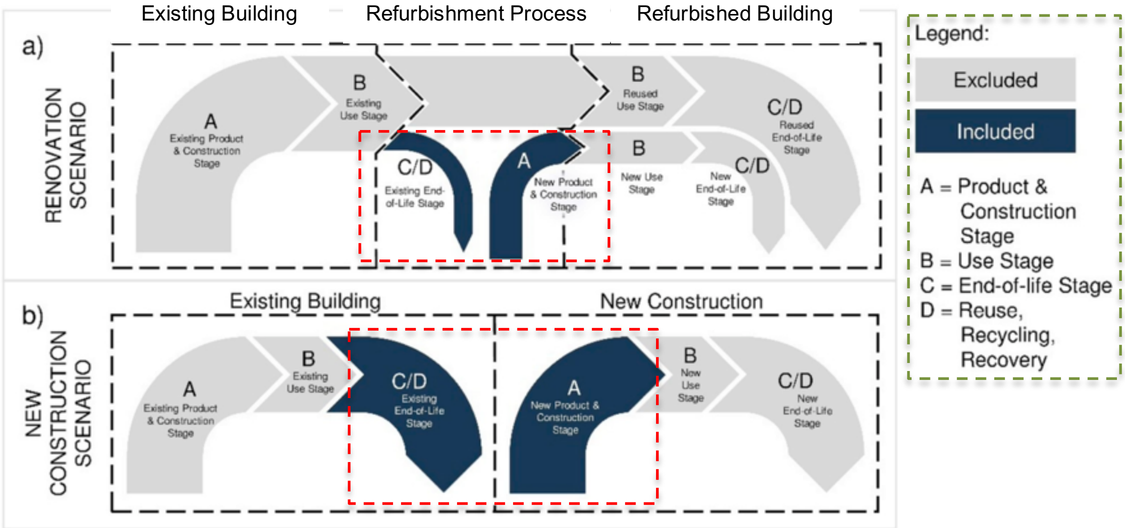


***Figure 4.7 Comparison of (a) refurbishment vs. (b) new construction scope based on the Athena study (Source: modified from Hasik, et al., 2019)***

The approach proposed in this case study by Hasik, et al. (2019) is recommended for conducting whole-building LCA on refurbishment projects to create a model for consistency and transparency in accounting for the benefits of building refurbishment. The approach uses comparatively clearer and precise terminology than previous approaches for differentiating between life cycle stages of refurbishment projects and it also defines a scope for whole-building refurbishment LCA that is consistent with the scope of whole-building LCA typically used for new construction projects. The results of this case study shows the potential benefits of building refurbishment (specifically adaptive re-use) over new construction or rebuilding from the results and outcomes achieved from Tally LCA and also highlights the major areas where waste reductions can be achieved. This shows more weight or preference towards the refurbishment scenario in terms of waste reduction, life cycle and economic impact.

To demonstrate the strength of the proposed approach, Hasik, et al., 2019 conducted a whole-building LCA of a case study adaptive re-use project and compared it to an equivalent new construction scenario. The case study validates the proposed approach and provides a model for future studies comparing refurbishment to new construction while also highlighting the benefits of refurbishment/renovation/re-use over new construction/rebuild. Furthermore, comparison of refurbish and rebuild scenarios in this case study gives an indication of the factors that aid the decision of whether to refurbish or rebuild and simplifies these key factors with situation and area specific significance of each of the key factors identified in this research project.

### 4.3.2 Goal and Scope of this Case Study

The primary goal of this case study by Hasik, et al. (2019) was to analyse the environmental impacts of a building refurbishment project and compare its impacts to a theoretical new construction scenario. The selected building in this case study is a two-story, 5,500m$^2$, stand-alone building located in an urban area in Philadelphia, PA, which was built in 1948 as a beer bottling plant, warehouse, and shipping facility. Its construction includes a braced steel frame infilled with concrete floors wrapped in multiple sections of non-load bearing masonry envelope. The building was in operation until 1980, before getting seized. (Hasik, et al., 2019). After being un-used for almost 33 years, It was acquired by an architecture firm in 2013, which re-purposed the building as their new office and workshop. The firm re-used/utilised as much of the original building as possible. However, some changes were made during the refurbishment process, which mainly included a full replacement of windows, full replacement of roof thermal and moisture layers, and the addition of raised access floors and internal partition walls (Hasik, et al., 2019).

The office required space for individual work areas, model fabrication lab, small and large meeting rooms, storage, and parking. The functional unit for the comparison is one building providing the work and support space (about 5,500m$^2$) for the architectural firm consisting of 125 employees for 60 years. The scope of the assessment of this case study included the life cycle stages and building systems as shown in Figure 4.8. This case study focused on assessing environmental impacts related to the use of building materials, and, therefore, excluded the construction installation (A5), use (B1), and demolition (C1) stages primarily consisting of labor and equipment use. For the same reason, the operational energy use (B6) and operational water use (B7) stages were also excluded by Hasik, et al. (2019), as highlighted in red in Figure 4.8.

### 4.3.3 Inventory and Analysis

In order to produce the 3D BIM model of the existing building, the structure was laser scanned and uploaded into the Autodesk Revit package. The BIM model was then manually updated based on on-site inspection, comparison to latest construction documents, and communication with the design team for the refurbishment project. The update included geometrical adjustments of individual components (where needed) and the definition of the components' materials (e.g., defining a section of a wall as a brick wall). Any components added during refurbishment were modeled in Revit based on actual dimensions and specifications as required for construction (Hasik, et al., 2019).

The next step included the use of the Tally LCA plugin for Autodesk Revit to assign LCA data to the components within the model. The LCI data within Tally is built on the GaBi LCI database as explained in Chapter three of this research project.

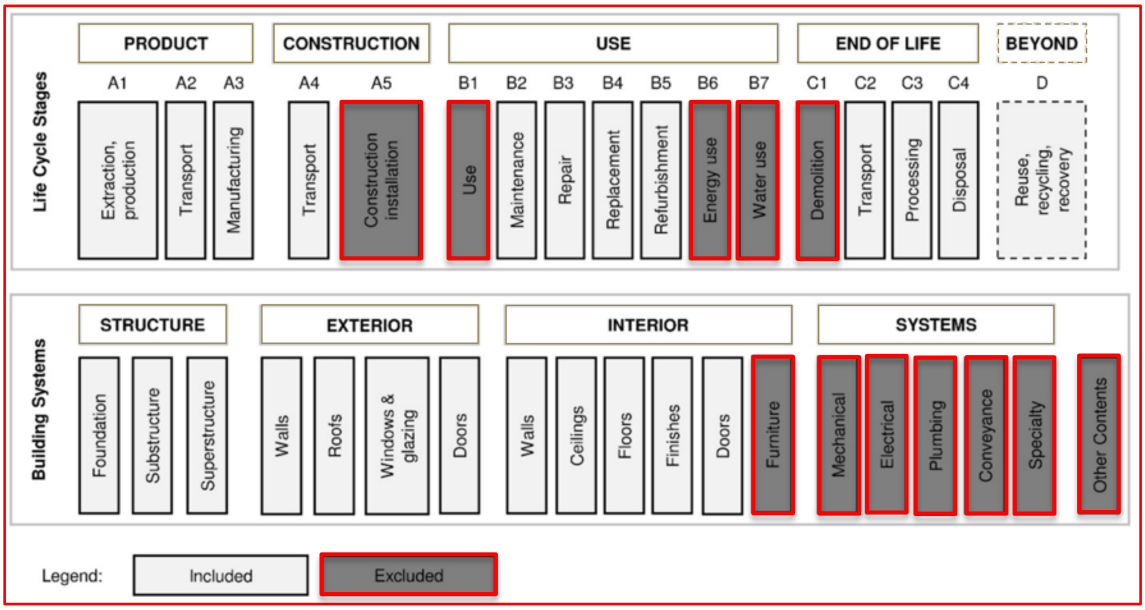


***Figure 4.8 Scope of assessment across life cycle stages and building systems (Source: modified from Hasik, et al., 2019)***

This case study used Tally's default service life data, although it should be noted that there may be different replacement needs for re-used components in the refurbishment scenario; something that was not considered in this case study (Hasik, et al., 2019). For example, Tally assumes that structural steel frame lasts the full lifetime of the building (60 years in this study); however, the selected building's steel frame had already been in service for 65 years at the time of the refurbishment (Hasik, et al., 2019).

The BIM model included all component types that Tally can assess; this includes ceilings, curtainwall panels and mullions, doors, floors, roofs, stairs, railings, structural columns and framing, walls, and windows. Electrical and mechanical equipment, controls, plumbing fixtures, fire detection and alarm system fixtures, elevators, furnishings, excavation and other developments are not in the scope of this assessment.

The two scenarios (refurbishment and new construction) considered in this case study by Hasik, et al. (2019) required results from two separate Tally assessments corresponding to two different phases of the project namely:

1. Existing (i.e. original structure);
2. New (i.e. components added during refurbishment).

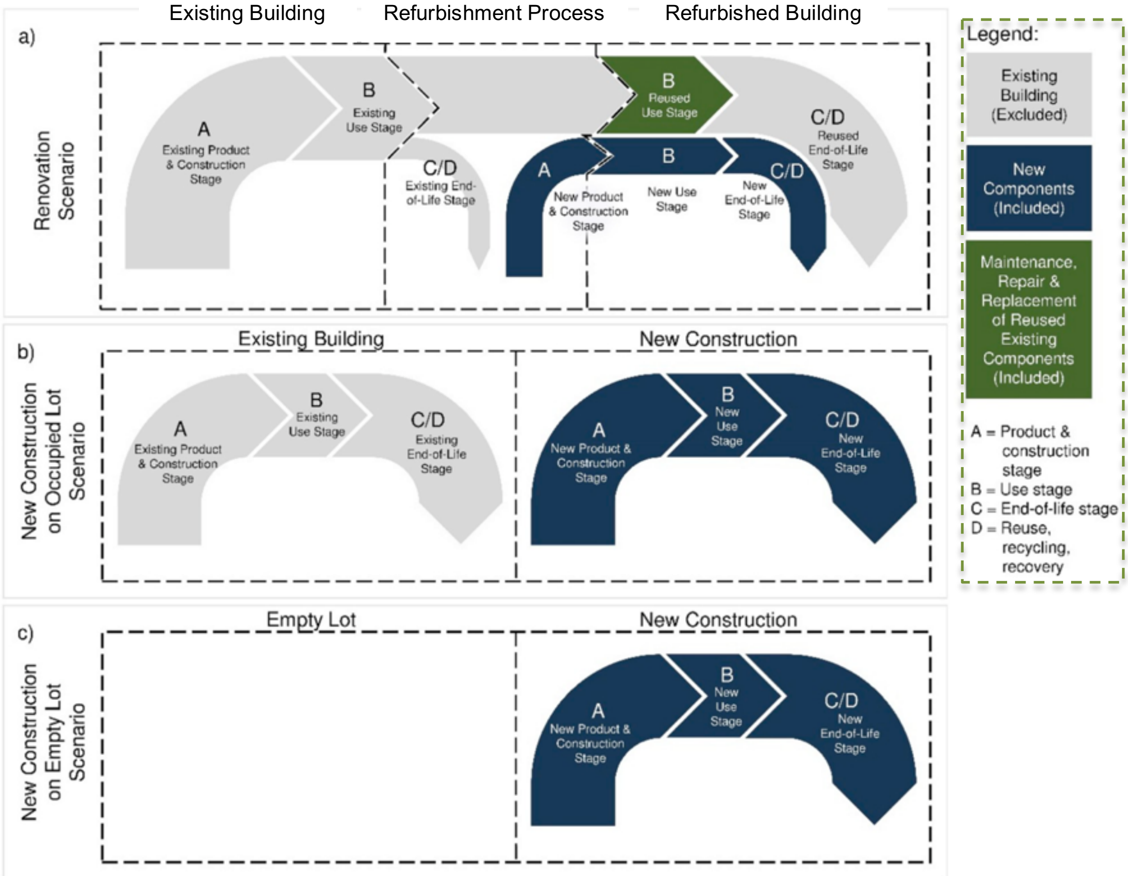


***Figure 4.9 Recommended scope for comparative LCA of (a) refurbishment scenario to (b) new construction scenario (Source: modified from Hasik, et al., 2019)***

In this case study, Hasik, et al. (2019) did the comparison of refurbishment to new construction according to the scope shown in Figure 4.9 by selectively combining relevant stages for the new construction and refurbishment scenarios. Environmental impacts associated with the new construction scenario were calculated by combining results from both the existing and new phases of the project and including all life cycle stages, as shown previously in Figure 4.9b. Refurbishment impacts were calculated by combining all life cycle stages of the newly added components and the use stage of the re-used components as previously shown in Figure 4.9a.

### 4.3.4 Impact Assessment Method

As discussed previously, Tally LCA software calculates environmental impacts based on the TRACI 2.1 impact assessment method (Hasik, et al., 2019), further details on Tally LCA assessment methods are discussed in Chapter 3. While TRACI 2.1 normally includes both environmental and human health impact categories, this case study by Hasik, et al. (2019) focused only on environmental impact categories that can be assessed using Tally. This primarily includes the following six impact categories: acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone depletion potential (ODP), smog formation potential (SFP), and non-renewable energy demand.

### 4.3.5 Refurbishment Results

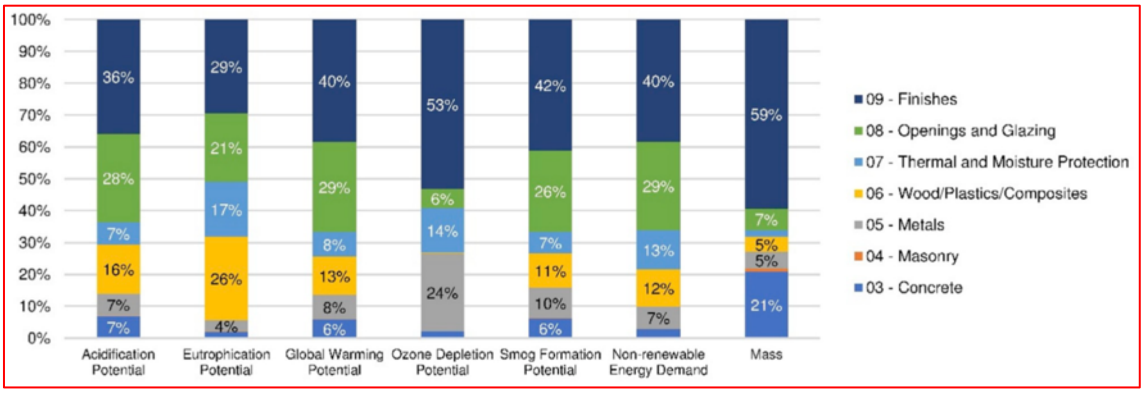


***Figure 4.10 Life cycle impact assessment refurbishment results by CSI division (source: modified from Hasik, et al., 2019)***

Figure 4.10 shows the refurbishment results by Construction Specification Institute (CSI) Master Format Division. Finishes (59%) and Concrete (21%) produce the majority of the mass of components within the refurbishment scope. The masonry division can be avoided in terms of mass and all impact categories as the only new components falling within this division are small areas of added CMU and brick walls. The mass associated with other divisions are fairly and evenly distributed across the remaining 20%.

Finishes contributed to 29–53% of impacts across all categories and include components such as raised access floors, gypsum board, ceramic tiles, carpet, paint, and self-leveling concrete floor. Accounting for 20% of the global warming potential (GWP) of refurbishment, the raised access floors were the largest single contributor to impacts in this division due to the steel and concrete in the floor panels. The impact of the panels is doubled because of the expected service life of 30 years, requiring full replacement at least once during the lifetime of the building. The expected service life was based on an Environmental Product Declaration (EPD) for a similar raised access floor; however, the actual service life could be substantially shorter or longer depending on the actual use and maintenance conditions. Carpet and paint were the next two largest contributors in this division, accounting for about 6% and 5% of refurbishment GWP respectively. These impacts are extremely large, when compared to the 2% contribution of each of these components contributed to the mass of refurbishment materials. The painted areas included exposed structural elements which accounted for a third of the paint's global warming potential. It is important to note that the impact of the paint on structural steel is likely an over-estimate given the use of a default 10-year replacement (repainting) cycle.

Since there was not much added concrete during the refurbishment, the impacts from the concrete division were minor. The largest impacts were seen in the acidification, GWP, and smog categories, accounting for about 6–7% of those impacts. The concrete was mostly added for floor infills, floor leveling, retaining wall repair, and new concrete sills (Hasik, et al., 2019).

Although the wood/plastics/composites and thermal and moisture protection divisions account for only 7% of mass, the two divisions combined contribute to over 14% and up to 49% of impacts across all impact categories. Components in the newly added roof and skylight are the primary contributors. The skylight panels (made of glass fiber reinforced plastic) and the EPS insulation are the two materials with highest impacts, especially in the eutrophication, global warming, and energy demand categories (Hasik, et al., 2019). The reasons for these components' disproportionate impacts are that they are both plastics made of fossil fuels, using energy intensive production processes, and that both are difficult to recycle (i.e. both are assumed as 100% landfilled at EOL in Tally).

Openings and Glazing account for 7% of mass but over 20% of impacts in all categories except for ozone depletion. The primary contributors in this division are the aluminum frames (33% by mass) and glazing units (51% by mass) in the newly added windows. The aluminum frames are especially carbon and energy intensive, accounting for 67% of the division's global warming potential impacts and 70% of the primary energy demand. Other components within this division include door frames and hardware.

The metals division accounts for comparatively small portion of the impacts across all other categories. The only exception is the ozone depletion category where it accounts for 24% of the impacts; however, it should be noted that the absolute results in this category are small overall. Since there was minimal addition of structural elements during the refurbishment, most of these impacts come from steel studs in partition walls and stairs.

### 4.3.6 New Construction Results

As shown in Figure 4.11, the concrete and masonry divisions account for the majority of mass in the new construction scenario (58% and 22% respectively), with finishes accounting for 12%, metals for 8%, and all other divisions accounting for about 1% each. concrete is also the major contributor to the acidification, global warming and smog formation potential categories, accounting for 46%, 38%, and 43% of those impacts respectively. In all other categories, concrete accounts for 15–23%. Since the building is primarily supported with a steel structure, it is possible that much of the concrete and its cement content could be lower if current practices (e.g. concrete mixes with supplementary cementitious materials) were used for similar new construction project (Hasik, et al., 2019).

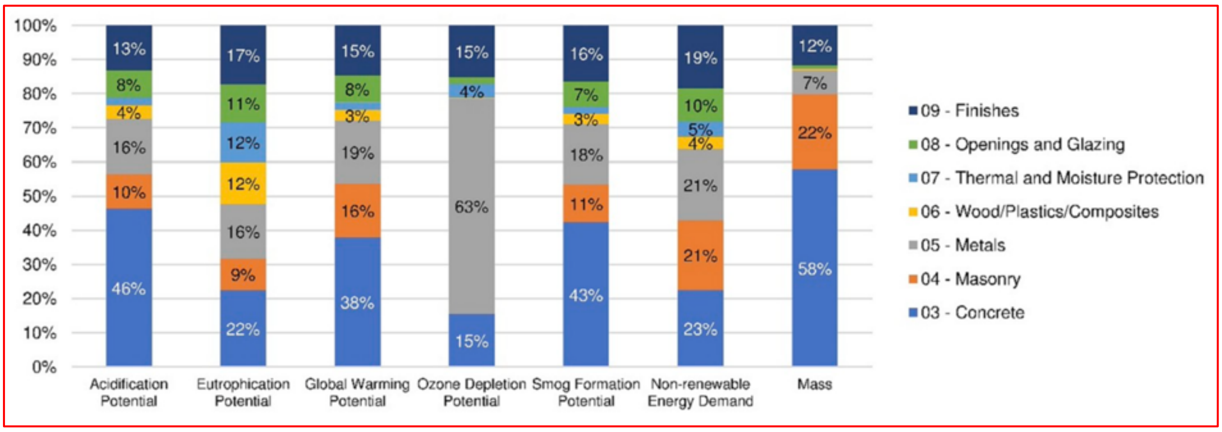


***Figure 4.11 Life cycle impact assessment new construction results by CSI division (source: modified from Hasik, et al., 2019)***

Hasik, et al. (2019) mentioned that metals' contribution of 63% to ozone depletion potential (ODP) is primarily due to the hot-rolled structural steel in the structural frame (77% of Metals' ODP); however, the absolute results in this category are relatively small. As the building for this case study was originally designed to carry heavy machinery on each of its two main floors, the steel members may potentially be larger than what would be necessary for the construction of a modern office building. As such, the amount of hot-rolled structural steel would likely be lower in a new construction project for commercial use (Hasik, et al., 2019). The masonry division from the performed analysis consists mostly of brick and mortar used in the building facade.

### 4.3.7 Comparison of Results

In this case study by Hasik, et al. (2019), refurbishment helped in avoiding between 53-75% of the impacts from the new construction scenario (see Figure 4.12). The largest reductions in environmental impact and building mass were observed in the concrete, masonry and metals divisions. The wood/plastics/composites, thermal and moisture protection, and openings and glazing divisions saw little to no changes between new construction and refurbishment, as shown for the GWP category in Figure 4.13. This is because many components falling within these divisions had to be replaced during refurbishment or have shorter lifetimes. The most notable contributors in these divisions are the newly added roof and windows.

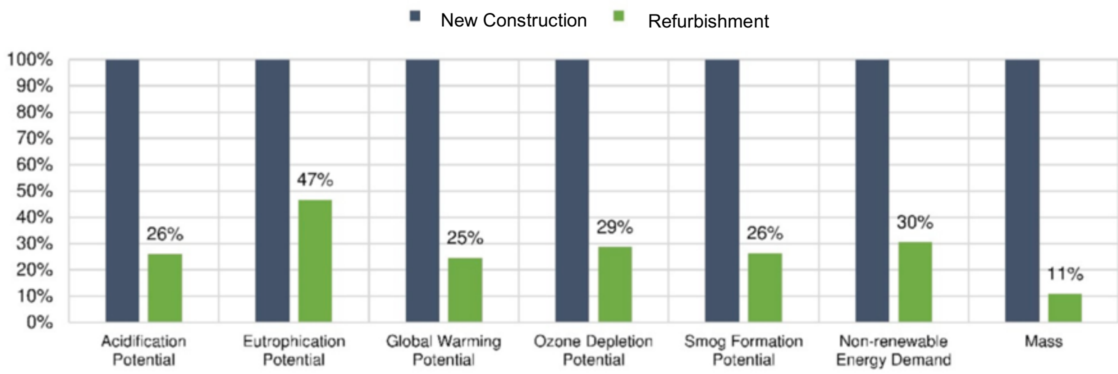


***Figure 4.12 Comparison of the total life cycle impacts of new construction and refurbishment (source: modified from Hasik, et al., 2019)***

The finishes division saw only a slight percentage reduction between the new construction and refurbishment scenarios (see Figure 4.13). Components falling within this category are the interior terracotta wall tiles that were retained from the existing building (for new construction), and floor finishes, partition walls, ceilings, carpet, and paint added during refurbishment (Hasik, et al., 2019). Raised access floors added during the refurbishment were the largest single contributor to impacts in this division, amounting to 20% of GWP of refurbishment and offsetting some of the benefits that would be associated with re-use of an existing floor.

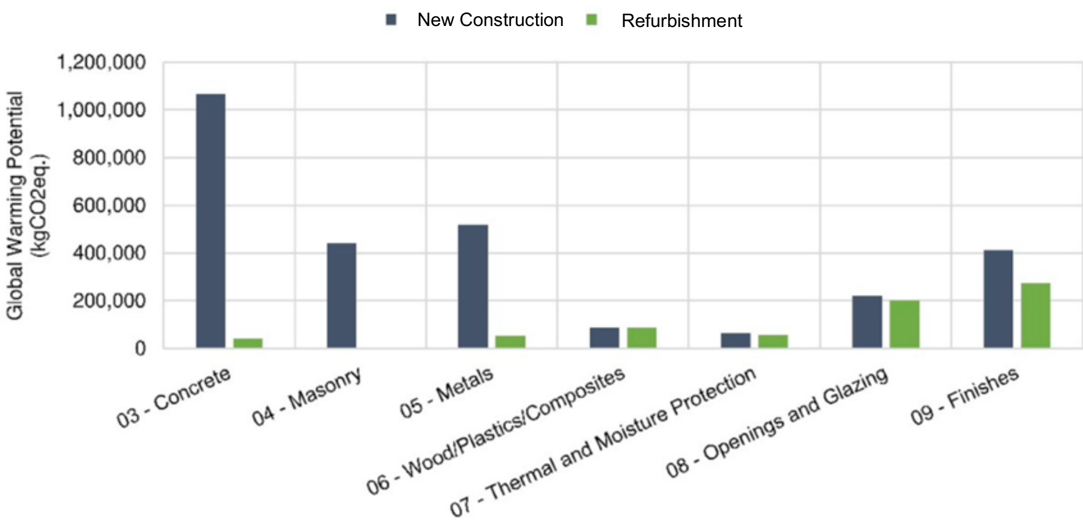


***Figure 4.13 Global warming potential by CSI division for new construction and refurbishment (source: modified from Hasik, et al., 2019)***

### 4.3.8 Outcomes from this Case Study

Studies conducting LCA of building refurbishment projects typically face the issue of defining an appropriate study boundary and selecting the right scenarios for a comparative assessment (Hasik, et al., 2019). Defining the study boundary involves selecting life cycle modules to be included for the existing building and for the newly added building components. Comparative assessment scenarios may include the existing building in its original condition, existing building with functional improvements (e.g. energy or structural retrofit measures), new construction substituting the existing building on the same site (where the existing building must be demolished), and new construction on an empty lot.

The EN 15978 standard defines refurbishment as a sub-module of an existing building where the full life cycle of all newly added components is counted towards the refurbishment. Based on the standard and the building refurbishment boundary described in Vilches, et al. (2017), the use stage (module B) of the re-used components from the existing building should also be included as impacts of refurbishment, as the prolonged life-time of the building may result in additional use, maintenance, repair, and replacement of the retained components (Hasik, et al., 2019). However, the standard is unclear in its description of what elements of waste management should be included. Therefore, Hasik, et al. (2019) recommended including modules A-C of newly added components together with module B of the reused components when calculating the impacts of refurbishment and comparing it to a new construction scenario.

The refurbishment scenario of this case study by Hasik, et al. (2019) was found to help reduce environmental impacts associated with the life cycle of building components by 53–75%. The most significant components added during refurbishment were the roof, access floors, and new windows, while the new construction scenario was overwhelmingly burdened by manufacturing intensive structural (concrete and steel) and envelope components (brick and terracotta walls). These findings are consistent with other studies finding structural and envelope systems to account for majority of embodied impacts of buildings (Scheuer, et al., 2003; Bribián, et al., 2009). The case study illustrates that these building elements may have longer effective lifespans than the typically assumed 50 or 60 year study period used for building LCAs, and their reuse can therefore greatly reduce the burdens associated with constructing new buildings. Another finding is that interior upgrades contributed to large percentages of the impacts associated with refurbishment. The case study also showed the strength of the proposed approach by allowing for direct comparison with a new construction scenario using a consistent boundary and scope (Hasik, et al., 2019).

This case study by Hasik, et al. (2019) explains the in-depth use and utilisation of Tally (LCA) plug-in tool for Revit BIM package. Using the same terminolgy of this case study, the Tally trails in this research project are performed for the application of the key identified decision-making factors.

## 4.4 Evaluation of Key Identified Waste Causing Factors

Following the identification of the waste causing factors and the life cycle comparison from the case studies in previous sections of this chapter, below are some of the key measures that would help in the mitigation of these factors. Taking account of these measures and the waste causing factors during the development of the frameworks, would help in achieving the desired outcome in the shape of the key decision-making factors.

### 4.4.1 Contractual clauses to penalise poor waste performance

A good practice is to penalise the sub-contractors or trade contractors for poor waste management. This is achievable by adding a clause in the contract of each of the sub-contractors, which normally includes measurement benchmarks linked to specific financial penalties for wasteful work practices. By instructing each sub-contractor to provide weekly or monthly data on waste arising, management and disposal, this provides an audit of where the waste is being generated, so that it could be prevented on the future projects (Danity & Brooke, 2004). This initiative would let the sub-contractors to make sure that they follow the right procedure for waste minimisation.

### 4.4.2 Supply chain alliances with suppliers/recycling companies

This measure aims at dealing with waste in the most effective manner to reduce the impact produced (Danity & Brooke, 2004). Partnerships with suppliers could lead to excessive materials being removed, re-processed and in some cases, re-used. Such practices are also supported with financial incentives for waste minimisation in highly reputed companies.

### 4.4.3 Improved education of the workforce

It has also been identified from the first case study of this chapter that attitudes of operatives or site workers/labours also accounts for a significant proportion of on-site wastage (Ali, et al., 2018b). “Toolbox talks” are a strategy followed on most of the C&D projects to educate operatives in the benefits of waste minimisation and promote better environment. Hence, education needs to be promoted within the industry and more waste related courses need to be introduced for the improvisation of the workforce in terms of waste management, handling and minimisation.

### 4.4.4 Design management to prevent the over specification of materials

Avoiding over specification is often identified as offering considerable scope for financial savings on all of the construction projects (Danity & Brooke, 2004). The appointment of dedicated design managers with a brief to minimise waste is often seen and acknowledged as a proactive and effective step in ensuring waste reduction (Ali, et al., 2018b).

### 4.4.5 Stock control measures to avoid the over ordering of materials

As discussed in the case study one of this chapter, over-ordering of materials emerged as a particularly significant area of site management control leading to materials wastage (Ali, et al., 2018b). Tighter and strict stock control measures leading to the careful monitoring of on-site progress would surely help to reduce the amount of unnecessary waste. Merely raising awareness of this issue amongst site managers had demonstrably shown to reduce waste levels in several of the case study projects in the past (Danity & Brooke, 2004).

### 4.4.6 Standardisation of design to improve buildability and reduce the quantity of off-cuts

Standardisation of design/plan has the potential to dramatically reduce the current production of construction waste. A substantial reduction in off-cuts could be achieved by designing room areas and ceiling heights in multiples of standard material sizes (Ali, et al., 2018b).

### 4.4.7 Environmental assessments of the project during the design phase

One of the subject related case studies had shown the benefit of conducting regular design and production reviews where the waste minimisation strategies were considered as a primary performance criterion (Danity & Brooke, 2004; Ali, et al., 2018b). This has to be permanently incorporated as part of the design development process that would ensure the building meet the client's criteria with the minimum waste production during all phases of the project (Ali, et al., 2018b).

## 4.5 Development of Framework Towards the Identification of Key Decision-making Factors

This section highlights different scenarios for the existing building that is being considered refurbish or rebuild and newly build structure that would be considered for the same decision-making process when it reaches the end of design life (EODL). Based on these scenarios, multiple frameworks have been developed in this section that highlights the key factors, which will be further used and revised for the identification of the key decision-making factors for refurbish and rebuild. Following are the scenarios that needs to be taken into account for the decision-making process:

### 4.5.1 If the building is in use or not?

If a building is being considered for any renovation/refurbishment or full demolition, it is recommended to identify and consider its current use. Knowingly, there will be two cases:

**Case 1:** If the building is not in use, then there is a need to find out the total time the building is not being used for. If it has been discarded for several years, it may be the case that the building has now reached the end of its design life or the structure may have become weak due to the building not being serviced or maintained. Also an asbestos survey is mandatory if the building was built before the year 2000 in order to comply with the Control of Asbestos Regulations 2012 (Kim & Hong, 2017). Once the survey is done and asbestos (if found) are removed by the asbestos removal company, the building will then be in a position to be considered for modification or rebuilding. The flowchart in the Figure 4.14 represents the initial procedure for the decision-making of the building that is not in use.

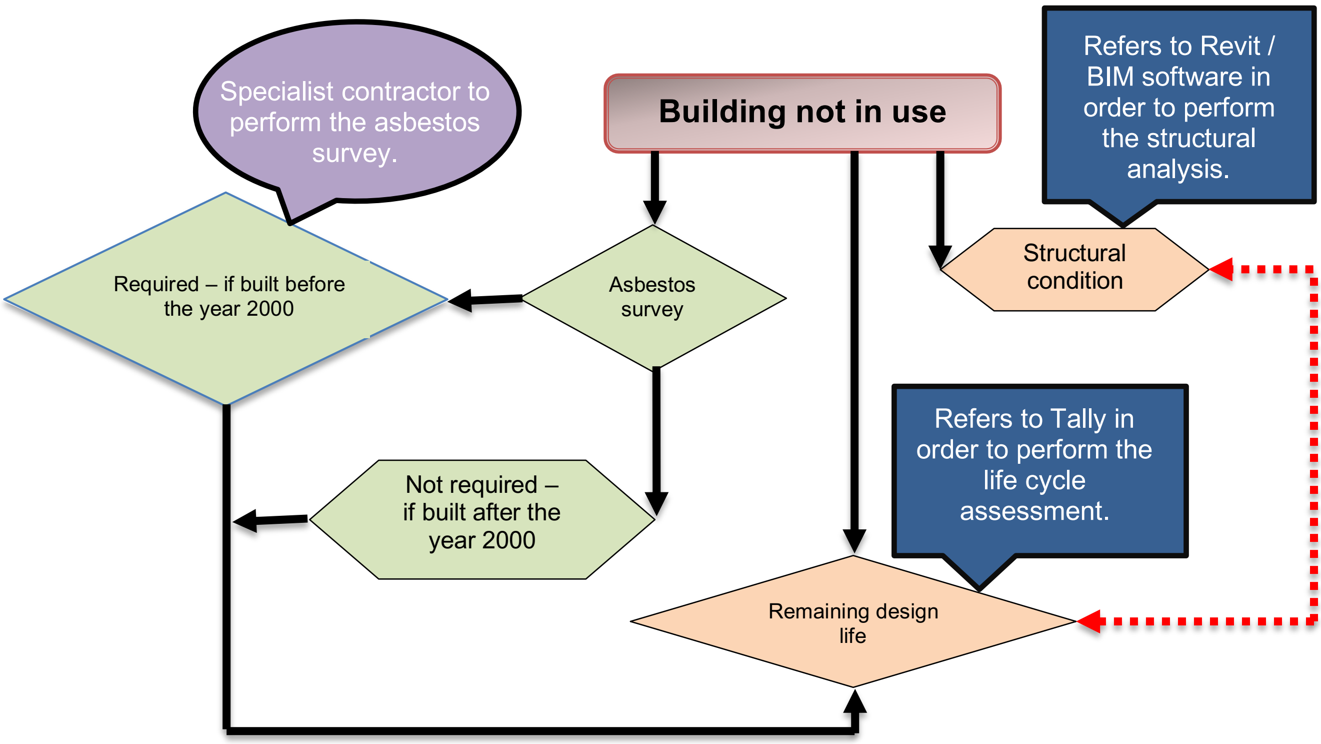


***Figure 4.14 Framework for building not in use (Source: The Author)***

Further strategy will be depending upon the type of construction or development the owner wants to do. However, after the removal of asbestos, the owner can legally hire any designer or a consultant for a better advise on the proposed development of the site.

**Case 2:** If the building is in use, there is a need to check if the proposed development will have any direct or indirect impact to its current use. There are two scenarios in this case.

**Case 2a (Change of use):** If the building is currently being operated as a hotel and the proposed development is a conversion into an educational institution, then the following questions will need to be answered and addressed:

Q1) Is the current structure sufficient enough for the educational purpose?

- Of course, the layout of the hotel will not be sufficient for the educational purpose. However, there can be changes or refurbishments within the main structure of the building such as, removal of partition walls between the two or 3 three rooms in order to merge them as one and convert into a classroom or lecture room. Similar changes can be done internally to achieve the outlook of an educational institution, but on a larger scale, this may be difficult and could cost more money and time. For a change of use, not only the internal partitions need to be adjusted but also the plumbing and electrical fixtures will need to be redone.

Q2) What is the remaining design life of the existing building?

- If the existing building is reaching the end of its design life, then the most preferred option is to demolish and rebuild. This will fulfil all the necessary requirements for the design of the educational institution and a newly developed building will also be in place with a design life of 60-125 years (Dias, 2013). However, the heritage buildings have a design life of more than 300 years because of the durability of the material and proper maintenance (Iyer-Raniga & Wong, 2012). Furthermore, inspection, repair and maintenance of heritage buildings are being done on a regular basis, as these structures have utmost importance in the society due to their history. Also, the planning for new development on the heritage building sites are not permitted, thus these buildings are out of equation in this scenario.

**Case 2b (No change of use):** If the building is being considered for an upgrade with no requirement to the change of use to the property, then the most preferred option is the modification/refurbishment of the building and this is the normal practice followed within the industry. However, this factor is considered for the development of the decision-making framework, some additions and details of other aspects linked to this factor, are required.

Once it has been established that the purpose of building will remain the same, the probability then favours refurbishment as the feasible option in most cases, but the proposed framework is about having an equal balance between cost and the environmental impact including the reduced waste generation. Thus, in order to achieve this and come up with a strategic solution, some questions need to be answered and addressed:

Q1) What is the remaining design life of the existing building?

- Refer to the answer of Q2 in scenario 2a.

Q2) What is the maintenance cost of the existing building?

- When considering the option to refurbish any existing building, it is very important to check the current cost of maintenance of the building and its $CO_2$ emissions (this can be achieved from the LCA of the building). If the maintenance cost of the building is significantly higher than the newly build structure, then the demolition and rebuild will be a feasible option. Of course, this would cost more initially but it will be economical in the longer run both in terms of cost and the environment.

Q3) How much area is required for the upgrade?

- The size of the upgrade work has to be taken into account because it will determine the cost of the project. For this purpose, the evaluation of the area required for the proposed change of use, needs to be done. The proposed area will determine if the proposed development can actually be built within the existing site area.

Q4) What is the cost of upgrade?

- Lastly, there will be a need to figure out the approximate cost of the upgrade works. The proposed development can be of any size depending upon the nature of the proposed commercial use and the minimum capacity required for operational staff and visitors. In the proposed framework in Figure 4.15, the cost is calculated via Revit cost calculation tool. The Revit model will later be used to input building data, including every material and component quantity, information and classification into Tally for life cycle assessment (LCA) of the structure and its components, similar to the second case study of this chapter.

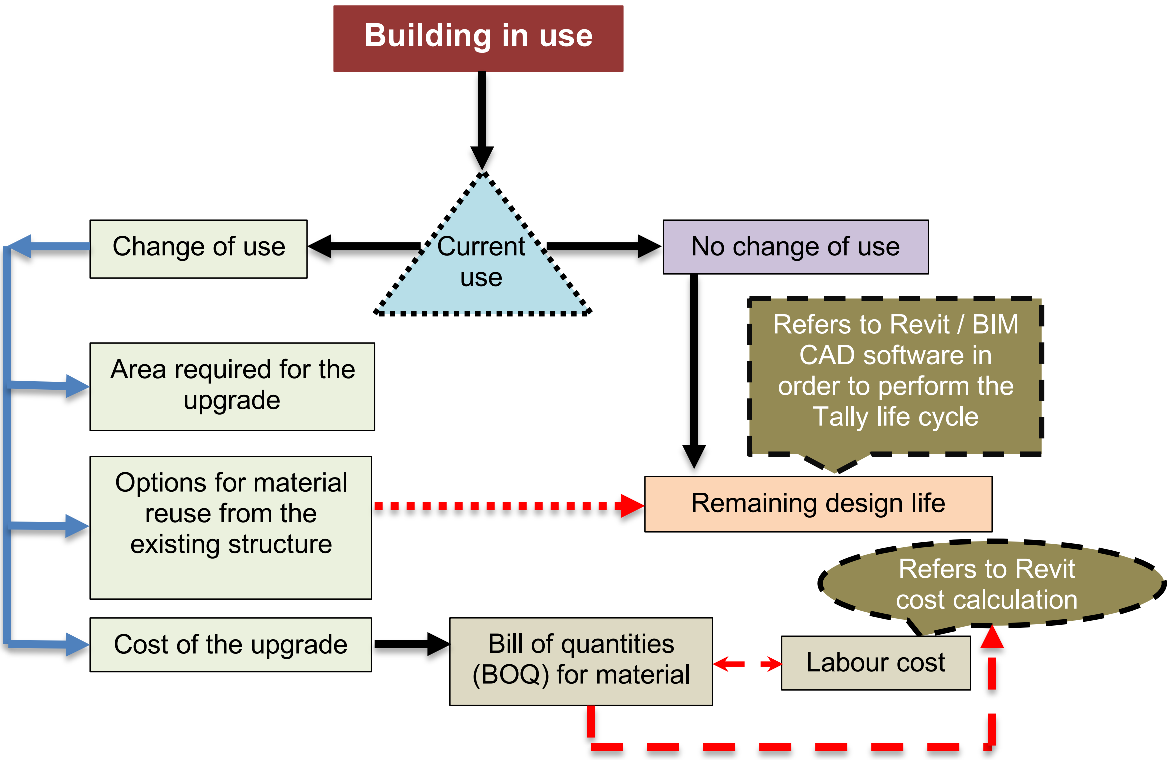


***Figure 4.15 Framework for building in use (Source: The Author)***

### 4.5.2 Current use of the building

This section is linked with the previous section. If the building is in use as stated in the previous section, there is a need to determine if it is commercial or residential? Similarly, again there will be two cases.

**Case 1:** Supposedly, if the building is residential and located in an urban area, a consent will be required from the neighboring properties for demolition and rebuilding of the new property at the proposed development premises. There are different types of residential buildings with different development perspectives. Some of the main types of residential buildings and the possibilities of development for each type are listed in Figure 4.16.

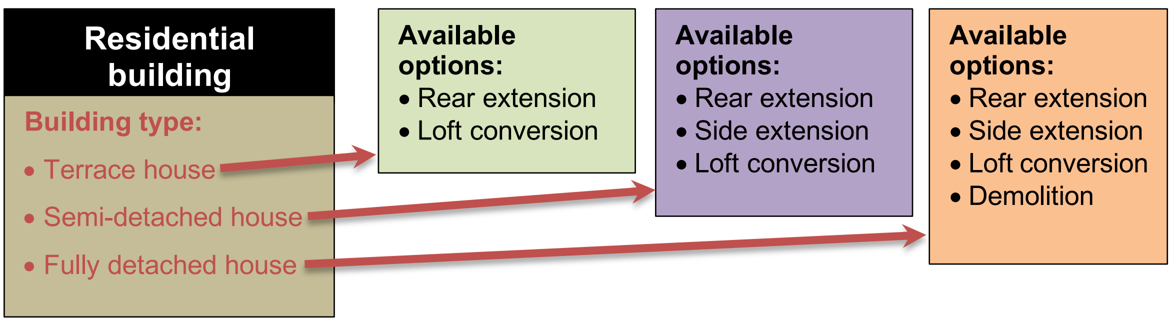


***Figure 4.16 Residential building types and development possibilities (Source: The Author)***

Hence, in terrace and semi-detached houses, there will be no possibility of getting the planning permission for the demolition as the terrace houses are fully attached from both sides and semi-detached houses are attached on one side and detached on another.

This section concludes that demolition and rebuilt option is only applicable for the fully detached houses. Thus, the terrace and semi-detached houses will only have one option for refurbishment and extension. However, in this case, the decision-making framework will be useful in the creation of waste-efficient design for extension or refurbishment.

**Case 2:** If the building is listed as commercial, there will be a need to address and comply with the planning policies for commercial buildings. All the relevant policies are highlighted in the Town and Country Planning Act 1990.

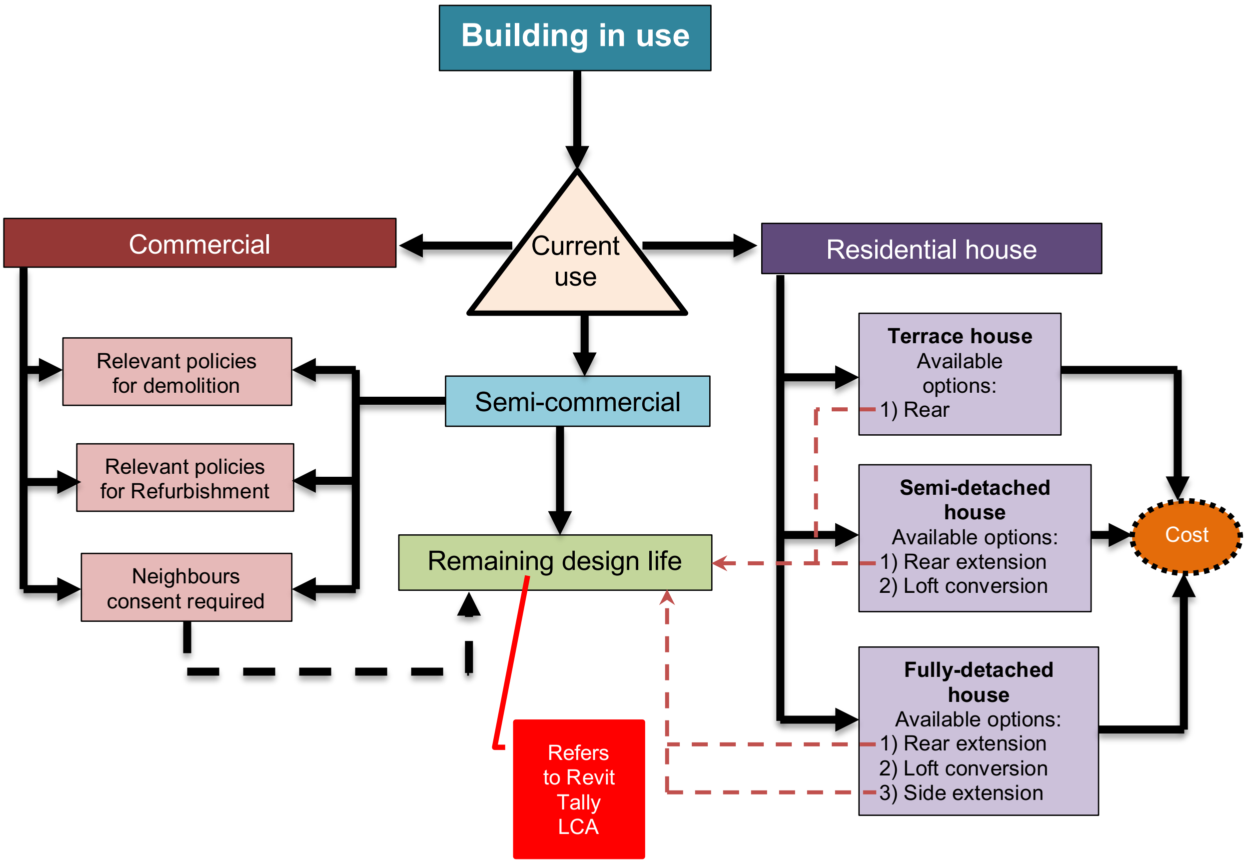


*Figure 4.17 Framework for the change of use scenario (Source: The Author)*

### 4.5.3 Location of the building

Location of the building is one of the primary factors, which plays an important role in the decision-making of whether to rebuilt or refurbish.

For instance, if the building is located in an urban area with too much public movement and local amenities are located within a walking distance, it will be difficult to get the planning permission for a demolition and rebuild project, as this will affect the everyday life of the local community and will also have a considerable negative impact on the environment. In addition, many documentations and supporting documents such as, neighbours' consent, environmental assessment, flood risk assessment (if the building is located within the flood risk zone), health and safety assessment (HSE), design and access statement with detailed demolition plan, etc. will be required in order to get the planning application approved by the Local Planning Authority (LPA).

In order to generate all the above listed documents, a well experienced and competent consultant/surveyor will need to be hired. And indeed, there will be a higher cost to it. Therefore, it is vital to consider the location of the building before coming up with any decision of whether to refurbish or rebuild.

### 4.5.4 Current state of the building

Before assessing a building for any type of construction work, it is necessary to check its current state. This will determine the maximum number of materials within the building that can be reused or recycled, such as doors, windows, handrails, beams and sanitary etc. Probably, a relevant building survey will do the job.

In normal practice, waste audits (or pre-demolition audit as defined in the European Demolition Protocol) are carried out before any refurbishment or demolition project, for any materials to be re-used or recycled, as well as for hazardous waste. However, any demolition, refurbishment or construction project needs to be well planned and managed in order to reduce environmental and health impacts while providing important cost benefits. Based these analyses, there should be a decision criteria for refurbishment, when a building has more than 50% of remaining design life. The 50% indicated here is a good threshold, which represent an average reasonable value for decision-making in general, which is suitable for this kind of application considering the role of the economic cost and the environmental impact. This includes all the other factors and material assessment too such as life of individual component in a building, condition of electrical fixtures and plumbing lines and the overall assessment of the design life based on these individual assessments. However, the structural life of the building remains in priority within the list of above identified factors for assessment. If the building structure has more than 50% remaining design life, only then other components should be considered for the design life assessment.

Below, the Figure 4.18 highlights the factors to consider and the calculation process to calculate the percentage out of the total material that can be re-used or recycled.

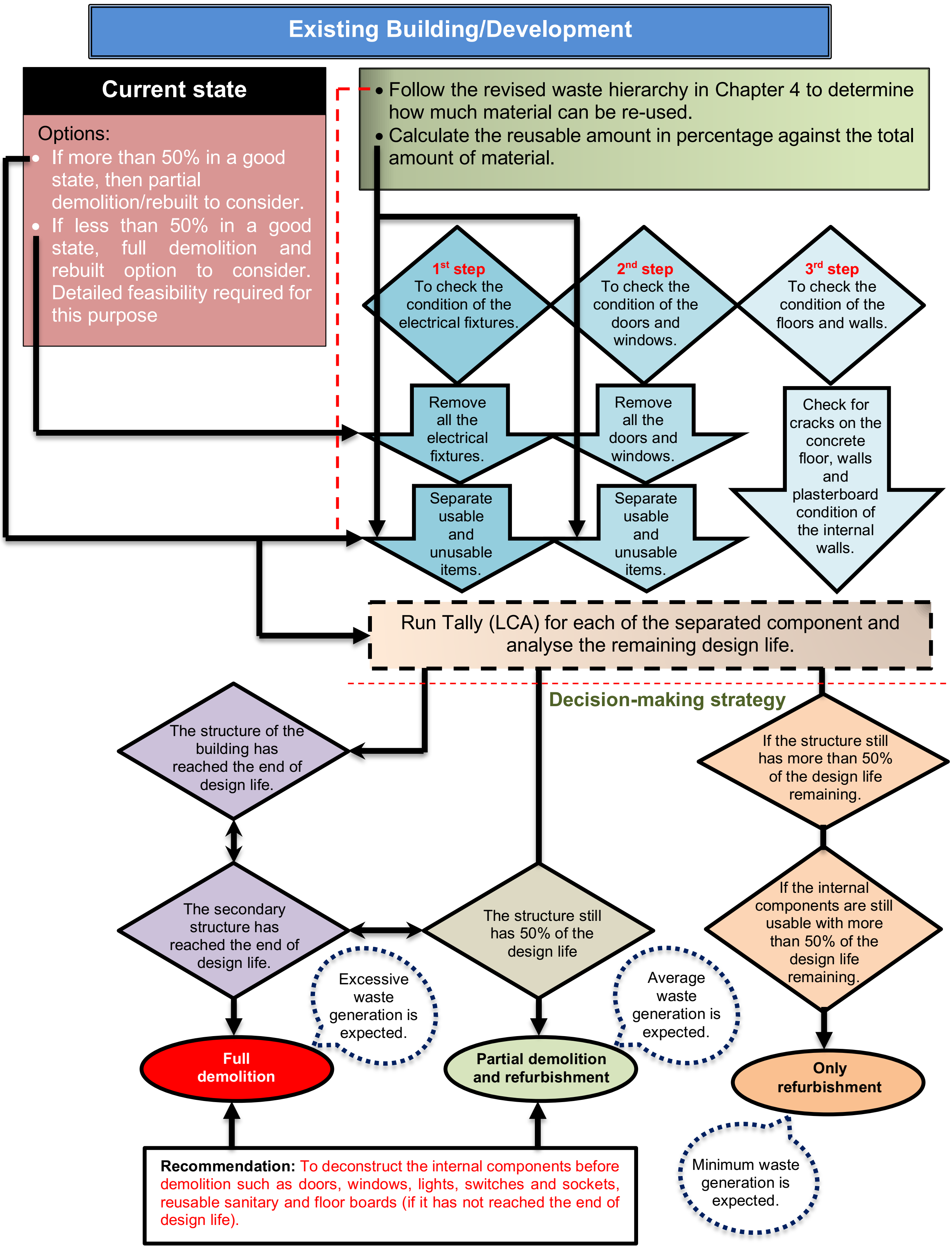


*Figure 4.18 Proposed decision-making framework for existing buildings (Source: The Author)*

The proposed framework in Figure 4.18 establishes the initial criteria for the decision-making of existing buildings. This decision can be made once the life cycle assessment (LCA) has been performed on Tally for each of the components of the building. Based on the remaining design life of each of the components and overall percentage of remaining design life of the building, a decision can be made that should favour the less environmental impact, least waste generation and less cost. This framework complies with relevant British Standards (BS) code of practice BS 15686-1 and BS 15686-2 (BS ISO 15686-1, 2000; BS ISO 15686-2, 2001), as it incorporates assessment of the design service life of buildings via Tally. Considering the fact that an existing building can have various scenarios such as current condition, existing design life and condition of the individual components (doors, windows, floor, roof) etc., the framework in Figure 4.19 proposes some steps to be taken before assessing life cycle assessment of an existing building. Having the initial steps being properly considered and followed would let the designers to make the design-making easily when they reach the final step of performing the life cycle assessment of the Revit model on Tally.

In normal practice, consideration is usually given to full demolition once it has been decided that the existing building cannot be reused or refurbished. In some cases, where the design life of material reaches its end, then the structure gets retained, while the rest of the components are demolished or removed. However, with 50% remaining life of a building, it is economically and environmentally feasible to refurbish or partially rebuild and demolish the building, as this will reinstate the building to its original condition and add some more operational life to it.

The framework in Figure 4.19 highlights the decision-making criteria for newly designed buildings. Following the evaluation of different scenarios discussed in the previous section of this chapter, it has been observed that new structures have relatively less factors to consider as compared to the existing ones. The main reason is the design life of the structure, as the new building has a full design life and has all the new components that complies with the latest British Standard codes. This also indicates that the cost would play a major role between the comparison of the two structures. A newly designed building is more efficient in terms of less $CO_2$ emissions and has less maintenance cost.

For newly designed building, the considerations are generally given to refurbishment scenarios, as they have a high remaining design life. However, in this research project, different scenarios are considered for the newly designed structures that resulted in different outcomes for each scenario. Although, the basic rule of maximum design life consideration is applied to all new buildings. The proposed framework in Figure 4.19 incorporates with the relevant British Standard codes BS 7543, BS 15686-1, BS 15686-2 and BS 8000.

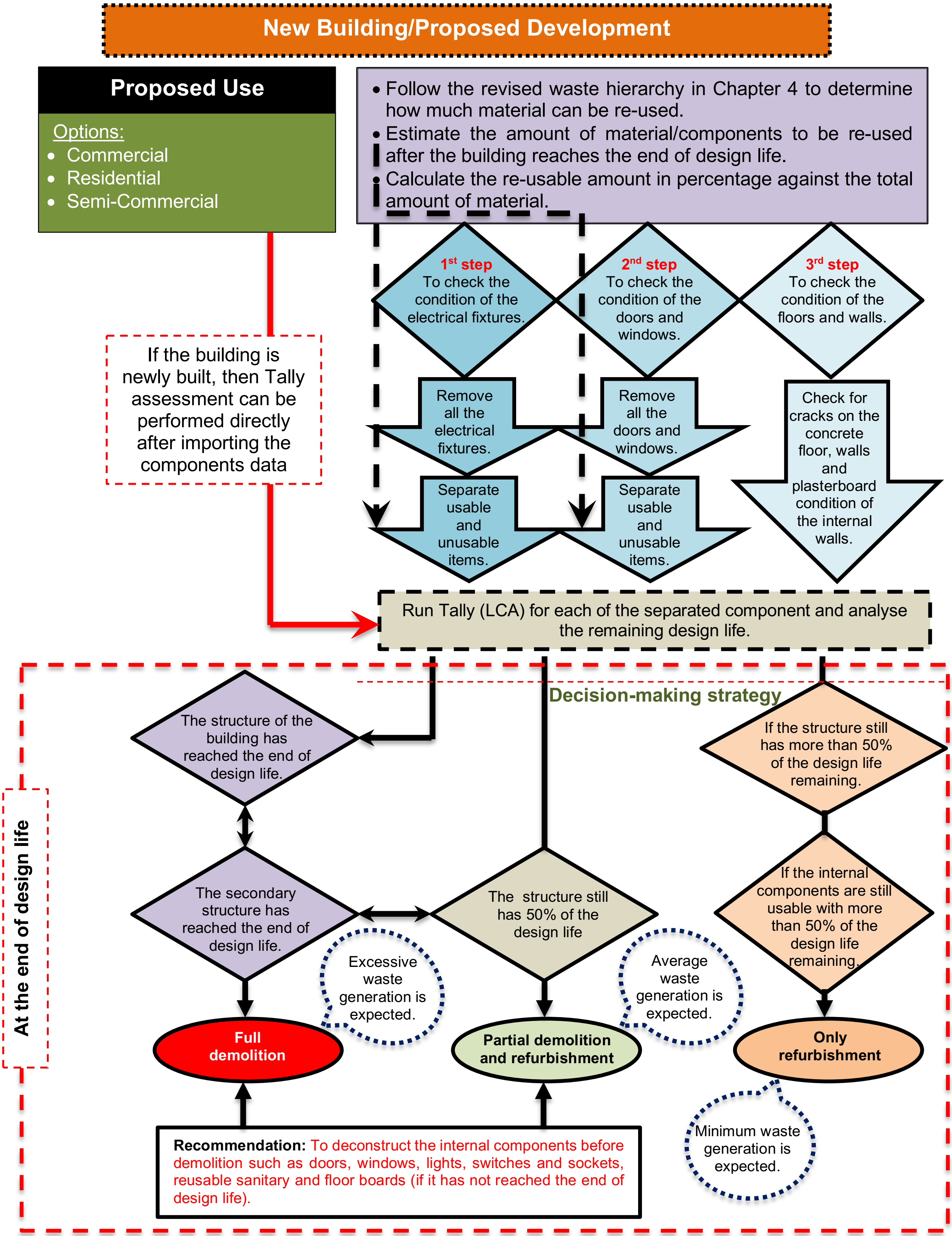


*Figure 4.19 Proposed decision-making framework for new buildings (Source: The Author)*

## 4.6 Road Pavement Condition – Modes of Failure and Related Recycling and Refurbishment

### 4.6.1 Why Pavement Deteriorates?

Pavement mainly deteriorates due to the following reasons (Ali, 2001):

1 Traffic Loading;
2 Weather Effects (temperature changes and moisture);
3 Chemical Attacks;
4 Hydraulic Attacks;
5 Weathering and aging of pavement binders and materials;
6 Bad design and construction and lack of maintenance.

### 4.6.2 When is needed to Rebuild or Repair a Highway Pavement?

It is recommended to rebuild the highway pavement when it fails due to one of the following modes of failure, in which the first mode is the pre-dominant mode of failure for the corresponding type of pavement.

**1) Modes of Failure of Flexible (Asphalt) Pavement**

a. The predominant mode of failure is pavement deformation (rutting). This takes the form of a structural rutting i.e. when there is a subgrade rutting, which cause all the pavement layers to rut and deform because of the loss of the foundation strength in terms of the loss of sub-grade support. The reasons for this could be a reduction in the bearing ability of the soil due to increase in moisture content or rising water table.

b. The second mode of failure of flexible pavement is fatigue cracking, which takes place at the bottom of the base of the road and that fatigue cracking propagate to the surface of the pavement through all the bound layers in which case all the bound layers need to be re-constructed.

**2) Modes of Failure of Rigid (Concrete) Pavement**

a. The predominant mode of failure is fatigue cracking, which takes place at the bottom of the concrete slab representing the road base, which means that the road base needs to be re-constructed or to be re-built.

b. The second mode of failure is differential settlement and/or erosion, which takes place under the deflective concrete slab during which the sub-base material will be eroded due to the deflection of the overlaying slab and water entering the sub-base and weakening and eroding its material and the material beneath the sub-base layer. This necessitates the replacement of the concrete slab, which is the main layer sustaining the traffic loading, and the re-construction of the affected sub-base.

### 4.6.3 Deciding on the Pavement Condition

In general, other conditions of road pavements that may require partial re-construction/refurbishment or replacement of the surface layer or other bound layers is when that layer rut or deform or severely cracked. Regarding flexible pavement (asphalt pavement) this type of rutting is called layer or material rutting due to bad design and construction of that layer and requires replacement of that layer. Other cases where the surface layer needs to be replaced is when it becomes severely defective due to for example having a wide spread of potholes, cracks and loose material, which necessitate the plaining (shaving or removal) of that layer and replacing it with a new one.

The flexible and concrete pavement conditions including failure are best summarised in the following Table 4.4 (Ali, 2001).

***Table 4.4 The failure condition of flexible (pavement) pavement by deformation/rutting and/or fatigue cracking) (Ali, A. 2001)***

**Combined Deformation and Fatigue Cracking Criteria of Failure in Flexible Pavements**

**The conditions associated with the wheel track tracking or rutting and cracking are as follows:**

**The following classifications are used:**

**1) Sound: - No cracking; rutting under 2m straight edge less than 10mm.**

**2) Critical (requires attention/ repair):**
**(a) No cracking; rutting between 10 and 20mm.**
**(b) Cracking confined to a single crack in the wheel tracks; with rutting less than 20mm.**

**3) Failed (requires reconstruction):**
**- Cracking extending over the area of the wheel track and/or rutting greater than 20mm.**

**Measurements should be made when pavement temperature is as close as possible to 20°C. Measurements are typically taken at 20-50m spacing along the road depending on the purpose of the survey and/or the general pavement condition.**

Amer Ali – IC 2001

The rigid (concrete) pavement conditions including failure are best summarised in the following Table 4.5 (Ali. A. 2001).

***Table 4.5 The failure condition of rigid (concrete) pavement by cracking (Ali, A. 2001)***

Rigid Pavements

The rigid (concrete) pavement is in a failed condition and requires reconstruction when:

wide cracking ( **>1.2 mm** wide) exceeds **250 m** over a length of **100 m** of the lane concerned.

*That is, a rigid pavement fails if the* $\sum_{i=1}^{i=n} \boldsymbol{l_i} > \mathbf{250}\,\boldsymbol{m}$

Where $l_i$ is the length of crack i that has a width > 1.2 mm (ignoring any crack that has a width of <=1.2mm). This is done over a 100 m long concrete road bay/lane.

Amer Ali - IC 2001

### 4.6.4 Recycling and Refurbishment of Flexible Pavements

The old materials removed from the fully or partially re-constructed or re-built pavement will be used in the foundation (sub-base and capping) of new roads, new footways and cycle ways. The re-use of such removed road materials can be re-used in two ways, namely:

#### 4.6.4.1 Flexible Pavement In-Place Recycling

This can be Cold in-place recycling when new/fresh materials is mixed with the removed road pavement and the relayed as a base layer for the road, replacing the old recycled base. This is more environmental friendly as it does not need heating of the mixed materials.

It can be Hot in-place recycling, which is same as cold in-place recycling but it requires the mixed materials to be heated and then replaced into the layer of the pavement, which means there is a need to use the heat and energy.

The in-place recycling technique encourages the consumption of 100% reclaimed asphalt pavement (RAP) from the existing pavement, which allows the use of suitable recycling agents to rejuvenate the aged asphalt. Hot in-place recycling (HIR) is one of the pavement rehabilitation techniques used primarily for the surface distresses, limited up to 25 to 50 mm (Finlayson, et al., 2011). The pavement temperature before paving is usually around 110°C (Ma, et al., 2022). The existing pavement is softened with flame heating. This is followed by scarification, rejuvenation, and compaction by an HIR train equipped with all the construction units. The cost-effectiveness of in-place recycling might be attributed to the saving of asphalt binder and virgin aggregates, lower traffic disruption, and lower transportation costs. Repaving with HMA overlay is applied when HIR is not sufficient to restore the required pavement properties (Ma, et al., 2022). A series of studies have explored the concept of incorporating RAP (up to 30%) during HMA production in asphalt plants. Results have shown that the incorporation of RAP can increase the stiffness but also reduce the dissipated creep strain energy of the asphalt mixtures (Huang, et al., 2011; Ma, et al., 2022).

Cao et al. (2019) assessed the cost and environmental concerns between HIR and the conventional milling and filling techniques with assumed service life, indicating that HIR could save 5% of the costs and reduce by 16% the overall environmental impact (Cao, et al., 2019).

In contrast to HMA mixtures in asphalt plants, HIR mix is produced in situ with 100% RAP asphalt emulsion, using a fire heating method, but a lower mixing and compaction temperature, which might lead to different mixture performances and pavement service life. Furthermore, the quality control and LCCA of the pavements between HIR and HMA are also worth investigating. This study, therefore, aims to conduct comprehensive comparisons between HIR and HMA mixes and pavements, including performance evaluation, pavement life prediction, and LCCA (Ma, et al., 2022). To achieve this, HIR mixes from three different projects were collected by Ma, et al. (2022) and recompacted in the laboratory. One common HMA surface mix was also obtained from the asphalt plant for comparison. The asphalt mixture performance tester (AMPT), superpave indirect tensile strength (IDT) tests, and tensile strength ratio (TSR) tests were adopted for performance evaluation. Field cores were collected to assess the in situ construction qualities. ME software was used for modeling and pavement life prediction (Ma, et al., 2022).

In this case study by Ma, et al. (2022), a comprehensive comparison of pavement surface rehabilitation using HIR and HMA was conducted, including the performance evaluation, pavement service life prediction, and LCCA. HIR mix from three different sections and the plant mix from the same region were collected, while field cores were also obtained to assess the pavement condition after HIR surface treatment. Table 4.6 summarised the major comparison results of the asphalt mixtures and pavement performances with HIR and HMA surface rehabilitation techniques. The main conclusions from this case study by Ma, et al. (2022) were summarised as follows:

1. HIR mixes showed acceptable rutting and moisture resistance. Cracking resistance is the main issue that HIR mixes would encounter. HMA has a stronger coating between asphalt and aggregates than the HIR mix even with the lower asphalt binder content, indicated by higher IDT strength and DCSEf;

2. The incorporation of recycling agents in the HIR mix would soften the RAP binder and increase the effective binder content of HIR mixes, which improve the ductility and cracking resistance of the asphalt mixtures (Ma, et al., 2022);
3. The DCSEf of field cores reflected the decrease of more than 40% in the cracking resistance of the existing pavement surface before HIR rehabilitation. The HIR technique showed consistent construction qualities as laboratory mixes, which could restore the cracking resistance of existing pavement (Ma, et al., 2022);
4. ME prediction results indicated that pavement after HIR surface treatment would yield a larger value of roughness index and encounter severe fatigue cracking as well as low-temperature cracking issues (Ma, et al., 2022);
5. LCCA results reflect the ability of HIR surface rehabilitation to achieve a saving of over 50% of the initial cost compared with the conventional HMA milling and filling technique. Along with the overlay, HIR surface rehabilitation is expected to save the construction cost for the whole life cycle. Various traffic volumes or load conditions and further pavement monitoring should be considered for LCCA validation (Ma, et al., 2022).

***Table 4.6 A summary of asphalt mixtures and pavement performance with two rehabilitation techniques (Source: Ma, et al. 2022)***

| Mixture performances and pavement response | HIR | HMA milling and filling |
|---|---|---|
| Mixtures | | |
| Flow number (cycles) | High | NA |
| Resilient modulus at 25°C (psi) | High | NA |
| IDT strength at 25°C (psi) | NA | High |
| $DCSE_f$ at 25°C ($KJ/m^3$) | NA | High |
| TSR(I-M) & (F-T) | NA | High |
| Pavement | | |
| IRI (in./mile) | High | NA |
| Fatigue cracking (% lane area) | High | NA |
| Thermal cracking (ft/mile) | High | NA |
| Permanent deformation (in) | NA | Little high |
| Predicted life (years) | 8 | 12 |
| Initial cost saving | Up to 50% | NA |
| Cost saving of 48 years | Up to 20% | NA |

*Note*: NA = Not available.

#### 4.6.4.2 Flexible Pavement Off-Site Recycling

The procedure for the off-site recycling is same as in-place recycling, but material is taken to off-site in this case. Obviously, off-site recycling incurs some environmental impact due to the transportation of the materials from the road to the recycling plant location and then back to the road site.

### 4.6.4 Recycling and Refurbishment of Rigid Pavements

For a rigid (concrete) pavement, which is in a failed condition, the following procedure, which is called “Crack and Seat” has been used to recycle and refurbish it.

A specialised plant which has heavy metal disc mounted at the end of the lorry or plant with a mechanism to drop and lift that heavy disc on top of the concrete pavement slab in a process that is repeated whilst the lorry is progressing slowly along the concrete bay. The lorry may make several round journeys doing the cracking task along and across the identified concrete bay and making sure that the whole concrete bay is broken down (cracking) into small pieces including some initial seating (settlement and levelling of cracked surface) ready for more seating using heavy roller to roll the cracked surface. After the Crack and Seat process is completed, then a new layer of asphalt material or a concrete slab will be laid on top of the cracked and seated concrete surface.

# Chapter 5. **Identification, Application and Validation of the Key Decision-making Factors**

## 5.1 Chapter Overview

This chapter highlights the identification of the key decision-making factors that aid the decision of whether to refurbish or rebuild an existing building that is about to reach its design life. Following the identification of the key decision-making factors, the factors are then applied to Revit/BIM plug-in Tally. Three different buildings are assessed in Tally for the purpose of application of the key identified factors. Each selected building for Tally application, consist of different material and type, as this further justifies the authentication and importance of each factor in the application process. After application, the factors are compared with the answers of the expert opinion survey in order to validate and prioritise each factor accordingly.

## 5.2 Factors affecting the Construction and Demolition process

Prior to the identification of the key decision-making factors, there is a need to summarise all the previously identified factors for waste, its contribution and reduction in order to create a matrix chart and highlight the important and key factors from the chart.

Planning approval may be required to demolish a building or structure. Early engagement with the local planning authority is recommended in order to ascertain if this may be needed. Information on this can be found on the relevant Local Planning Authority's (LPA) website. Some supporting information on situations where a demolition may require planning approval is also provided there. Before listing the identified key decision-making factors, it is important to highlight and discuss the following factors that affects the construction and demolition processes directly and indirectly:

### 5.2.1 Factors affecting recovery of materials in the demolition process

The extent to which materials may be recovered effectively in the demolition process depends on a range of factors, including the following ones:

- **Safety –** This may increase project costs, if not being implemented properly on and off the site;
- **Time –** Selective demolition needs more time than traditional demolition, so higher costs are expected. Optimal solutions regarding potential recyclability and re-use should be considered;
- **Economic feasibility and market acceptance –** The cost of removing an element (e.g. a roof tile) should be compensated for by its price, while, at the same time, the re-used element should be competitive and accepted by future

users. For some materials, e.g. iron/metal/scrap, market prices fluctuate strongly depending also on seasonality;

- **Space –** When there is a space limitation on a site, separation of materials collected should take place in a sorting facility. Space limits specifically require good planning;
- **Location –** The number of recycling facilities in the surroundings of the project site or the local supply waste management services may limit the potential recovery of materials from a deconstruction project;
- **Weather –** Some techniques may be dependent on certain weather conditions that may not coincide with project timing.

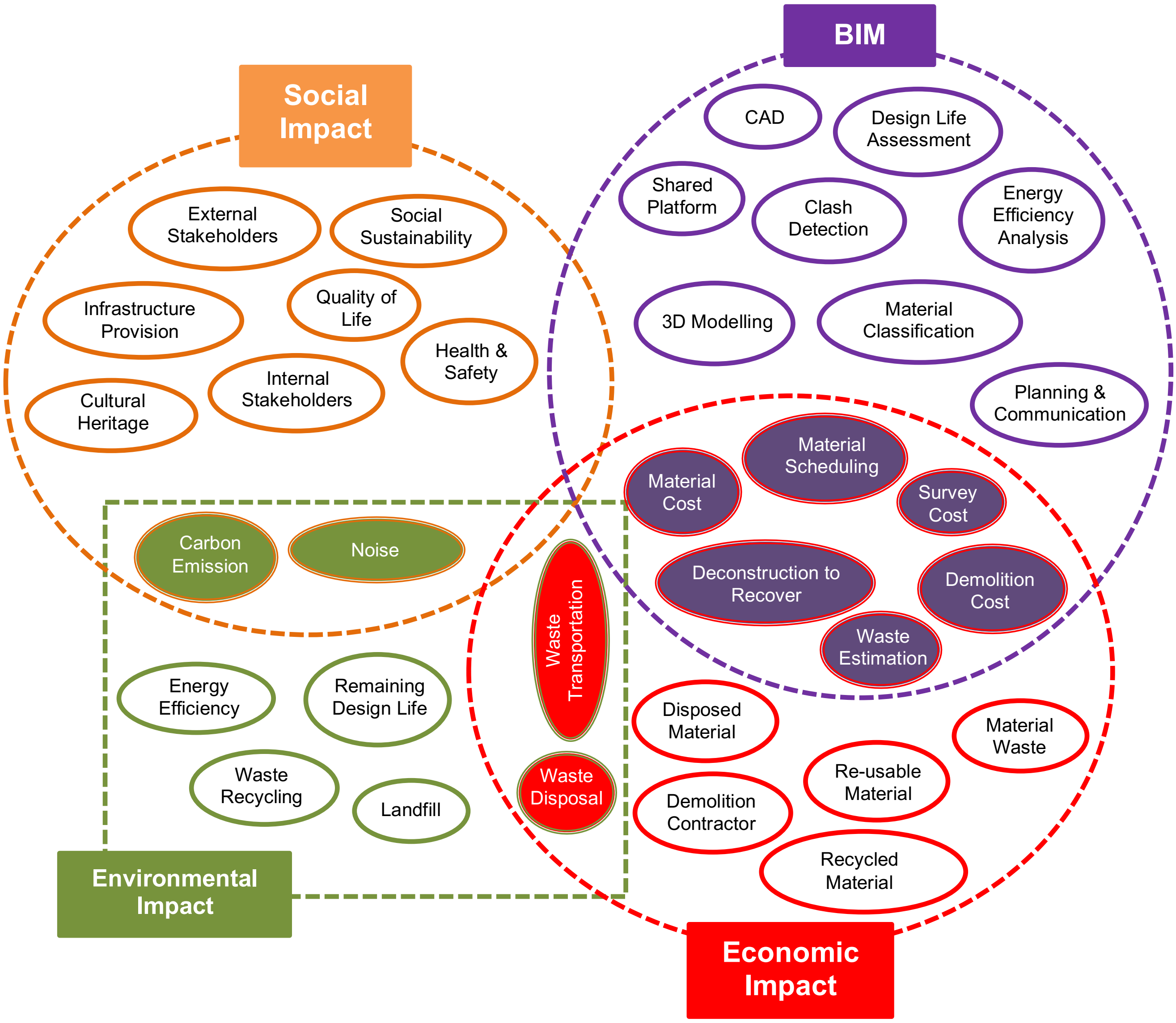


***Figure 5.1 Matrix diagram of demolition factors (Source: the Author)***

The matrix chart for the demolition factors (see Figure 5.1) indicates four impact factors and each impact factor has multiple sub-factors and some of them falls under two impact factors, so the factors that falls under more than one impact factor are considered to be vital for the key decision-making criteria and thus these factors have been listed separately within the combined impact factors category below:

#### 5.2.1.1 Social and Environmental Impact

- Carbon Emission;
- Noise.

#### 5.2.3.3 BIM and Economic Impact

- Material Cost;
- Survey Cost;
- Material Scheduling;
- Demolition Cost;
- Deconstruction to Recover;
- Waste Estimation.

#### 5.2.3.4 Economic and Environmental Impact

- Waste Transportation;
- Waste Disposal.

### 5.2.2 Factors Influencing the Reusability of Building Materials

The reusability of recoverable building materials is affected by factors such as environmental (Viitanen, et al., 2010), design and construction as well as operation and management factors (Kibert, 2003). Specification of reusable building materials during building design and construction phase (Webster & Costello, 2006; Guy, et al., 2006), is a major factor that determines the level of reusability of recoverable materials at the end-of-life of a building (Akanbi, et al., 2018). Other factors that influence the reusability of recoverable materials include: use of bolt and nut joints instead of nails and gluing (Crowther, 2005), use of prefabricated assemblies (Crowther, 2005; Guy & Ciarimboli, 2008; Akanbi, et al., 2018), re-use of gypsum and masonry waste and layering of building element according to anticipated life span etc. The use of finishes on building materials reduces the possibility of re-using such materials as recovered (Crowther, 2005; Guy, et al., 2006; Tingley, 2013).

### 5.2.3 Factors influencing recyclability of building materials

All the factors that influence reusability of recoverable building materials also indirectly impact the recyclability of the materials. For instance, a re-usable material may not be usable as recovered because of the damage or worn out. although, it could be considered for recycling and then re-use (Akanbi, et al., 2018). For example, a carpet that is used in a building for several years, then ripped out and installed in a new building project would be considered re-usable (Akanbi, et al., 2018). Though, a carpet that is installed in a building, ripped out and re-manufactured into wall insulation would be considered recyclable or a recyclable material. Likewise, a steel beam in a building that is recovered at the end of design life (EODL) of a building and used as a beam in a new building construction is an example of direct re-use. In the same vein, re-manufacturing of the same steel beam into an entirely different material as a result of damage to the original steel beam is an example of recycling. Specification of recyclable materials is one of the factors that influence the recyclability of recoverable building materials (Akanbi, et al., 2018). Another factor that connects to the specification factor is avoidance of the use of toxic and materials for the construction (Crowther, 2005; Akanbi, et al., 2018). The use of toxic and hazardous materials makes it impossible for the materials to be recyclable at the end of design life of the building. Layering of building element also improve the efficiency of recycling as well as economic value of the recovered recyclable materials (Akanbi, et al., 2018).

The matrix diagram in Figure 5.2 Indicates the key decision-making factors that are being considered in refurbishment. Further, it simplifies the factors into four different sections, while some factors falls under the combination of two impact factors are listed separately.

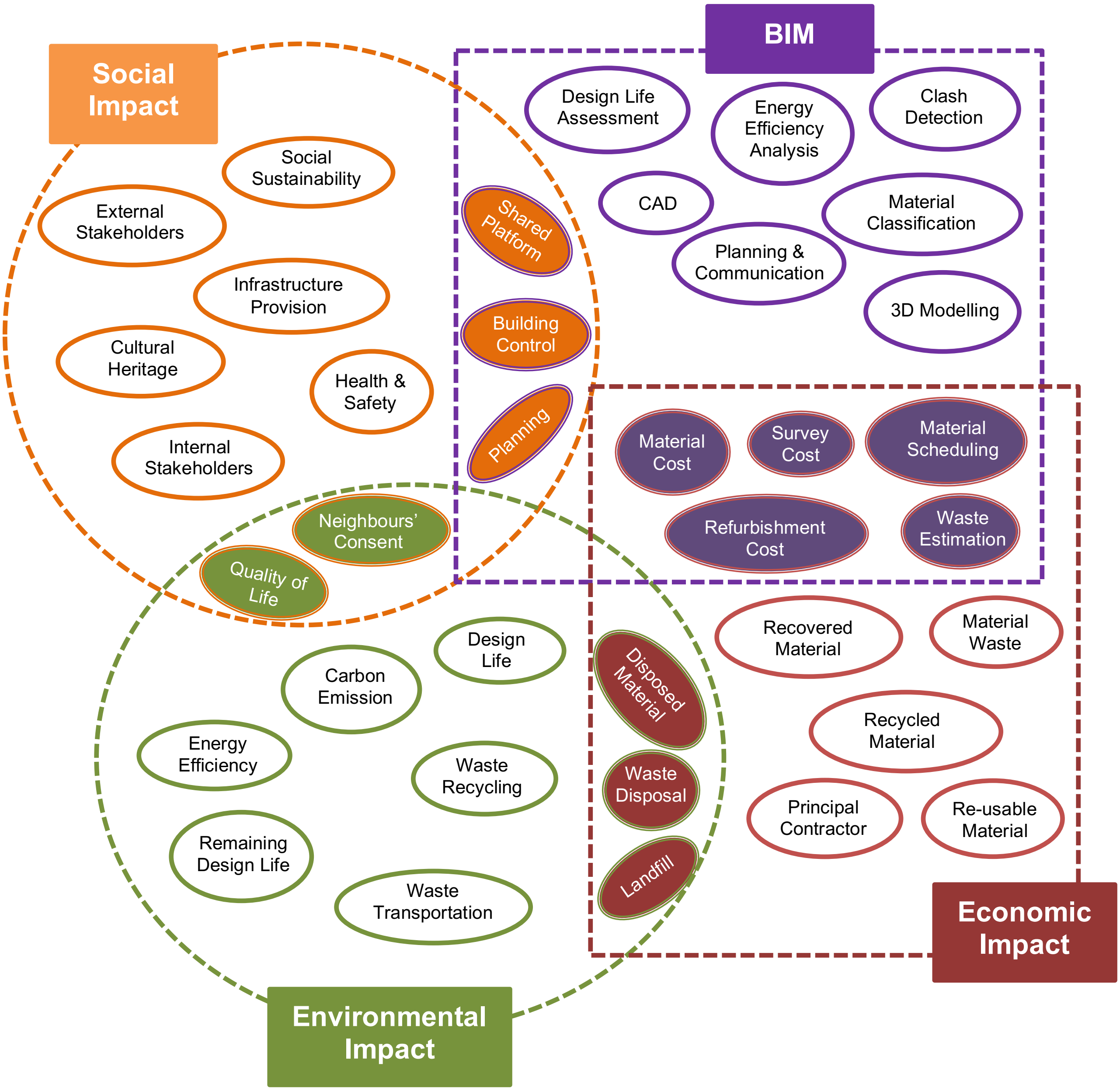


***Figure 5.2 Matrix diagram of refurbishment factors (Source: The Author)***

### 5.2.3.1 Social & Environmental Impact

- Quality of Life;
- Neighbours' Consent.

### 5.2.3.2 Social Impact & BIM

- Shared Platform;
- Building Control;
- Planning.

### 5.2.3.3 BIM & Economic Impact

- Material Cost;
- Survey Cost;

- Material Scheduling;
- Refurbishment Cost;
- Waste Estimation.

#### 5.2.3.4 Economic & Environmental Impact

- Disposed Material;
- Waste Disposal;
- Landfill.

### 5.2.4 Combined CWM Factors

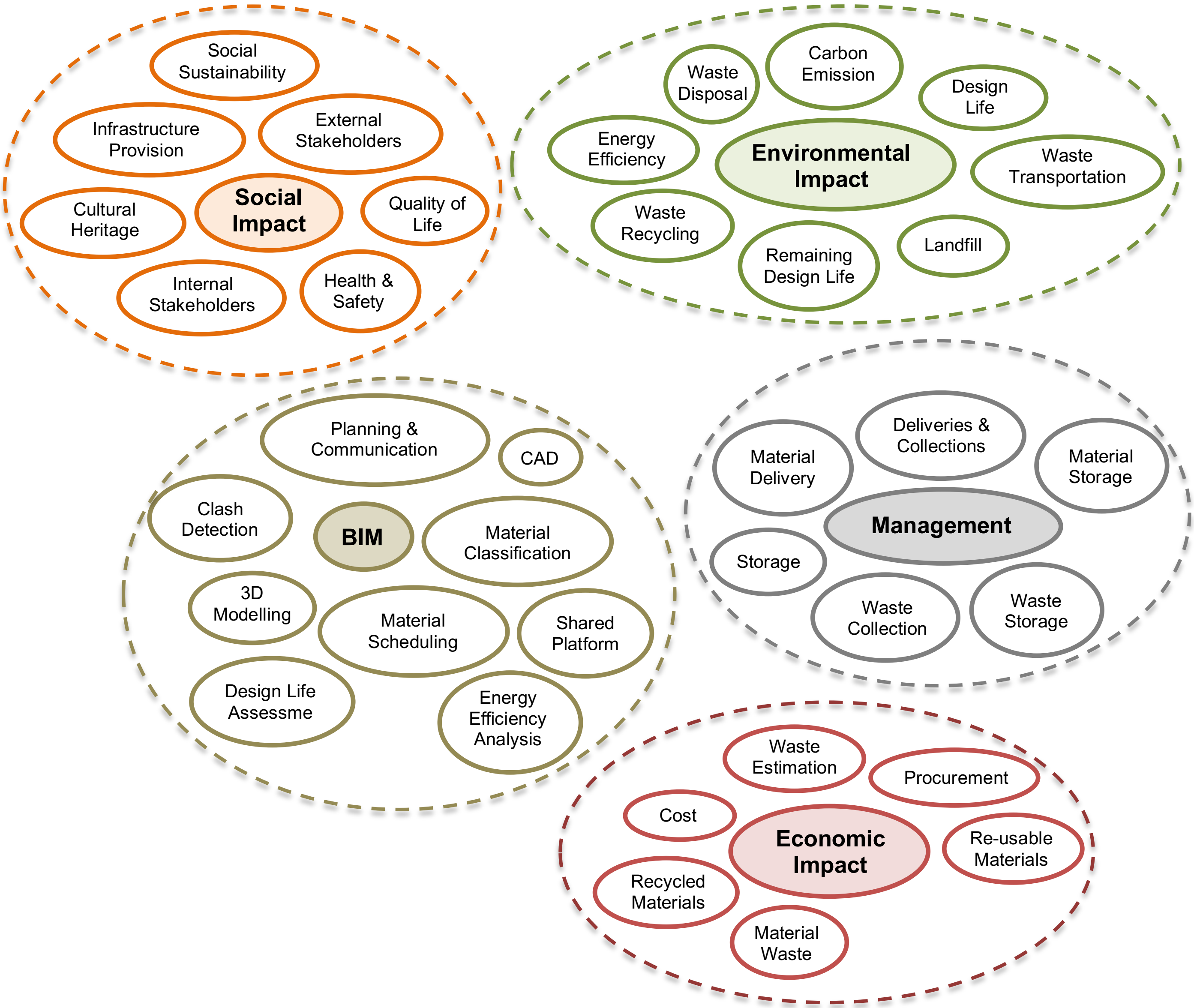


*Figure 5.3 Combined CWM factors (Source: The Author)*

Following the matrix diagrams that illustrated the key factors for refurbishment and demolition scenarios in Figure 5.1 and 5.2, a combined diagram has been generated in Figure 5.3, which illustrates the main factors to be considered for the decision-making process. However, many of the factors listed in Figure 5.3 have similarities and falls under the same category such as:

1. **Waste Transportation, Collection, Recycling and Disposal –** These impact factors are directly related and can be combined into one category such as 'Material Waste Estimation and Transportation'.
2. **BIM, Carbon Emission and Remaining Design Life –** As this research project used Tally as the main source of assessing the life cycle assessment of the building, which includes remaining design life, BIM and other relevant tools, so these two factors can be combined into one category namely 'Remaining Design Life/Life Cycle Assessment'.
3. **Social Sustainability and Cultural heritage –** Buildings with historical values are of immense importance, especially in the UK and there is a high cost involved in the maintenance of these buildings too. Such buildings are called heritage buildings. These buildings have social impact factors too, so these two factors can be combined into one category named as 'Historical Significance'.

Similarly, other factors in Figure 5.3 also have correlation with some other impact factors. This section combined all the previously considered factors contributing waste generation and reduction. Thus, after listing and assessing the relationship between these factors, the final key decision-making factors are identified and listed in the next section of this chapter.

## 5.3 Identified Factors to consider for Decision-making of whether to Refurbish OR Rebuild

The identified factors, which have resulted from the analysed case studies and the developed frameworks are as described below (1-11):

### 1) Existing Condition of Building

This is the first identified key factor for the decision-making process. Taking account of Figures 4.14 and 4.15 in Chapter four, accessing the condition of the building is identified as one of the first key steps in this process. The existing conditions of buildings are assessed through several ways. One of the easiest methods is by using visual survey. The exterior of each building structure can be viewed from the ground level and all important information would need to be documented and some areas of deterioration are noted through annotated sketches and plans. However, with recent new technology, detecting building defects would be more effective by implementing non-destructive test. For instance, detecting a rusty steel bar within a wall can be detected by using a scanning instrument. By implementing visual inspection only, not many things about the condition of building can be discovered. It is very important to assess the current conditions of a building in the best possible way using the modern technology. This is because decision on maintenance and rebuild is complex and one of the recommended solutions is by referring to the existing conditions of the building. Hence, factor of existing building condition need to be considered during the decision-making process of whether to refurbish or rebuild.

### 2) Age of the Property

Based on the second case study and framework in the Figure 4.18 in Chapter 4, the need to take account of the age of the building is necessary, as it highlights the potential of the building. Age of the building provides vital information and specifically indicates level of maintenance service required, if a decision is to be made on maintenance, as Lateef (2008) argues that one of the important elements that need to be considered in allocation of maintenance resources is the building's age. In general, the older is the building, the more attention and focus to special maintenance works need to be carried out. Based on the consideration of life cycle management and facility management, which are connected to each other, maintenance works such as a major refurbishment and retrofitting of building equipment need to take place when a building has reach its economic life span. To implement this, large allocation of funds are required from the building owner. Therefore, the building stakeholders would also need to consider this factor during their decision-making process of maintenance cost of a building.

More importantly, the age has an impact on the architectural value of the building. Every structure has a different design life, which is based on its durability and the type of material used during its construction. For instance, the concrete structures have a design life of 100-120 years, whereas the design life of steel structure is 75-100 years (Ali, et al., 2018b). Therefore, it is vital to determine the age of the property and check if the building has been maintained and serviced properly since it has been constructed, as this will aid the decision-making process.

### 3) Remaining Design Life / Life Cycle Assessment (LCA)

The lifecycle of a building or infrastructure project has been widely recognised, comprising of five stages: planning, design, construction, maintenance, and demolition. Where the construction, maintenance and demolition phases are mainly considered for the life cycle assessments (LCA) and life cycle impact assessments (LCIA)

Once the age of the building is identified, the remaining life can be calculated as shown in equation 5.1. However, the remaining design life needs to be calculated for each of the main or re-usable material and component, especially the structural material such as beams, columns, roof, structural floors and foundations etc., which can be calculated via Tally LCA. In this section, there are two cases:

**Case 1:** When there is an existing building and it require some demolition and refurbishment. Then, in order to maximise the efficiency in the usage of building material, there will be a need to figure out the remaining design life of the existing material. This can be done by taking account of the year when the building came into operational, then subtract those years from the maximum design life of a material:

Remaining design life = maximum design life – used design life (Equation 5.1)

When calculating the remaining design life of each of the material, there will be a need to check the total design life, which can be found on the material description published on the supplier's or manufacturer's website. Some of the typical building material design life are listed in the Table 5.1 below:

***Table 5.1 Total design life of commonly used materials (Source: Ali, et al., 2018b)***

| Material | Design Life (years) |
|---|---|
| **Plasterboard/Gypsum board** | 40-60 |
| **Timber (different types)** | 30-45 |
| **Insulation** | 20-60 |
| **Steel** | 75-100 |
| **Concrete** | 100-120 |

After the calculation of the remaining design life and considering the new proposed development that shall replace the existing development, actions can be taken that should be in favour of the minimum cost and waste generation.

However, it is important to take a holistic approach and evaluate existing buildings that are due to be considered for either demolition and rebuild or refurbishment and re-use. Life cycle assessment (LCA) is often used as a method to estimate the life-cycle impact of a building, and life-cycle cost assessment (LCCA) estimates the financial burden. Many different LCA tools exist that quantify different aspects of the LCA for the building sector.

Based on thorough research, the design life of buildings in this project have been calculated via Revit/BIM tool named Tally. This BIM tool runs the Life Cycle Assessment (LCA) for both existing building and new development. A detailed Tally based report can be generated by entering the building's specific information into the software, an example of this has been provided in the case study two in Chapter four. Tally's methodology for calculating the LCA has been described in Chapter three.

**Case 2:** If there is a new proposed development on an empty land, then design life of each of the main material should be noted throughout the construction project as this will minimise the waste and save cost of future planned or unplanned refurbishment works on the building. This case is not relevant for the of the decision-making of existing buildings.

However, a better practice should be followed and the properties of each of the material of the new development shall be inserted into the CAD software, so that if in the future, the building is again considered for some changes, the decision-making will be easier by running the lifecycle assessment of the CAD based model, which will identify the remaining design life of the majority of the materials and components within the building.

### 4) Historical significance

Taking account of the literature review on some of the past case studies and decision-making strategies, historical significance of a building is considered as another key factor in the decision-making process (Silberman, 2011). Maintaining historical significance of such buildings is very important, especially in the UK, as these buildings are considered as antique and most of these have a long history. Many sites of historical significance are being converted into tourist attractions too. Furthermore, historic buildings are important assets as part of humanity's cultural capital; they record historical development, social and economic advancement, scientific progress, collective memory, and culture-history (Silberman, 2011).

Although the conservation movement worldwide has helped to preserve some historic buildings, many are still under threat. There are claims that such buildings are old-fashioned, expensive to maintain, offer poor user comfort and are energy inefficient.

**Environmental Value of Historic Buildings –** Building green has become a standard building practice in the construction industry nowadays. Demolishing an inefficient property may seem to be the best way of reducing energy use and to make way for new buildings, as it is often expensive to upgrade and difficult to refurbish old houses to meet sustainability standards (Boardman, et al., 2005). A key foundation of this argument is that greenhouse gas (GHG) emissions of highly efficient new housing can be far lower than that of houses built in the past due to effective use of insulation and technologies. This is the underlying premise of the argument supporting the 40 Percent House Project in advocating the demolition of a total of 3.2 million houses from 2005 to 2050 in the UK (Boardman, et al., 2005; Power, 2008). Demolishing houses built in the past is considered to be a way to improve environmental efficiency.

With increasing recognition that green buildings out-perform conventional buildings in terms of environmental, social and economic considerations, much less is known about how green building initiatives might be incorporated into historic buildings and little work has been done to examine how they could be maintained and refurbished for sustainability (Ding, 2013). If the challenges of climate change and reduced GHG emissions are to be successfully tackled, there is potentially enormous benefit to be gained from maintain and refurbishing the historic building stocks in order to make the current built environment more environmentally-friendly and energy efficient (Bromley, et al., 2005; Bullen, 2007). The historic building stock has the greatest potential to lower the environmental load of the built environment significantly within the next 20 or 30 years (Bullen, 2007). Mickaityte, et al. (2008) in developing a conceptual model for sustainable building refurbishment suggests that sustainable maintenance and refurbishment of historic buildings uses 23% less energy than new construction. Mao (2007) further suggests that it will take approximately 65 years for a green and energy-efficient building to recover the energy and resources lost in the demolition of an historic building, even if 40% of the building materials from the demolition are recycled. Power (2008) further states that building, demolition and renovation waste make up about one-third of all landfill that is detrimental to the environment. Consequently, sustainable maintenance and refurbishment of historic buildings may be a more practical way to respond to climate change and other negative impacts on the environment (Ding, 2013).

A research project undertaken by the Empty Homes Agency, UK, reveals that refurbishing historic homes can save up to 35 tonnes of $CO_2$ per property by removing the need for the energy locked into new build materials and construction (Ireland, 2008).

The research also reveals that in UK there is not much difference in terms of performance between new built and refurbished housing over an operating period of 50 years (Ireland, 2008).

Taking account of the above information on the historic buildings and their maintenance, this factor has been considered as one of the key factors in the decision-making process.

### 5) Environmental Impact

Another important factor to consider during the decision-making process. A research project undertaken by the Empty Homes Agency, UK, reveals that refurbishing historic homes can save up to 35 tonnes of $CO_2$ per property by removing the need for the energy locked into new build materials and construction (Ireland, 2008). The research also reveals that in UK there is not much difference in terms of performance between new built and refurbished housing over an operating period of 50 years (Ireland, 2008).

Research undertaken by the UK Government reveals that the energy produced from non-renewable sources consumed in building accounts for about half of the UK's emission of carbon dioxide (Cabinet Office, 2000). Over 90% of non-energy minerals used are needed to supply the construction industry with materials (Cabinet Office, 2000). However, each year, about 70 million tonnes of construction and demolition materials end up as waste landfill. It is questionable whether the decision to demolish is justified for its energy-efficiency, given that the energy performance of renovated homes can improve significantly over time (Sustainable Development Commission, 2006; Ireland, 2008).

In general, there will be more use of energy and waste generation for landfill during the process of demolition and rebuilding, rather than renovating. However, if the new-build home is built from sustainable materials, and is built to a high level of energy performance, these initial energy differences could be offset by lower ongoing energy usage. It is ideal to review the energy situation of the house before planning for refurbishment or remodeling. Furthermore, it is mandatory to adhere to building regulations, so going beyond the minimum standard, and making the house as energy efficient as it can be, will be a sensible decision. The more energy efficient the house is, the less it will cost to heat in the future.

Again, for this purpose, Tally life cycle assessment (LCA) tool has been utilised. This tool has the capacity to assess the approximate $CO_2$ emission of the building based on its material properties and data.

### 6) Maintenance and Repair

This factor also falls under cost or the economic impact, but having listed this as a separate factor determine its importance, Maintenance and repairs of any building, whether exiting or newly built, does vary upon the type and its usage, thus it is required to consider the overall capacity and usage of the building.

Preparing estimates for maintenance cost allocation is complex and difficult. The types of factors that need to be considered in decision-making of maintenance cost vary for the existing significant building. The nature of such maintenance works are difficult to predict in term of final content, extent, and specification. When preparing the cost plan, it is essential to gain advice from experts where the nature of the work involves any issues of technicality of any part of the building.

Identification of dominant factors can provide more information regarding the maintenance cost of buildings. Besides, this would be able to assist building managers to familiarise on the degree of risk and uncertainty that need to be mitigated in the future. In literature reviews, there is no empirical study investigating on the dominant factors that affect the decision-making process with regards to the maintenance cost. Therefore, this factor possess a key value in the decision-making of existing buildings in order to identify the dominant factors that have been considered by building managers in decision-making process of the maintenance cost and shows their relationship towards the maintenance performance.

Twenty years ago, housing associations were apparently “only just beginning to address the issues of longer term cost profiles and financing strategies for major repairs” (Whitehead, et al., 2014). Since then, the management of repairs and maintenance - which also requires and results in growing knowledge about costs - has faced a number challenges including: allocating resources to the most appropriate stock; delivering planned maintenance programmes and spending these budgets on time; controlling (relatively expensive) responsive repair work; involving tenants and leaseholders in decisions; managing and monitoring performance to get the best out of maintenance contracts. More recently, a number of the researchers involved in these earlier analyses have noted that Housing Associations now have long experience of managing repairs and maintenance so operating and management risks are regarded as “fairly easy to price” (Whitehead, et al., 2014).

Nationally, this means that estimating maintenance costs is more difficult than other operating costs like service charges, ground rents and utility bills (at least for the time being) because “there are no wide coverage databases of information publicly available to allow comparisons” and what historical data exist have to be “derived from similar installations or components and need to take into account various factors that will be specific to the proposed scheme. Some of these factors will be difficult to express in financial terms” (Whitehead, et al., 2014).

### 7) Cost comparison (Refurbishment vs Rebuilt)

Having discussed and assessed the multiple factors for waste reduction via decision-making of whether to refurbish or rebuild, it has been observed that there is a need to compare the cost for refurbishment with rebuilding, as this will provide the key difference between the cost of the two compared scenarios. For more realistic and reliable cost figures, all types of direct and in-direct costs need to be calculated for each scenario, whether refurbishment has lower cumulative emissions compared to new build in the long run depends on whether the practicable performance standards for refurbishment are the same or better than the standards set new construction. It is worth noting that the economic reasons for redevelopment (rising land and building values) have historically been largely independent of energy performance because location plays such an important role in determining these values and energy performance can be difficult for prospective building owners and occupiers to assess.

### 8) Demolition Cost

The demolition cost is considered as another key factor in the decision-making process. It highlights the significance and the level of works required to be carried out for demolition. The demolition cost (C) of a project comprises labour costs ($C_j$), material costs (benefits from salvaged materials) ($B_m$), plant costs ($C_p$), environmental compliance costs ($C_e$), and administrative costs ($C_a$) as presented in Eq. 5.2:

$$C = C_j - B_m + C_p + C_e + C_a \qquad \text{(Equation 5.2)}$$

Factors such as overtime and various other compulsory employee benefits must be accounted as a part of $C_j$.

$B_m$ is the material costs, which in fact represents the income breakdown made from scrapping all recyclable materials and the resale of second hand materials.

The plant costs associated with a demolition project, $C_p$ include transport costs and the hire of trucks or bins to be picked up. These amounts directly depend on how efficient the demolition team is in terms of stacking and sorting and more importantly how much materials can be salvaged. Salvaged materials that are to be recycled or re-used will also incur transport costs. The size of the job and company will determine the amount of each type of plant required, and thus the cost varies accordingly. Plant may have to be hired if the work is beyond the normal scope of the company. The plant costs incorporate maintenance, storage, transportation, fuel and depreciation costs for companies that own their own equipment.

Having calculated the demolition cost from the above equation would provide an approximate figure, which can be compared with the refurbishment cost, however other key factors need to be considered during the decision-making process.

### 9) Refurbishment Cost

Following the demolition cost estimation, the cost estimation for refurbishment scenario is another important factor. As discussed in previous chapters, cost play an important role in the decision-making and also to determine the amount of refurbishment works to be compared with the amount of demolition works. Comparison may not be feasible in all scenarios, thus there are other factors listed within this strategy to aid the decision-making of whether to refurbish or rebuild.

### 10) Comparison of Refurbishment Time and Demolition Time

This section estimates the time for both developments. The estimated time for the refurbishment will then be compared with the estimated time for rebuilt. As more time means more work force, hence more cost. Simply, in this case, the scenario having the lowest estimated time will be preferred. However, this may not be the scenario in all cases, as this factor has a direct relationship with cost too.

### 11) Material Waste Estimation and Transportation

Material is the primary source of waste. Maximum accuracy in material estimation and management ensures minimum waste generation. Once the design life of the building is identified, material can then be estimated depending on the type and design of project. Again, the design phase already includes minimum material wastage plan as it requires designer and the engineer to work collaboratively on the plans and make sure the minimum material wastage plan is in place.

Minimum material wastage highlights the economical aspect, as this will keep the material cost at minimum.

## 5.4 Application of the Key Decision-making Factors

This section involves the Tally based trails of three buildings. These trails includes the implementation of the key decision-making factors that were highlighted in the previous section of this chapter. For application, CAD models were imported to Revit and then analysed on Tally and several lifecycle checks have been performed on each of the CAD models. These models are initially created in Revit and then imported into Tally in order to perform the life cycle assessment (LCA). Tally (LCA), a computer plug-in for Autodesk Revit, is primarily designed to allow architects and engineers to quantify the environmental impact of building materials for whole building analysis as well as comparative analyses of design options. While working on a Revit model, the user can define relationships between BIM elements and construction materials from the Tally database. The criteria used to make a decision of whether to refurbish or rebuild is based on the chart shown in Figure 5.4.

| PRODUCT | CONSTRUCTION | USE | END-OF-LIFE | MODULE D |
|---|---|---|---|---|
| **A1. Extraction**<br>**A2. Transport (to factory)**<br>**A3. Manufacturing** | **A4. Transport (to site)**<br>***A5. Construction Installation*** | B1. Use<br>**B2. Maintenance**<br>**B3. Repair**<br>**B4. Replacement**<br>**B5. Refurbishment**<br>***B6. Operational energy***<br>B7. Operational water | C1. Demolition<br>**C2. Transport (to disposal)**<br>**C3. Waste processing**<br>**C4. Disposal** | **D. Benefits and loads beyond the system boundary from:**<br>**1. Reuse**<br>**2. Recycling**<br>**3. Energy recovery** |

***Figure 5.4 Lifecycle stages, processes included in Tally modeling scope (Source: Tally)***

Understanding the impact of building materials traditionally involves life cycle assessment (LCA), an in-depth form of analysis performed on whole buildings, manufactured building products and materials, and material assemblies. While LCAs provide a complete picture of the environmental impacts associated with a building, the practice of LCA is relatively new and confounding for most building professionals. Until recently, LCAs were typically conducted after construction, rather than during the design and planning process when the data could influence design decisions.

The particular reason for choosing the three semi-commercial buildings in this research project (including the use of Tally plug-in for Revit/BIM software) is that they represent good examples of both commercial buildings and residential buildings in addition to the fact that they have a variety of the most common types of building materials including bricks, masonry, concrete, metal, timber and gypsum etc. As seen in all three Tally assessments, the materials and components in each building have different design life left due to the nature of its use and age (when it was first installed). Although, there is one set of results for each building type, the set of results are applicable and transferrable across all the three types of buildings, as the principles are similar in terms of the Life

Cycle Analyses (LCA), remaining design life and the Life Cycle Cost (LCC) for each of the material and components of the building.

As discussed previously, existing design and assessment tools do not address many economic, social and performance facets over the life span of a building, and do not provide building assessment results for all dimensions of sustainable development. There is a need for different assessment tasks within the design process to be analysed, and approaches for the further development of building assessment tools to be considered. Therefore, Tally was chosen as part of this research project to overcome these issues.

Although, many vital information regarding the three analysed semi-commercial buildings could not be accessed or gained due to the unavailability of the owners and relevant stakeholders, some of the technical data was retrieved from the old archives of the developers that in the recent past worked as a principal contractor during the construction or refurbishment of these buildings. The other set useful information regarding these buildings was achieved from the Local Planning Authority's (LPA) planning portal, which included all the design related information, any changes or previous planning permissions that were made on each of these buildings and approval or rejection of any planning permission (with detailed decision notice) made in the past. Due to the nature and location of these buildings, limited design related information was available for public access on the LPA's website, due to which full access to the design drawings of the buildings could not be achieved by the author.

TALLY allows Revit users to imbue their BIM with the complete information about the building materials and architectural products their structures will ultimately contain. Tally quantifies a building or material's embodied environmental impacts to land, air, and water systems. Essentially, Tally adds another layer of detail to BIM by recognising materials that are not modeled explicitly, like the steel in concrete assemblies, and by taking into account a model's diverse range of material classes. In doing so, Tally gives its users the power to conduct whole building LCAs during design and to use LCA data to run comparative analyses of various design options that show their differing environmental impacts. Autodesk Revit is one of the most popular CAD software, that is used in widely within the construction industry, but it lacks on conducting the Life Cycle Analyses for buildings within the package, but the introduction of Tally plug-in for Revit has solved this query for many users who has to work simultaneously on two different software packages for design and LCA related issues.

### 5.4.1 Tally Assessment 1 – Existing Building (60 years old)

This Tally trail is performed on an existing building with existing/old material in order to determine the remaining life of each of the component of the building and also to make a decision on whether to refurbish or rebuild the structure when it reaches the end of design life (EODL).

**Project Details**

- Project: Existing Building Report – two-storey residential house;
- Location: South-West London;
- Gross Area: 212m$^2$;
- Building's current life: 60 years;
- Structure type: Semi-detached house;
- Surroundings: Residential area.

**On-site construction**

- 100 kWh electricity use;
- 100 kWh heating energy use;
- 1000 gallons water use.

**Operational energy**

- 100 kWh annual electricity use;
- 100 kWh annual heating energy use.

**Goal and scope of assessment**

- To assess the current material condition of the existing building and make a decision of whether to refurbish/re-use or rebuild/recycle.

As this trailed building is 60 years old, it cannot be considered as an old building, and still has more than half of the life left in it. A concrete structure is often considered to have a life span of at least 120 years. However, in some scenarios, the owner wants to make changes (refurbishment) or to change the use of the property with additional planning applications. Considering the scenario that the owner wants to make changes to the structure and looking to make a decision that is in the best of interest of all the relevant stakeholders that includes the client and the local authority, a Tally trial is conducted. The trial performed on this Revit model highlights the application of the key identified decision-making factors. As this is an LCA based trial, the preference is given to the environmental impact, however, other relevant key factors in this case are also implemented, which are based on the results gained from the environmental impact assessment sub-categories.

Highlighting the exiting condition of the building from the Tally LCA trial, Figure 5.5 indicates that the operational energy generates the higher amount of $CO_2$ and risks the environmental impact. In this instance, the operational energy is indicating towards the option to rebuild.

On the other hand, refurbishment is considered to have the less environmental impact in this case and also having the minimum impact in all potential emissions, as maintenance and replacement (B2-B5) only accounts for 13% of the global warming potential (GWP), as shown in Figure 5.5.

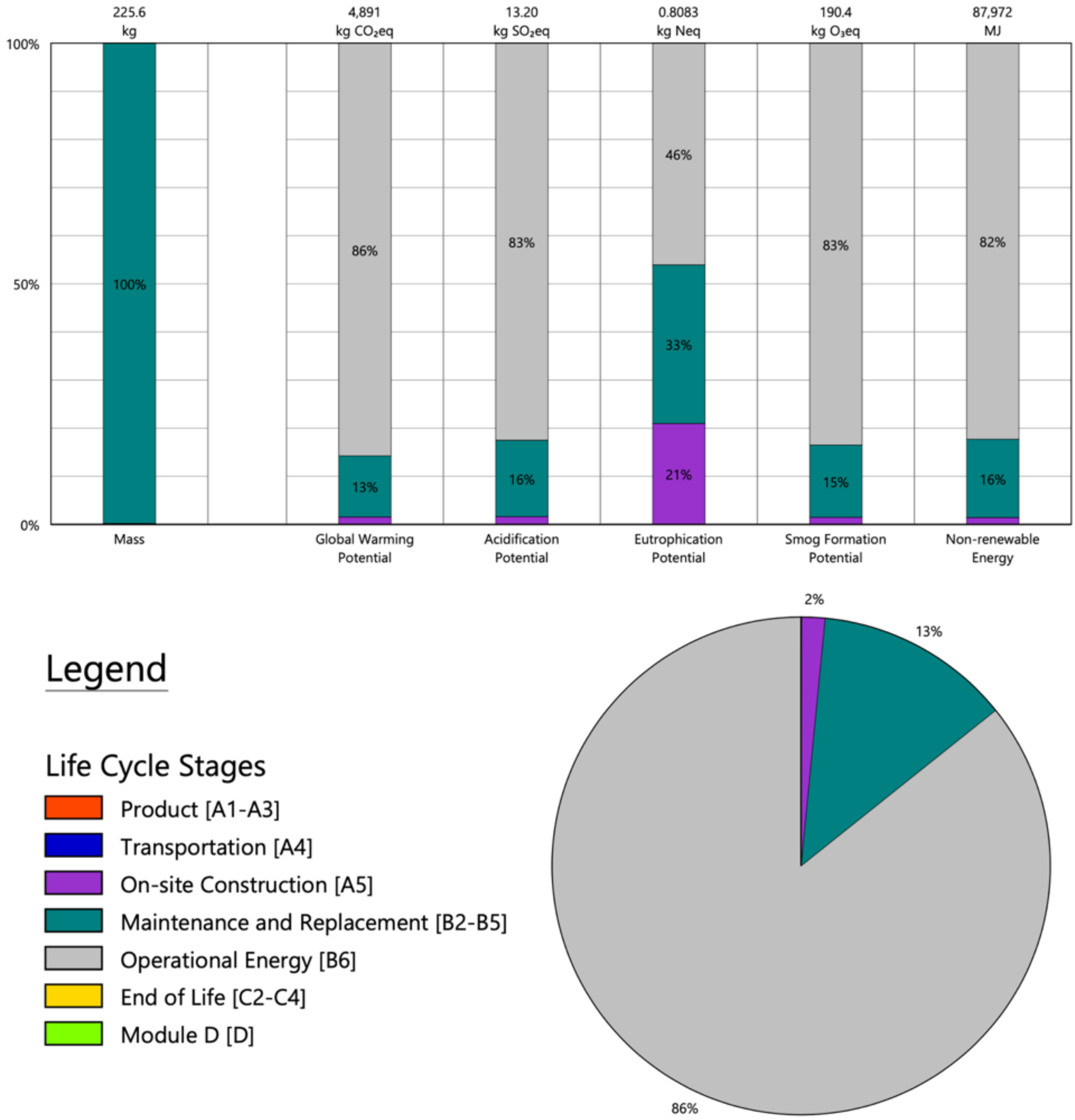


***Figure 5.5 Results per lifecycle stage (source: The Author)***

Since the GWP contribution for on-site construction phase is significantly low, which falls under the module A5 (construction Installation), this indicates that the installation of the components will have a lower environmental impact. However, the volumes of the mapped steel/metal to the columns are higher than the ones which were mapped as rebar, even though the rebar exists in both vertical and structures. In Tally plug-in tool, the quantities of the design object and components were detected as same with the Revit Architecture model, this highlights the accuracy of Tally, which is found to be considerably high. However, quantities of some of the materials included within the components were not detected by Tally. This does not have the major impact on the overall results, as the amount of the undetected material is very low and furthermore, the components are already detected that possesses all the properties and relevant values required to perform the Tally LCA.

The breakdown of each of the life cycle stages of the building in Figure 5.6 indicates that concrete, wood, masonry, metals and plastic generates more $CO_2$ during the refurbishment phase. However, the rebuilding would produce maximum $CO_2$, which would certainly affect the environment and also the surroundings.

An important factor to consider here is that the building site is located in a residential estate with one residential property sharing the party wall with this building, as it is a semi-detached property. Hence, demolishing it and rebuilding a completely new structure would surely have a massive impact on the local residents and the environment. This impact factor has the maximum weightage and favours the refurbishment scenario. However, the purpose of this Tally trail is to assess the condition of the building and apply the key identified decision-making factors, where necessary and applicable.

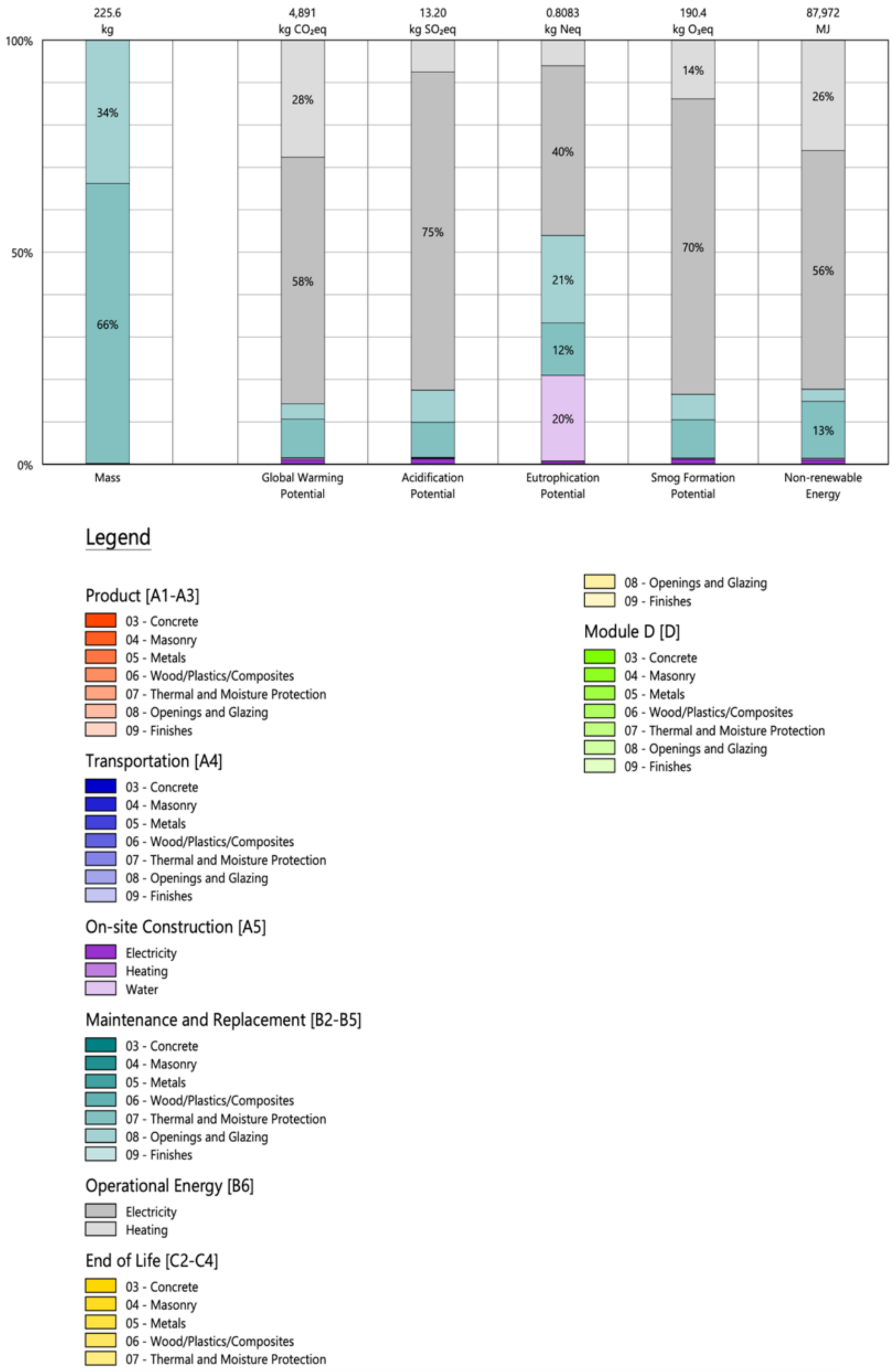


***Figure 5.6 Results per lifecycle stage, itemised by division (Source: The Author)***

A detailed set of results per division in Figure 5.7 highlights the maximum energy emissions are produced from the thermal and moisture protection layer, which are installed in roofs and exterior walls. Whereas, openings and glazing takes the second spot. This is due to the age factor, as the building is not very old and still has a fairly good amount of design life left. The masonry division (see Figure 5.7) under the maintenance and replacement (B2-B5) module consists almost of brick and mortar used in the building façade, but is considered to be in good state due to its long remaining life.

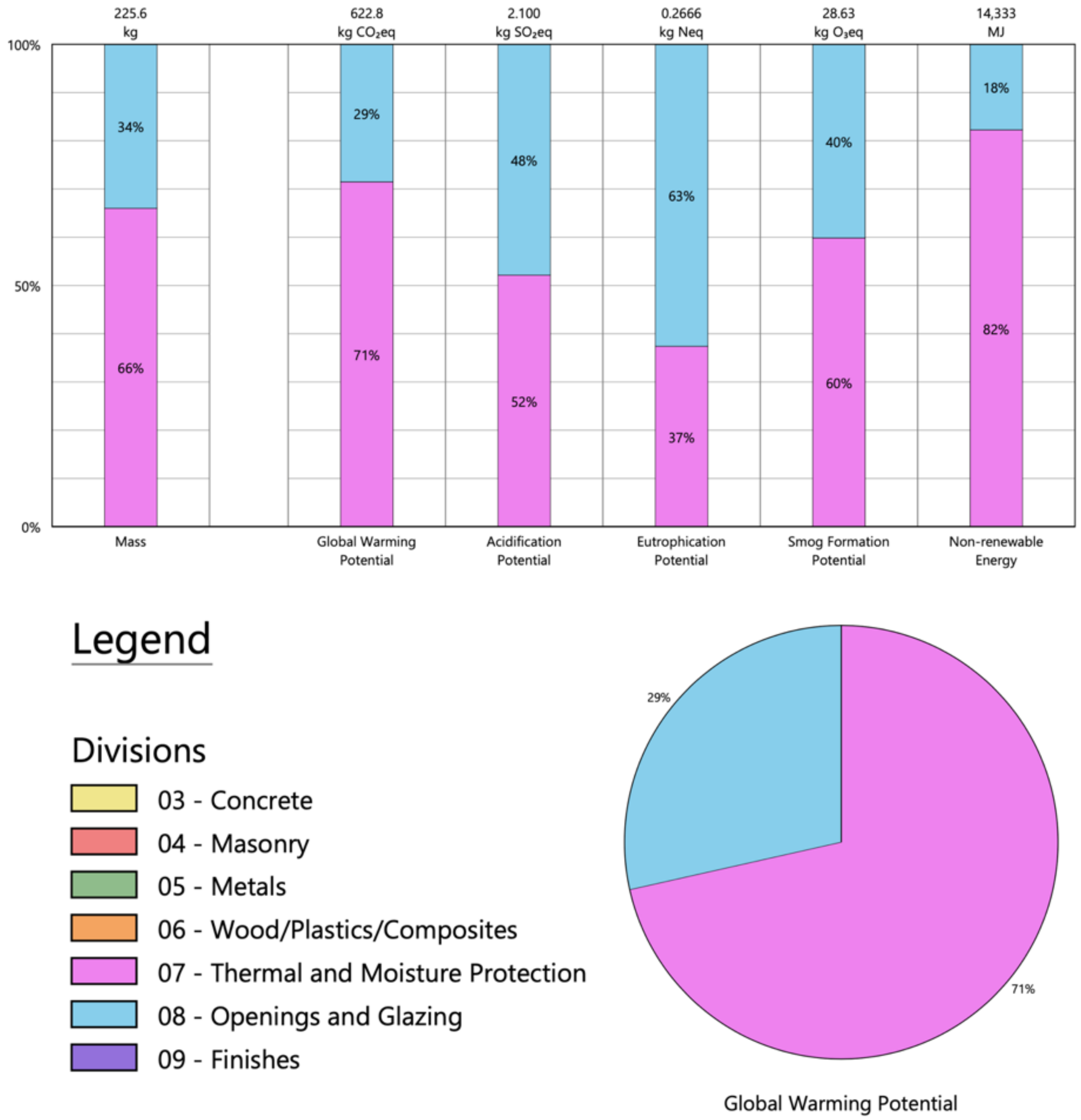


***Figure 5.7 Results per division (Source: The Author)***

Considering the remaining design life of the building and the LCA generated by Tally, the refurbishment seems to be a viable option for this building, but there is another important factor to consider, which is the cost. As shown in figure 5.8, all of the main materials that have the potential for higher emissions are highlighted, out of which, thermal and moisture protection layers possess the highest percentage of GWP, which is 62%. The sub-categories of these materials are also highlighted in Figure 5.8, which includes adhesive acrylic, insulation, fasteners, roofing materials and galvanised steel support and steel etc. On the other side, paint and interior gypsum boards possess the least amount of GWP.

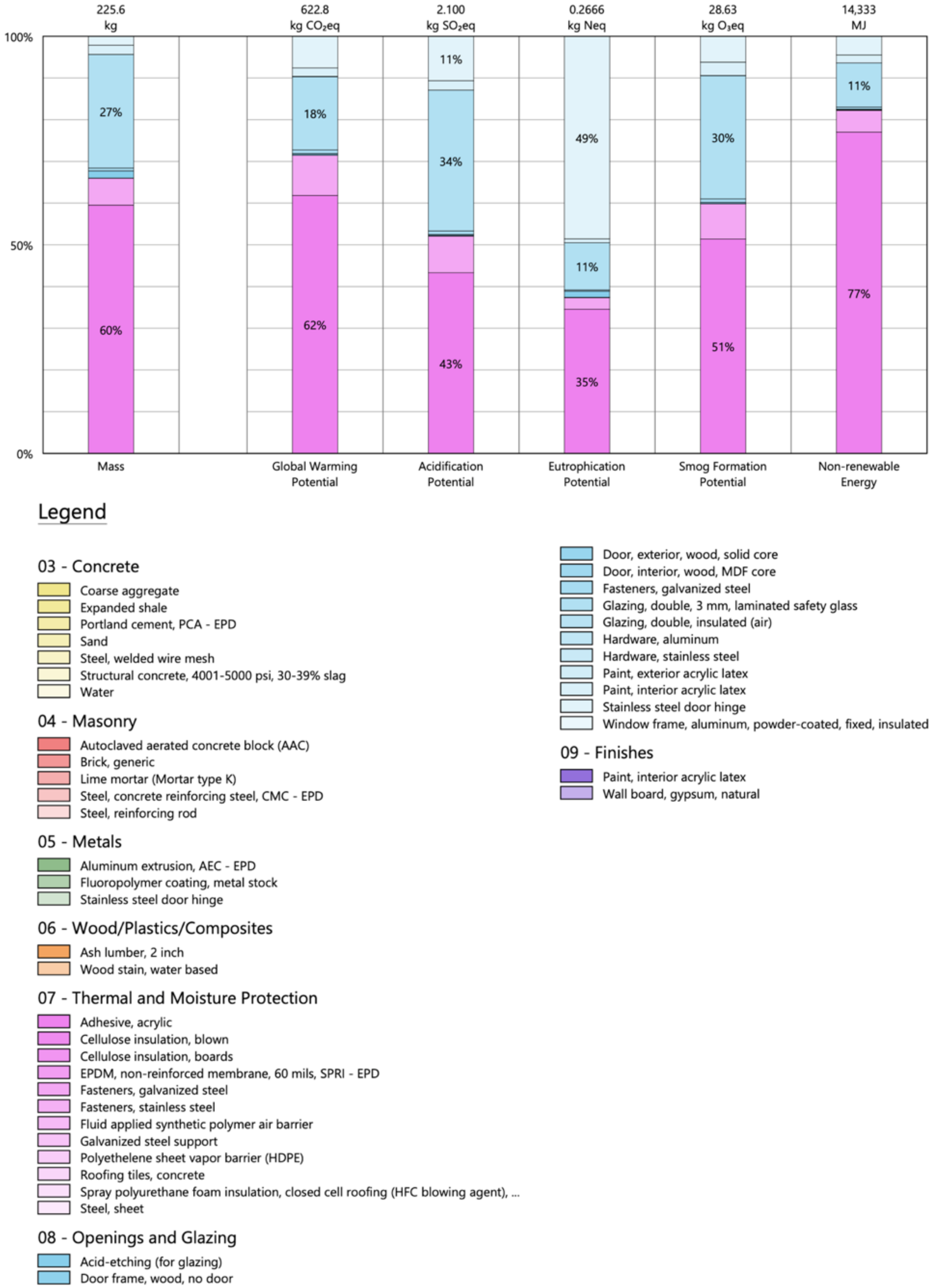


***Figure 5.8 Results per division, itemised by material (Source: The Author)***

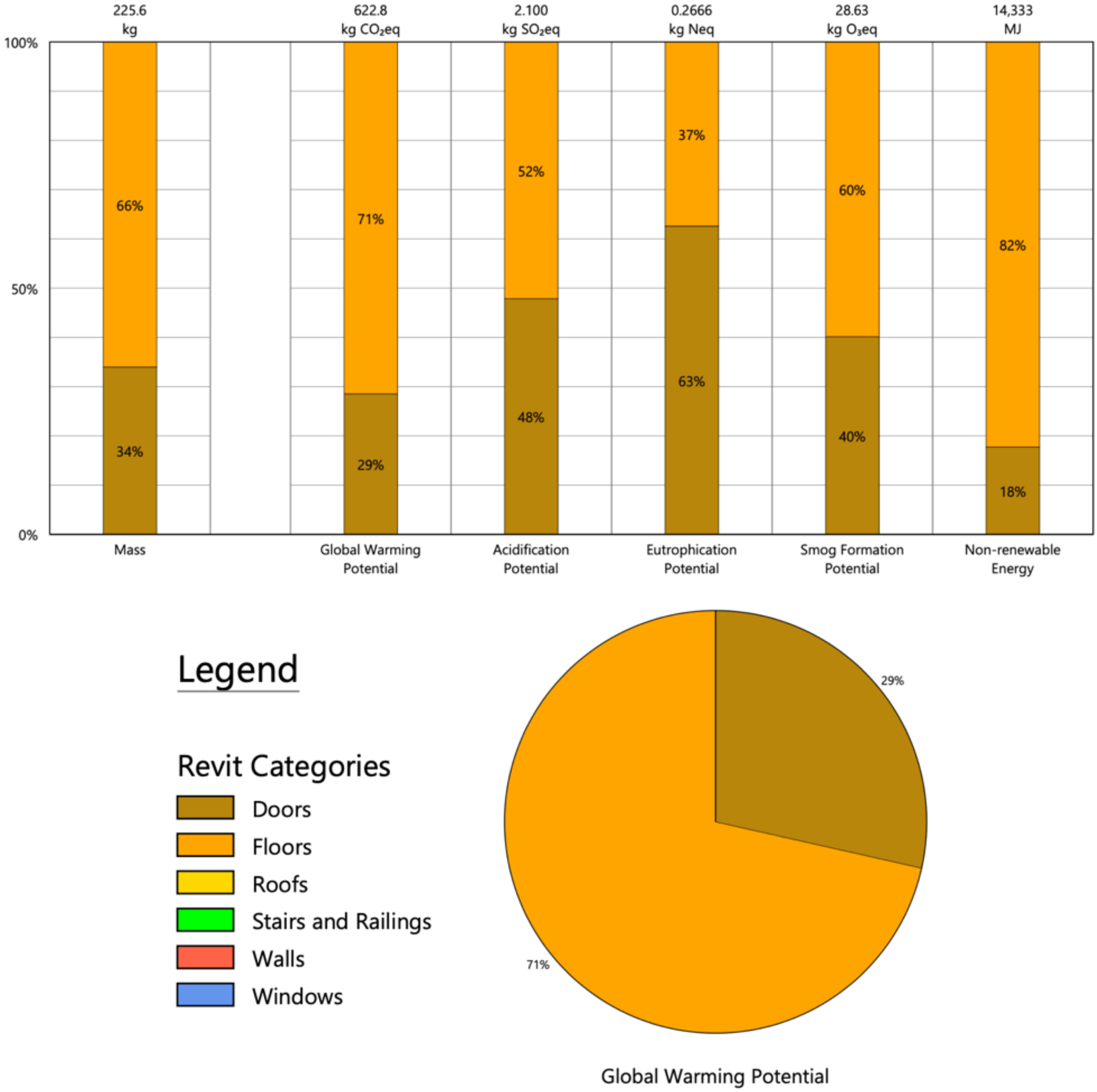


***Figure 5.9 Results per Revit category based on Tally (Source: The Author)***

Considering the results from the imported Revit categories in Tally as shown in Figure 5.9, it has been clearly observed that the floors and doors contributes to the highest amount of global warming potential (GWP) i.e. 71% and 29% respectively. This indicates the replacement of these components will be necessary if the decision to refurbish is being made. Further to this decision (if made), the new components replacing the existing components need to be manufactured with the recommended materials that are durable and have the least proportion of $CO_2$ emissions as described in the relevant British Standards (BS) for each of the component.

*Table 5.2 Environmental impacts total for assessment 1 (Source: The Author)*

| | Product Stage | Construction Stage | Use Stage | End of Life Stage | Module D |
|---|---|---|---|---|---|
| **Environmental Impact Totals** | **[A1-A3]** | **[A4-A5]** | **[B2-B6]** | **[C2-C4]** | **[D]** |
| Global Warming (kg CO2eq) | 1.806 | 73.67 | 4,816 | 3.930E-004 | -0.8048 |
| Acidification (kg SO2eq) | 0.005544 | 0.2095 | 12.99 | 1.820E-006 | -0.001578 |
| Eutrophication (kg Neq) | 2.227E-004 | 0.1694 | 0.6387 | 9.211E-008 | -6.394E-005 |
| Smog Formation (kg O3eq) | 0.0702 | 2.775 | 187.5 | 3.608E-005 | -0.02236 |
| Ozone Depletion (kg CFC-11eq) | -7.377E-009 | 1.156E-010 | 4.804E-006 | 7.243E-017 | 5.678E-009 |
| Primary Energy (MJ) | 24.01 | 1,428 | 98,555 | 0.006751 | -7.02 |
| Non-renewable Energy (MJ) | 22.58 | 1,236 | 86,713 | 0.006304 | -7.51 |
| Renewable Energy (MJ) | 1.426 | 193.4 | 11,946 | 4.449E-004 | 0.5187 |

Having assessed and considered the total environmental impact based on the provided material/component data and specifications in this assessment, the construction stage (A4-A5) and the use stage (B2-B6) is found to have the most amount of carbon emissions as shown in the Table 5.2. The components of the existing building are found to be reaching the end of their design life and thus these need to be replaced, as shown in Figure 5.9.

*Table 5.3 Environmental impacts per area for assessment 1 (Source: The Author)*

| | Product Stage | Construction Stage | Use Stage | End of Life Stage | Module D |
|---|---|---|---|---|---|
| **Environmental Impact Area** | **[A1-A3]** | **[A4-A5]** | **[B2-B6]** | **[C2-C4]** | **[D]** |
| Global Warming (kg CO2eq) | 0.01843 | 0.7518 | 49.14 | 4.010E-006 | -0.008212 |
| Acidification (kg SO2eq) | 5.657E-005 | 0.002138 | 0.1325 | 1.857E-008 | -1.611E-005 |
| Eutrophication (kg Neq) | 2.227E-006 | 0.001728 | 0.006517 | 9.399E-010 | -6.524E-007 |
| Smog Formation (kg O3eq) | 7.163E-004 | 0.02832 | 1.914 | 3.682E-007 | -2.281E-004 |
| Ozone Depletion (kg CFC-11eq) | -7.528E-011 | 1.179E-012 | 4.902E-008 | 7.391E-019 | 5.794E-011 |
| Primary Energy (MJ) | 0.245 | 14.57 | 1,006 | 6.889E-005 | -0.07163 |
| Non-renewable Energy (MJ) | 0.2304 | 12.61 | 884.8 | 6.433E-005 | -0.07665 |
| Renewable Energy (MJ) | 0.01455 | 1.973 | 121.9 | 4.540E-006 | 0.005292 |

Similarly, the environmental impacts per area also accounts for higher percentage in the construction and use stage as shown in Table 5.3. The renewable and non-renewable energy in the rebuild scenario would potentially have the less environmental impact. However, the overall cost of the project would rise. Thus, the replacement of old electrical fixtures and components with the new ones is a feasible and cost effective option.

#### 5.4.1.1 Life Cycle Inventory (LCI) Data

LCI data generated from the Tally report is based on multiple phases of construction. Whereas, in this project, the only relevant phase includes the cost and End-Of-Life (EOL) scenario. Thus, the key decision-making factors are only used to compare with the EOL of each component of the building.

**Model Components - Revit Categories**

Following components of the Revit/BIM model are detected by Tally for life cycle analysis.

- Ceilings;
- Curtainwall Mullions;
- Curtainwall Panels;
- Doors;
- Floors;
- Roofs;
- Stairs and Railings;
- Structure;
- Walls;
- Windows.

Materials and components are listed in alphabetical order along with a list of all Revit families and Tally entries in which they occur. The masses given here refer to the quantity of each material used over the building's life-cycle, which includes both product [A1-A3] and use/refurbishment [B2-B5] stages.

Additional provided data describing scope boundaries for each life cycle stage may be useful for interpretation of the impacts associated with the specific material or component. Each material or component is listed with its service life, or period of time after installation it is expected to meet the service requirements prior to replacement or repair. This value is indicated in parentheses next to the mass of the material associated with the listed Revit component family. Values for transportation distance or service life are show in each of the tables in this section and are user-defined with changes from the default values. Values for service life are shown and indicate materials identified by the modeler/designer as existing or salvaged.

#### 5.4.1.2 Components assessed for LCA – Assessment 1

This section includes all the materials and components of the building assessed in this Tally trial including their total mass in kg, end of life scope (recycle or landfill), product scope and transportation distance to site from the supplier for replacement purpose.

1. **Acid-etching (for glazing)**

- Used in the following Revit families: Glazing door.
- Used in the following Tally entries: Door, exterior, glass.
- Mass identified: 8 kg.

***Table 5.4 Acid-etching LCA (Source: The Author / Tally Report)***

| | |
|---|---|
| **Description** | Acid etching for application to glazing. Assumes 1 kg/m$^2$ of acid solution used and 0.51 MJ process energy. |
| **Life Cycle Inventory** | Acid solution (32% HCl concentration, 68% Water) 1 kg acid/m$^2$ glass. |
| **Product Scope** | Cradle to gate. |
| **Transportation Distance** | N/A. |
| **End-of-Life Scope** | 100% to landfill (inert waste). |

2. **Adhesive, acrylic**

- Used in the following Revit families: Floor-Grnd-Susp_65Scr-80Ins-100Blk-75PC
- Used in the following Tally entries: EPDM sheet, waterproofing.
- Mass identified: 134.2 kg.

***Table 5.5 Adhesive, acrylic LCA (Source: The Author / Tally Report)***

| | |
|---|---|
| **Description** | Generic acrylic construction adhesive. |
| **Life Cycle Inventory** | 5% Naphtha at refinery 95% Acrylate resin (solvent-systems) 0.5% NMVOC emissions. |
| **Product Scope** | Cradle to gate, plus emissions during application |
| **Transportation Distance** | By truck: 40 km. |
| **End-of-Life Scope** | 99.5% solids to landfill (plastic waste). |

3. **Aluminum extrusion, AEC - EPD**

- Used in the following Revit families: Railing 1100mm.
- Used in the following Tally entries: Aluminum, round tube.
- Mass identified: 31.3 kg.

*Table 5.6 Aluminium extrusion LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | Extruded aluminum part. Industry-wide EPD from the Aluminum Extruders Council. |
| **Life Cycle Inventory** | See EPD. |
| **Product Scope** | Cradle to gate. |
| **Transportation Distance** | By truck: 63 km. |
| **End-of-Life Scope** | 95% Recovered 5% Landfilled (inert material). |
| **Module D Scope** | Product has 36.4% scrap input while remainder is processed and credited as avoided burden. |

4. **Ash lumber, 2 inch**

- Used in the following Revit families: Private.
- Used in the following Tally entries: Stair, hardwood, tread only.
- Mass identified: 13.3 kg.

*Table 5.7 Ash Lumber LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | Kiln-dried Ash hardwood lumber of 2 inch nominal thickness as produced in the United Kingdom, focusing on the main production technologies. Ash is frequently used for mouldings, flooring, furniture, and doors. Link for interactive LCA data tool is provided at the link listed as "EPD Information". |
| **Life Cycle Inventory** | 100% Ash. |
| **Product Scope** | Cradle to gate, uncoated. |
| **Transportation Distance** | By truck: 83 km. |
| **End-of-Life Scope** | 14.5% Recovered 22% Incinerated with energy recovery 63.5% Landfilled (wood product waste). |
| **Module D Scope** | Recovered wood products credited as avoided burden. |

5. **Autoclaved aerated concrete block (AAC)**

- Used in the following Revit families: Boundary Wall Floor-Grnd-Susp_65Scr-80Ins-100Blk-75PC Wall-Int_12P-100Blk-12P.
- Used in the following Tally entries: Autoclaved aerated concrete block (AAC).
- Mass identified: 1100 kg.

*Table 5.8 Autoclaved concrete block LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | Autoclaved aerated concrete block (AAC), excludes mortar. |
| **Life Cycle Inventory** | 60-70% Quartz sand 20-30% Cement (type CEMI) 10-20% Quick lime 2-5% Gypsum. |
| **Product Scope** | Cradle to gate, excludes mortar anchors, ties, and metal accessories outside of scope (<1% mass). |
| **Transportation Distance** | By truck: 72 km. |
| **End-of-Life Scope** | 55% Recycled into coarse aggregate 45% Landfilled (inert material). |
| **Module D Scope** | Avoided burden credit for coarse aggregate, includes grinding energy. |

6. **Brick, generic**

- Used in the following Revit families: Boundary Wall Wall-Ext_102Bwk-75Ins-100LBlk-12P.
- Used in the following Tally entries: Brick.
- Mass identified: 1300 kg.

*Table 5.9 Brick, generic LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | Common extruded brick, excludes mortar. |
| **Life Cycle Inventory** | 100% Fired brick. |
| **Product Scope** | Cradle to gate excludes mortar anchors, ties, and metal accessories outside of scope (<1% mass). |
| **Transportation Distance** | By truck: 72 km. |
| **End-of-Life Scope** | 55% Recycled into coarse aggregate 45% Landfilled (inert material). |
| **Module D Scope** | Avoided burden credit for coarse aggregate, includes grinding energy. |

7. **Cellulose insulation, blown**

- Used in the following Revit families: Boundary Wall Wall-Ext_102Bwk-75Ins-100LBlk-12P.
- Used in the following Tally entries: Cellulose insulation, blown.
- Mass identified: 110.6 kg.

*Table 5.10 Cellulose insulation (blown) LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | Blown-in cellulose insulation. |
| **Life Cycle Inventory** | Waste paper fibers Boric acid Boraxpentahydrate. |
| **Product Scope** | Cradle to gate. |
| **Transportation Distance** | By truck: 20 km. |
| **End-of-Life Scope** | 100% Landfilled (biodegradable waste). |

8. **Cellulose insulation, boards**

- Used in the following Revit families: Floor-Grnd-Susp_65Scr-80Ins-100Blk-75PC Modified roof.
- Used in the following Tally entries: Cellulose insulation, board.
- Mass identified: 130 kg.

*Table 5.11 Cellulose insulation boards LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | Cellulose insulation, boards. |
| **Life Cycle Inventory** | Waste paper fibers Tall oil resin Ferrochrome-lignine sulfonate Borax. |
| **Product Scope** | Cradle to gate. |
| **Transportation Distance** | By truck: 20 km. |
| **End-of-Life Scope** | 100% Landfilled (biodegradable waste). |

9. **Coarse aggregate**

- Used in the following Revit families: Floor-Grnd-Susp_65Scr-80Ins-100Blk-75PC.
- Used in the following Tally entries: Cast-in-place concrete, custom mix.
- Mass identified: 800 kg.

*Table 5.12 Coarse aggregate LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | Concrete mix ingredient: Gravel. |
| **Life Cycle Inventory** | Gravel. |
| **Product Scope** | Cradle to gate, excludes mixing and pouring impacts. |
| **Transportation Distance** | By truck: 31 km. |
| **End-of-Life Scope** | 55% Recycled into coarse aggregate 45% Landfilled (inert material). |
| **Module D Scope** | Avoided burden credit for coarse aggregate, includes grinding energy. |

**10. Door frame, wood (no door)**

- Used in the following Revit families: Doors
- Used in the following Tally entries: Door frame, wood.
- Mass identified: 10.9 kg.

*Table 5.13 Door frame LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | Wood door frame. |
| **Life Cycle Inventory** | 94% Pine, 6% Paint. |
| **Product Scope** | Cradle to gate, excludes hardware, jamb, casing, sealant. |
| **Transportation Distance** | By truck: 26 km. |
| **End-of-Life Scope** | 14.5% recovered, 22% incinerated with energy recovery, 63.5% landfilled (wood product waste). |
| **Module D Scope** | Recovered wood products credited as avoided burden. |

**11. Door, exterior, wood, solid core**

- Used in the following Revit families: Doors_ExtSgl_w-Glazing_Bars_3 Doors_ExtSgl_w-Glazing_Bars_Arched.
- Used in the following Tally entries: Door, exterior, wood, solid core.
- Mass identified: 38 kg.

*Table 5.14 Exterior door LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | Exterior wood door. |
| **Life Cycle Inventory** | 100% Wood. |
| **Product Scope** | Cradle to gate, excludes assembly, frame, hardware, and adhesives. |
| **Transportation Distance** | By truck: 26 km. |
| **End-of-Life Scope** | 14.5% Wood products recovered, 22% Wood products incinerated with energy recovery, 63.5% Wood products landfilled (wood product waste). |
| **Module D Scope** | Recovered wood products credited as avoided burden. |

**12. Door, interior, wood, MDF core**

- Used in the following Revit families: Doors_IntSgl.
- Used in the following Tally entries: Door, interior, wood, MDF core, flush.
- Mass identified: 120 kg.

*Table 5.15 Interior door LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | Interior flush wood door with MDF core. |
| **Life Cycle Inventory** | 40% Wood, 60% MDF. |
| **Product Scope** | Cradle to gate, excludes assembly, frame, hardware, and adhesives. |
| **Transportation Distance** | By truck: 26 km. |
| **End-of-Life Scope** | 14.5% Wood products recovered, 22% Wood products incinerated with energy recovery, 63.5% Wood products landfilled (wood product waste). |
| **Module D Scope** | Recovered wood products credited as avoided burden. |

### 13. EPDM, non-reinforced membrane, 60 mils, SPRI - EPD

- Used in the following Revit families: Floor-Grnd-Susp_65Scr-80Ins-100Blk-75PC.
- Used in the following Tally entries: EPDM sheet, waterproofing.
- Mass identified: 19 kg.

*Table 5.16 Non-reinforced membrane LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | Non-reinforced ethylene propylene diene terpolymer (EPDM) synthetic rubber roofing membrane, default thickness of 60 mils (1.5 mm). Industry-wide EPD from the Single Ply Roofing Industry. |
| **Life Cycle Inventory** | See EPD. |
| **Product Scope** | Cradle to gate. |
| **Transportation Distance** | By truck: 72 km. |
| **End-of-Life Scope** | 100% Landfilled (plastic waste). |
| **Module D Scope** | Non-reinforced EPDM single ply roofing membrane, 60 mils, A1-A3 - SPRI ts (2017). |

### 14. Expanded shale

- Used in the following Revit families: Floor-Grnd-Susp_65Scr-80Ins-100Blk-75PC.
- Used in the following Tally entries: Cast-in-place concrete, custom mix.
- Mass identified: 19 kg.

*Table 5.17 Expanded shale LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | Concrete mix ingredient: Expanded shale 45 pcf. |
| **Life Cycle Inventory** | Expanded shale. |
| **Product Scope** | Cradle to gate, excludes mixing and pouring impacts. |
| **Transportation Distance** | By truck: 6 km. |
| **End-of-Life Scope** | 55% Recycled into coarse aggregate 45% Landfilled (inert material). |
| **Module D Scope** | Avoided burden credit for coarse aggregate, includes grinding energy. |

**15. <u>Fasteners, galvanised steel</u>**

- Used in the following Revit families: Doors_ExtSgl_w-Glazing_Bars_3 Doors_ExtSgl_w-Glazing_Bars_Arched Doors_IntSgl Floor-Grnd-Susp_65Scr-80Ins-100Blk-75PC Modified roof.
- Used in the following Tally entries: Door frame, wood, metal roofing panels, formed Polyethelene sheet vapor barrier (HDPE).
- Mass identified: 16.2 kg.

*Table 5.18 Fasteners, galvanised steel LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | Galvanized steel part, appropriate for use as fasteners and specialized hardware (bolts, rails, clips, etc.). |
| **Life Cycle Inventory** | 100% Galvanized steel. |
| **Product Scope** | Cradle to gate. |
| **Transportation Distance** | By truck: 11 km. |
| **End-of-Life Scope** | 70% Recovered 30% Landfilled (inert material). |
| **Module D Scope** | Product has 16% scrap input while remainder is processed and credited as avoided burden. |

**16. <u>Fasteners, stainless steel</u>**

- Used in the following Revit families: Modified roof.
- Used in the following Tally entries: Concrete roofing tile, Insulated metal roof panels, custom.
- Mass identified: 80.3 kg.

*Table 5.19 Fasteners, stainless steel LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | Stainless steel part, appropriate for use as fasteners and specialized hardware (bolts, rails, clips, etc.). Data based on industry-wide EPDs for primary and secondary metal from the World Steel Association. |
| **Life Cycle Inventory** | 100% Stainless steel |
| **Product Scope** | Cradle to gate. |
| **Transportation Distance** | By truck: 11 km. |
| **End-of-Life Scope** | 98% Recovered, 2% Landfilled (inert material) |
| **Module D Scope** | Product has 58% scrap input while remainder is processed and credited as avoided burden |

### 17. Fluid applied synthetic polymer air barrier

- Used in the following Revit families: Floor-Grnd-Susp_65Scr-80Ins-100Blk-75PC.
- Used in the following Tally entries: Fluid applied synthetic polymer air barrier.
- Mass identified: 0.0 kg – not detected by Tally.

*Table 5.20 Polymer air barrier LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | Liquid-applied rubberized membrane. |
| **Life Cycle Inventory** | 34% Calcium carbonate, 30% Polymer blend (SBS), 1% Silica, 5% Titanium dioxide 30% Water. |
| **Product Scope** | Cradle to gate for materials only, neglects manufacturing requirements. |
| **Transportation Distance** | By truck: 55 km. |
| **End-of-Life Scope** | 70% Landfilled (plastic waste) (excludes water evaporation). |

### 18. Fluoropolymer coating, metal stock

- Used in the following Revit families: railing 1100mm.
- Used in the following Tally entries: Aluminum, round tube.
- Mass identified: 0.0 kg – not detected by Tally.

*Table 5.21 Fluoropolymer coating LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | Standard fluoropolymer coating for metals. This entry is used as a part of the larger MCA EPD for Roll Formed Steel Panels (EPD ID 13CA27321.101.1). |
| **Life Cycle Inventory** | 100% Fluoropolymer coating. |
| **Product Scope** | Cradle to gate, including application. |
| **Transportation Distance** | N/A. |
| **End-of-Life Scope** | 100% Landfilled (inert waste). |

**19. <u>Galvanised steel support</u>**

- Used in the following Revit families: Modified roof.
- Used in the following Tally entries: Metal roofing panels, formed.
- Mass identified: 89 kg.

*Table 5.22 Galvanised steel support LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | Hot dipped galvanised steel profile, for use with cladding systems. |
| **Life Cycle Inventory** | 100% Steel, hot dip galvanised. |
| **Product Scope** | Cradle to gate for deck only. |
| **Transportation Distance** | By truck: 31 km. |
| **End-of-Life Scope** | 98% Recovered, 2% Landfilled (inert material). |
| **Module D Scope** | Product has 44% scrap input while remainder is processed and credited as avoided burden. |

**20. <u>Glazing, double, 3 mm, laminated safety glass</u>**

- Used in the following Revit families: Doors_ExtSgl_w-Glazing_Bars_3 Doors_ExtSgl_w-Glazing_Bars_Arched.
- Used in the following Tally entries: Door, exterior, glass.
- Mass identified: 61.4 kg.

*Table 5.23 3mm double glazing LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | 2 lites 3 mm thick, inclusive of polyvinyl butyral. Note: this entry is appropriate for clear or tinted glass. |
| **Life Cycle Inventory** | 3% PVB film (30% adipic acid 70% PVB) 97% Glass. |
| **Product Scope** | Cradle to gate, excluding sealant. |
| **Transportation Distance** | By truck: 40 km. |
| **End-of-Life Scope** | 100% Landfilled (inert waste). |

### 21. Glazing, double, insulated (air)

- Used in the following Revit families: Windows - Bay Casement, Windows - Double Casement with vent, Windows - Double Vent.
- Used in the following Tally entries: Glazing, double pane IGU.
- Mass identified: 0.0 kg – not detected by Tally.

*Table 5.24 Insulated double glazing LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | Glazing, double, insulated (air filled), 1/8" (4 mm) float glass clear, inclusive of sealant, and spacers. |
| **Life Cycle Inventory** | Double-pane glass IGU (Air filled, with spacer and sealant). |
| **Product Scope** | Cradle to gate. |
| **Transportation Distance** | By truck: 40 km. |
| **End-of-Life Scope** | 100% Landfilled (inert waste). |

### 22. Hardware, aluminum

- Used in the following Revit families: Windows - Bay Casement, Windows - Double Casement with vent, Windows - Double Vent.
- Used in the following Tally entries: Window frame, aluminum.
- Mass identified: 38.6 kg.

*Table 5.25 Aluminium LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | Milled aluminum applicable for door, window or other accessory hardware. Data based on industry-wide EPDs for primary (EPD ID 4786092064.104.1) and secondary ingot (EPD ID 4786092064.105.1) from the Aluminum Association. |
| **Life Cycle Inventory** | 50% Primary aluminum 50% Secondary aluminum. |
| **Product Scope** | Cradle to gate. |
| **Transportation Distance** | By truck: 11 km. |
| **End-of-Life Scope** | 95% Recovered 5% Landfilled (inert material). |
| **Module D Scope** | Product has 100% scrap input, burden reflects difference between recovered material and scrap input. |

**23. Hardware, stainless steel**

- Used in the following Revit families: Doors.
- Used in the following Tally entries: Door, exterior, glass, Door, exterior, wood, solid core Door, interior, wood, MDF core, flush.
- Mass identified: 28 kg.

*Table 5.26 Stainless steel LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | Finished, cast stainless steel, applicable for door, window or other accessory hardware. |
| **Life Cycle Inventory** | 100% Stainless steel. |
| **Product Scope** | Cradle to gate. |
| **Transportation Distance** | By truck: 11 km. |
| **End-of-Life Scope** | 98% Recovered, 2% Landfilled (inert material). |
| **Module D Scope** | Product has 58% scrap input while remainder is processed and credited as avoided burden. |

**24. Lime mortar (Mortar type K)**

- Used in the following Revit families: Boundary Wall Floor-Grnd-Susp_65Scr-80Ins-100Blk-75PC Wall-Ext_102Bwk-75Ins-100LBlk-12P Wall-Int_12P-100Blk-12P.
- Used in the following Tally entries: Autoclaved aerated concrete block (AAC) Brick.
- Mass identified: 0.0 kg – Not detected by Tally.

*Table 5.27 Lime morter LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | Lime mortar, traditionally used for historic masonry. |
| **Life Cycle Inventory** | 20-65% Sand 40-70% Limestone 5-15% Hydrated lime 7-15% Cement |
| **Product Scope** | Cradle to gate. |
| **Transportation Distance** | By truck: 72 km. |
| **End-of-Life Scope** | 55% Recycled into coarse aggregate, 45% Landfilled (inert material). |
| **Module D Scope** | Avoided burden credit for coarse aggregate, includes grinding energy. |

**25. Paint, exterior acrylic latex**

- Used in the following Revit families: Doors.
- Used in the following Tally entries: Door, exterior, wood, solid core.
- Mass identified: 0.0 kg - Not detected by Tally.

*Table 5.28 Paint, exterior acrylic latex LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | Acrylic-based latex paint for exterior applications. Associated reference primer. |
| **Life Cycle Inventory** | 20.5% Binding agent 35% Pigments and fillers, 40% Water, 4.5% Organic solvents. |
| **Product Scope** | Cradle to gate, including emissions during application. |
| **Transportation Distance** | By truck: 26 km. |
| **End-of-Life Scope** | 100% to landfill (plastic waste). |

**26. Paint, interior acrylic latex**

- Used in the following Revit families: Doors.
- Used in the following Tally entries: Door frame, wood door, interior, wood, MDF core, flush Wall board, gypsum.
- Mass identified: 53 kg.

*Table 5.29 Paint, interior acrylic latex LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | Acrylic-based paint for interior applications |
| **Life Cycle Inventory** | 21% Binding agent, 35% Pigments and fillers 42% Water, 2% Organic solvents. |
| **Product Scope** | Cradle to gate, including emissions during application. |
| **Transportation Distance** | By truck: 26 km. |

| | |
|---|---|
| **End-of-Life Scope** | 100% to landfill (plastic waste). |

27. **Portland cement, PCA - EPD**

- Used in the following Revit families: Floor-Grnd-Susp_65Scr-80Ins-100Blk-75PC.
- Used in the following Tally entries: Cast-in-place concrete, custom mix.
- Mass identified: 1231.8 kg – Approximate amount calculated by Tally.

***Table 5.30 Cement LCA (Source: The Author / Tally Report)***

| | |
|---|---|
| **Description** | Portland cement only. Data is based on Industry-wide EPD from the Portland Cement Association. |
| **Life Cycle Inventory** | See EPD |
| **Product Scope** | Cradle to gate. |
| **Transportation Distance** | By truck: 38 km. |
| **End-of-Life Scope** | 55% Recycled into coarse aggregate 45% Landfilled (inert material) |
| **Module D Scope** | Avoided burden credit for coarse aggregate, includes grinding energy |

28. **Roofing tiles, concrete**

- Used in the following Revit families: Modified roof.
- Used in the following Tally entries: Concrete roofing tile.
- Mass identified: 2360 kg.

***Table 5.31 Roofing tiles, concrete LCA (Source: The Author / Tally Report)***

| | |
|---|---|
| **Description** | Extruded high profile concrete tile, hardened and painted. Self-adhering asphalt felt underlay and fasteners not included in entry. |
| **Life Cycle Inventory** | 100% Concrete |
| **Product Scope** | Cradle to gate. |
| **Transportation Distance** | By truck: 72 km. |
| **End-of-Life Scope** | 55% recycled into coarse aggregate 45% landfilled (inert material) |
| **Module D Scope** | Avoided burden credit for coarse aggregate, includes grinding energy |

**29. Sand**

- Used in the following Revit families: Floor-Grnd-Susp_65Scr-80Ins-100Blk-75PC.
- Used in the following Tally entries: Cast-in-place concrete, custom mix.
- Mass identified: 0.0 kg – not detected by Tally.

***Table 5.32 Sand LCA (Source: The Author / Tally Report)***

| | |
|---|---|
| **Description** | Concrete mix ingredient: Sand. |
| **Life Cycle Inventory** | Sand. |
| **Product Scope** | Cradle to gate, excludes mixing and pouring impacts. |
| **Transportation Distance** | By truck: 51 km. |
| **End-of-Life Scope** | 55% Recycled into coarse aggregate 45% Landfilled (inert material). |
| **Module D Scope** | Avoided burden credit for coarse aggregate, includes grinding energy. |

**30. Spray polyurethane foam insulation, closed cell roofing**

- Used in the following Revit families: Modified roof.
- Used in the following Tally entries: Insulated metal roof panels, custom.
- Mass identified: 0.0 kg - not detected by Tally.

***Table 5.33 Spray foam insulation LCA (Source: The Author / Tally Report)***

| | |
|---|---|
| **Description** | Two-component polyurethane mixture insulation spray applied at installation site. Closed-cell spray foam for roofing systems is used on the external surface of low slope roofs. Its higher density provides additional compressive strength needed for roofing applications. HFC blowing agent is used. R Value: 6.2 (ft2hr°F/Btu)/in. |
| **Life Cycle Inventory** | See EPD. |
| **Product Scope** | Cradle to gate, includes emission of blowing agent during use (24% of total blowing agent). |
| **Transportation Distance** | By truck: 83 km. |
| **End-of-Life Scope** | 100% landfilled (plastic), including emission of blowing agent (16% of total blowing agent, 50% of blowing agent remains in product after disposal). |
| **Module D Scope** | Energy recovered from landfilling of packaging waste. |

### 31. Stainless steel door hinge

- Used in the following Revit families: Doors.
- Used in the following Tally entries: Door hinges, Door, exterior, glass door, exterior, wood, solid core Door, interior, wood, MDF core, flush.
- Mass identified: 12.9 kg.

***Table 5.34 Stainless steel door hinge LCA (Source: The Author / Tally Report)***

| | |
|---|---|
| **Description** | Stainless steel and aluminum door and window hinge. Data based on product-specific EPD from FSB. |
| **Life Cycle Inventory** | See EPD. |
| **Product Scope** | Cradle to gate. |
| **Transportation Distance** | By truck: 11 km. |
| **End-of-Life Scope** | 98% Recovered, 2% Landfilled (inert material). |
| **Module D Scope** | Product has a 0% scrap input while remainder is processed and credited as avoided burden. |

### 32. Steel, concrete reinforcing steel, CMC - EPD

- Used in the following Revit families: Boundary Wall.
- Used in the following Tally entries: Autoclaved aerated concrete block (AAC).
- Mass identified: 0.0 kg – not detected by Tally.

***Table 5.35 Concrete reinforcing steel LCA (Source: The Author / Tally Report)***

| | |
|---|---|
| **Description** | Concrete reinforcing steel (rebar) by Commercial Metals Company. Appropriate for use as reinforcement in concrete. EPD representative of conditions in the US. |
| **Life Cycle Inventory** | See EPD. |
| **Product Scope** | Cradle to gate. |
| **Transportation Distance** | By truck: 31 km. |
| **End-of-Life Scope** | 98% Recovered 2% Landfilled (inert material) |
| **Module D Scope** | Product has 100% scrap input, burden reflects difference between recovered material and scrap input. Credit given for the avoided burden associated with recovered material. |

**33. Steel, reinforcing rod**

- Used in the following Revit families: Floor-Grnd-Susp_65Scr-80Ins-100Blk-75PC Wall-Int_12P-100Blk-12P.
- Used in the following Tally entries: Autoclaved aerated concrete block (AAC).
- Mass identified: 0.0 kg – not detected by Tally.

***Table 5.36 Steel reinforcing rod LCA (Source: The Author / Tally Report)***

| | |
|---|---|
| **Description** | Common unfinished tempered steel rod suitable for structural reinforcement (rebar). |
| **Life Cycle Inventory** | 100% Steel rebar. |
| **Product Scope** | Cradle to gate. |
| **Transportation Distance** | By truck: 31 km. |
| **End-of-Life Scope** | 70% Recovered, 30% Landfilled (inert material) |
| **Module D Scope** | Product has a 16.4% scrap input while remainder is processed and credited as avoided burden. |

**34. Steel, sheet**

- Used in the following Revit families: Modified roof.
- Used in the following Tally entries: Insulated metal roof panels, custom Metal roofing panels, formed.
- Mass identified: 0.0 kg – not detected by Tally.

***Table 5.37 Steel sheet LCA (Source: The Author / Tally Report)***

| | |
|---|---|
| **Description** | Steel sheet. |
| **Life Cycle Inventory** | 100% Steel sheet. |
| **Product Scope** | Cradle to gate. |
| **Transportation Distance** | By truck: 18 km. |
| **End-of-Life Scope** | 98% Recovered, 2% Landfilled (inert material). |
| **Module D Scope** | Product has 16% scrap input while remainder is processed and credited as avoided burden. |

35. **Steel, welded wire mesh**

- Used in the following Revit families: Floor-Grnd-Susp_65Scr-80Ins-100Blk-75PC.
- Used in the following Tally entries: Precast concrete slab.
- Mass identified: 0.0 kg – Not detected by Tally.

***Table 5.38 Welded wire mesh LCA (Source: The Author / Tally Report)***

| | |
|---|---|
| **Description** | Steel rods further processed into wires appropriate for welded wire mesh reinforcement. |
| **Life Cycle Inventory** | 100% Carbon steel wire. |
| **Product Scope** | Cradle to gate. |
| **Transportation Distance** | By truck: 31 km. |
| **End-of-Life Scope** | 98% Recovered 2% Landfilled (inert material). |
| **Module D Scope** | Product has 16% scrap input while remainder is processed and credited as avoided burden. |

36. **Structural concrete, 4001-5000 psi, 30-39% slag**

- Used in the following Revit families: Floor-Grnd-Susp_65Scr-80Ins-100Blk-75PC.
- Used in the following Tally entries: Precast concrete slab.
- Mass identified: 0.0 kg – not detected by Tally.

***Table 5.39 Structural concrete LCA (Source: The Author / Tally Report)***

| | |
|---|---|
| **Description** | Structural concrete, 4001-5000 psi, 30-39% slag. Mix design matches National Ready-Mix Concrete Association (NRMCA) Industry-wide EPD. |
| **Life Cycle Inventory** | 14% Cement, 6% Slag, 7% Batch water, 40% Coarse aggregate. 33% Fine aggregate. |
| **Product Scope** | Cradle to gate, excludes mortar Anchors, ties, and metal accessories outside of scope (<1% mass). |
| **Transportation Distance** | By truck: 24 km. |
| **End-of-Life Scope** | 55% Recycled into coarse aggregate 45% Landfilled (inert material). |
| **Module D Scope** | Avoided burden credit for coarse aggregate, includes grinding energy. |

**37. Wall board, gypsum, natural**

- Used in the following Revit families: Boundary Wall Wall-Ext_102Bwk-75Ins-100LBlk-12P Wall-Int_12P-100Blk-12P.
- Used in the following Tally entries: Wall board, gypsum.
- Mass identified: 800.8 kg.

***Table 5.40 Gypsum board LCA (Source: The Author / Tally Report)***

| | |
|---|---|
| **Description** | Natural gypsum board. |
| **Life Cycle Inventory** | 100% Gypsum wallboard (Gypsum, Boric acid, Cement, Glass fibres, Ferrochrome-lignine sulfonate, Silane, Polyglucose, Perlite, Paper, Casein glue). |
| **Product Scope** | Cradle to gate. |
| **Transportation Distance** | By truck: 72 km. |
| **End-of-Life Scope** | 100% Landfilled (inert waste). |

**38. Window frame, aluminum, powder-coated, fixed, insulated**

- Used in the following Revit families: Windows.
- Used in the following Tally entries: Window frame, aluminum.
- Mass identified: 0.0 kg – not detected by Tally.

***Table 5.41 Aluminum window frame LCA (Source: The Author / Tally Report)***

| | |
|---|---|
| **Description** | Aluminum insulated fixed window frame. |
| **Life Cycle Inventory** | 100% Aluminum. |
| **Product Scope** | Cradle to gate, excludes hardware, casing, sealant. |
| **Transportation Distance** | By truck: 68 km. |
| **End-of-Life Scope** | 95% Aluminum recovered, 5% Aluminum landfilled (inert material). |
| **Module D Scope** | Product has 36.4% scrap input while remainder is processed and credited as avoided burden. |

**39. Wood stain, water based**

- Used in the following Revit families: Private.
- Used in the following Tally entries: Stair, hardwood, tread only.
- Mass identified: 0.0 kg – not detected by Tally.

*Table 5.42 Wood stain LCA (Source: The Author / Tally Report)*

| | |
|---|---|
| **Description** | Semi-transparent stain for interior and exterior wood surfaces. |
| **Life Cycle Inventory** | 60% Water, 28% Acrylate resin, 7% Acrylate emulsion, 5% Dipropylene glycol, 1.3% NMVOC emissions. |
| **Product Scope** | Cradle to gate, including emissions during application. |
| **Transportation Distance** | By truck: 42 km. |
| **End-of-Life Scope** | 38.7% solids to landfill (plastic waste). |

#### 5.4.1.3 Decision for Tally Assessment 1

Following the detailed analysis of each of the major components of the building, it has been witnessed that the components with higher remaining design life, possess more chances of being re-used in the refurbishment scenario. In terms of the rebuilding scenario, the building/structure is a semi-detached house, located in a residential area, therefore this would have a negative social impact such as the neighbours' consent would be required for the proposed development works, which in most cases are turned down by the local residents due to several environmental and social factors. Secondly, the Local Planning Authority (LPA) will not be in favour of the total demolition and rebuilding too unless the building has reached the end of its design life and the structure poses severe threat to the residents of the building and nearby occupiers/buildings.

Overall, the results from the Tally LCA indicates that the environmental impact would play a key role in the decision making of this structure and therefore it is recommended that the refurbishment option is more viable for this structure as it has almost 60 years of design life left and also each component of the structure is still is good condition.

Some components including electrical fixtures, floors and doors need to be replaced during the refurbishment. These components have been found to have reached nearly the end of their design and service life, and due to their rough use without regular maintenance, their design and service life is nearing to end earlier than expected. Replacement of these components and materials would certainly increase the overall cost of the planned refurbishment works, but this measure would have long lasting and positive impact on the overall environment and is also economically feasible in the longer run.

Therefore, based on the environmental and economic impact as the key identified decision-making factors, it has been concluded that a refurbishment is the most feasible option in this Tally Trial.

### 5.4.2 Tally Assessment 2 – Existing Building with New Material

This Tally trail is performed on existing building with new material in order to find the remaining life of the building and also to make a decision of whether to refurbish or rebuild when it reaches the end of design life (EODL).

**Project Details**

- Project: Existing Building Report – six-storey commercial building;
- Location: South-West London;
- Gross Area: 788m$^2$;
- Building's current life: 25 years.

**On-site construction**

- 100 kWh electricity use;
- 100 kWh heating energy use;
- 1000 gallons water use.

**Operational energy**

- 100 kWh annual electricity use;
- 100 kWh annual heating energy use.

**Goal and scope of assessment**

- Summary of existing building with new material.

The subjected building in this Tally trial is a 25 years old commercial building. Its construction includes reinforced concrete structure (reinforced columns and steel beams) with cavity wall (consists of concrete blocks, insulation and bricks) on the exterior boundary. Again, this building cannot be considered as an old building, as it still has around 95 years of design life left, if properly maintained and serviced. Furthermore, the building is already upgraded, as the new components are installed in it, which include doors and windows. In this case, a decision-making is required when the building is about the reach the end of its design and service life or if the owner wants to make changes. The performed Tally life cycle assessment (LCA) on this Revit model highlights the application of the key identified decision-making factors. As this trial based on the LCA, the preference is given to the environmental and social impact factors, however, other relevant key factors in this case are also implemented, which are based on the results gained from the sub-categories of the environmental impact assessment.

Considering the exiting condition of this commercial building from the Tally LCA, Figure 5.10 indicates that the product stage (A1-A3) generates the higher amount of $CO_2$, which is 79%. Whereas, the end of life (C2-C4) scenario generates about 12% of $CO_2$. Looking at the product stage in Figure 4.3, it mainly includes extraction, production, transportation and manufacturing, this indicates that the GWP emissions of the building are existing and the refurbishment would improve these statistics. The demolition of the structure would also produce considerably higher amount of $CO_2$ as shown in Figure 5.10, which accounts for 12%.

Thus, the refurbishment scenario is considered to have the less environmental impact in this case and also having the minimum impact in all potential emissions, as maintenance and replacement (B2-B5) only accounts for 1% of the total global warming potential (GWP) comparatively, as shown in Figure 5.10.

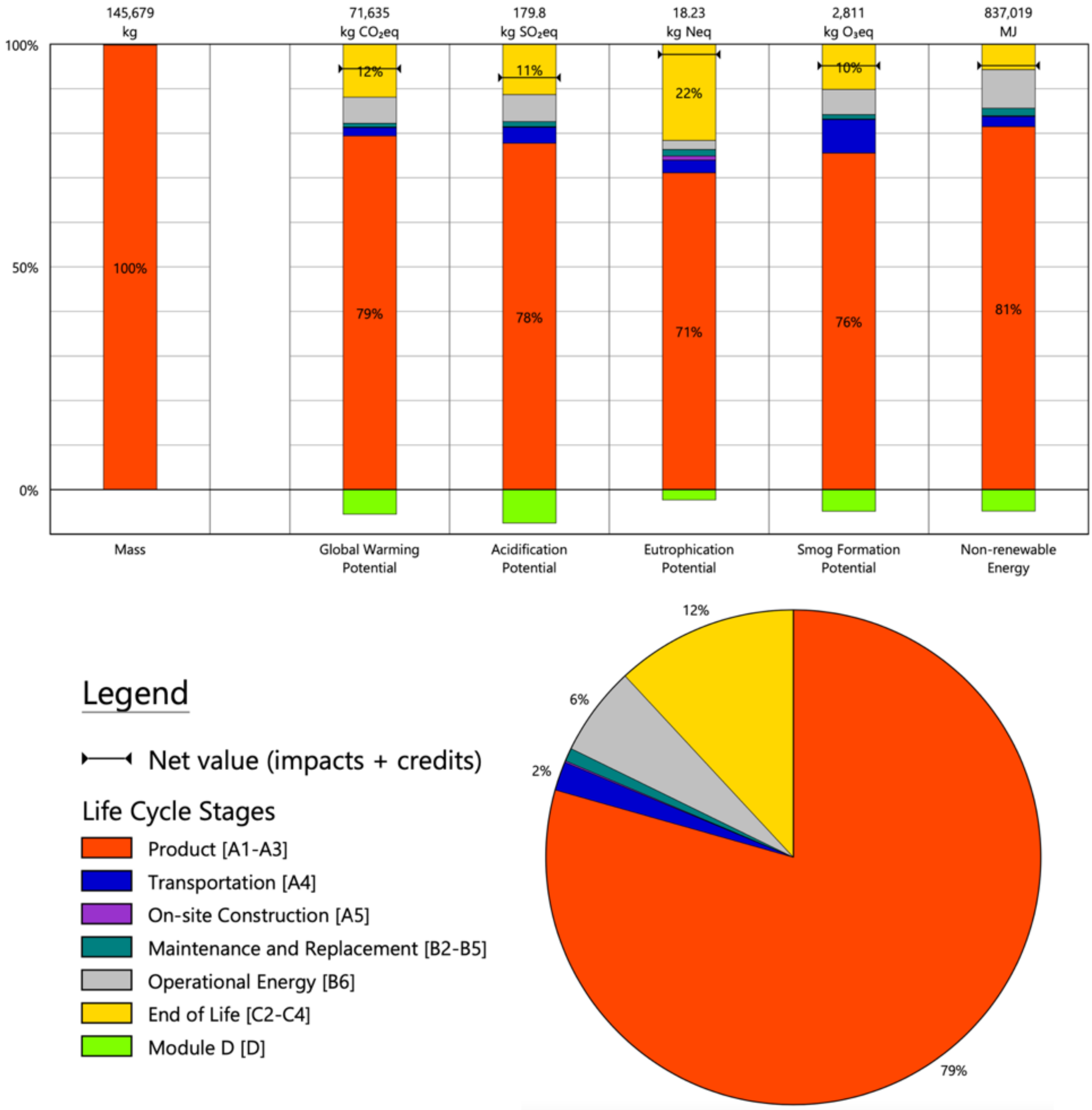


***Figure 5.10 Results per life cycle stage (Source: The Author)***

Since the GWP contribution for the transportation phase is only 2% in the construction scenario, this can be assumed that whether the decision is to demolish and rebuild or refurbish/re-use, in both the cases, the transportation of the construction materials and components would have the similar GWP impact. Also, the installation of the components will have a much lower environmental impact. The quantities, properties and specifications of each of the components within the building were successfully imported into Tally in order to perform the LCA.

The breakdown of each of the life cycle stages of the building in Figure 5.11 indicates that concrete, masonry, metals, woods and plastic generates more $CO_2$ during the product phase (A1-A3), also known as the construction and installation phase. This means that the construction activity on this site would eventually emit this amount of $CO_2$. Based on these statistics, the demolish and rebuild scenario would produce maximum $CO_2$, which would certainly affect the environment and also the surroundings. However, other important and relevant key decision-making factors also need to be considered in this analysis.

As this building is stand-alone, located within a commercial estate in an urban area with no property or building sharing the party wall with this building, the demolition and rebuild scenario is possible in this situation. However, other requirements from the LPA needs to be met in order to get approval for such demolition and construction projects. Supposedly, if the planning application gets approved for the demolish/rebuild scenario, then other relevant key decision-making factors comes into place in order decide whether to refurbish or rebuild. So far, the refurbishment scenario seems to be feasible and effective in this case.

As shown in Figure 5.11, the maintenance and replacement (B2-B5) module accounts for minimum amount of global warming potential (GWP). So, the refurbishment and replacement of components of this building would be environmentally acceptable. Again, the replaced components should include the materials that are environmental-friendly and cost effective too.

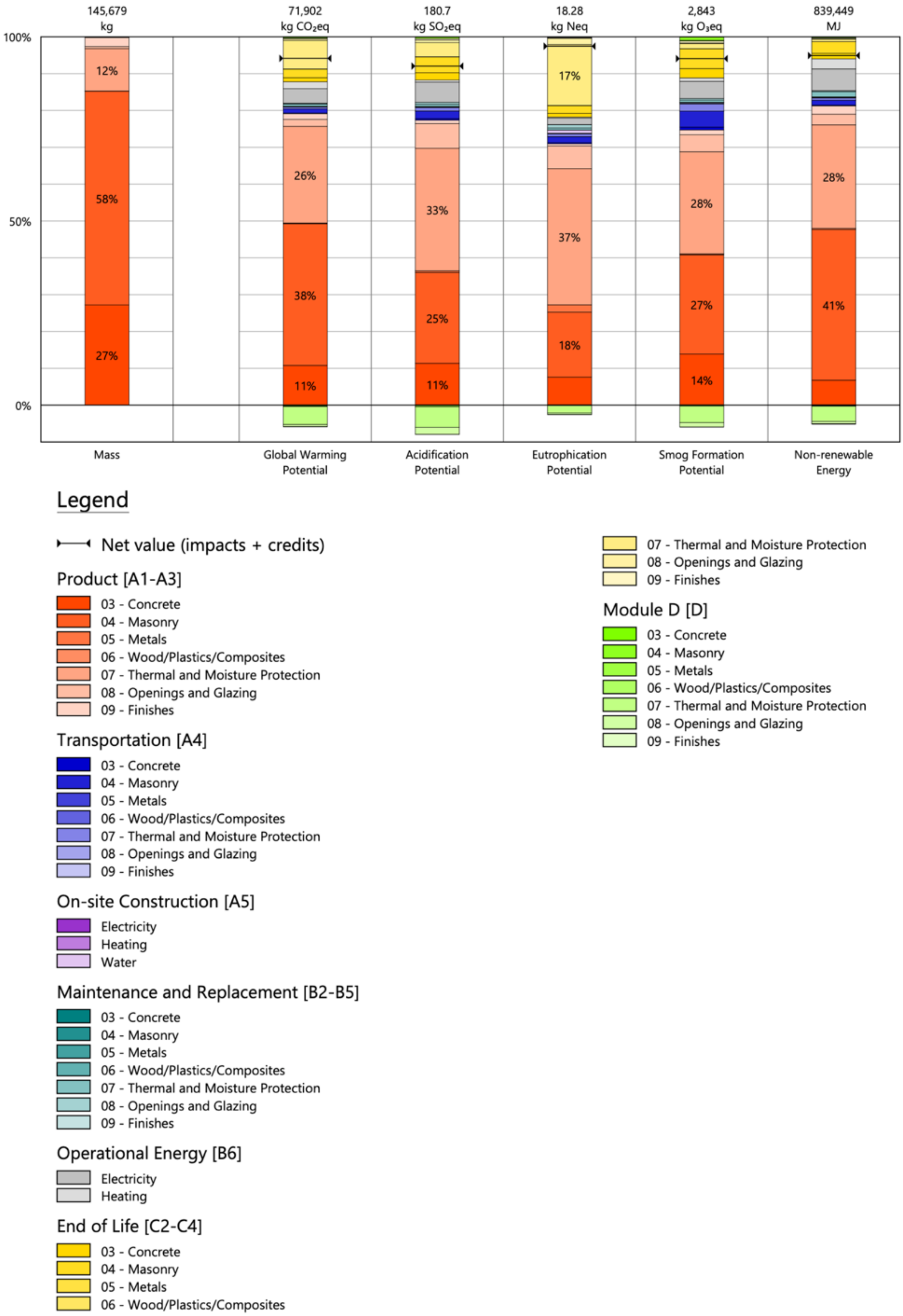


***Figure 5.11 Results per life cycle stage, itemised by division (Source: The Author)***

Masonry accounts for the maximum amount (48%) of $CO_2$ emissions as shown in Figure 5.12. On the other hand, thermal and moisture protection also accounts for considerably higher amount of $CO_2$, which is 34%. Again, this is because the building is considerably new and still has good amount of design life left.

The masonry and concrete division under the maintenance and replacement (B2-B5) module mostly consists of bricks, concrete blocks and mortar used in the building facade (see Figure 5.12 and Figure 5.13), but it is considered to be in good state due to its long remaining design life.

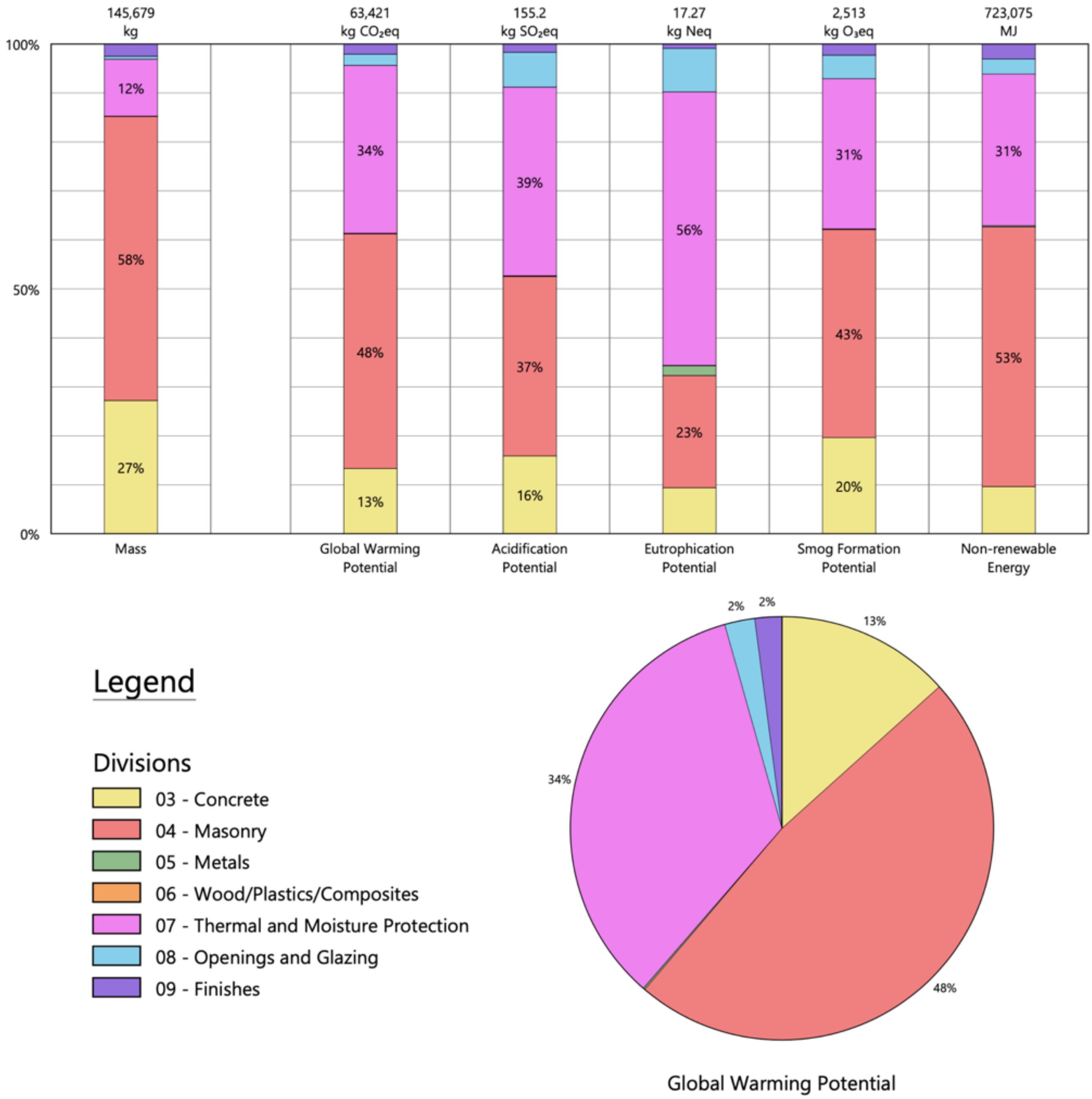


***Figure 5.12 Results per division (Source: The Author)***

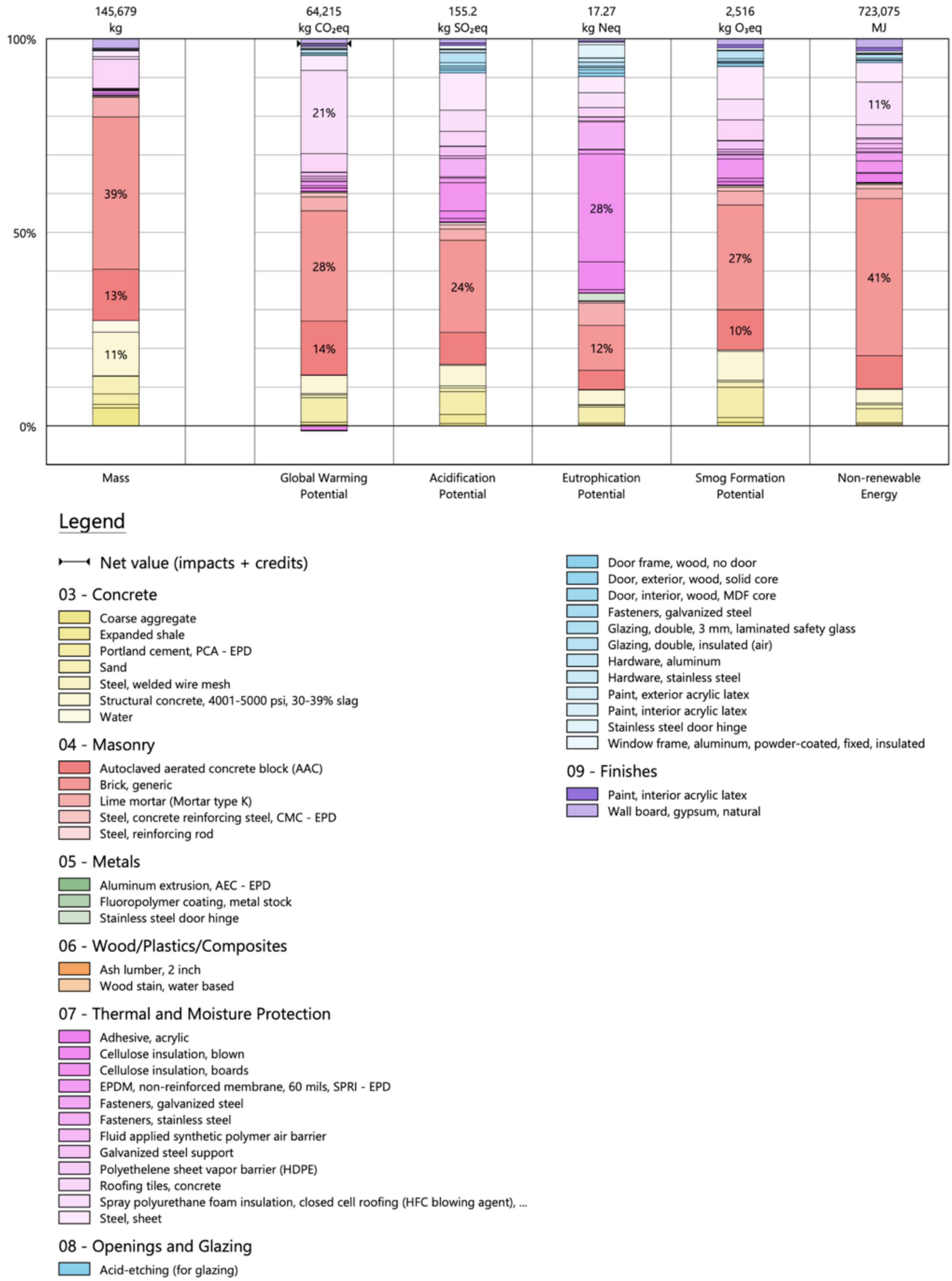


***Figure 5.13 Results per division, itemised by material (Source: The Author)***

As per the results obtained from the imported Revit categories in Tally (see Figure 5.14), it can be seen that walls, roof and floors contributes to the highest amount of global warming potential (GWP) i.e. 43%, 32% and 22% respectively. This highlights the importance that these components will need to be replaced with the new components in the refurbishment scenario.

Windows and doors accounts for only 1% from the total global warming potential (GWP), therefore these components are negligible in terms of mass and all impact categories. The mass associated with other Divisions are fairly evenly distributed as shown and highlighted in Figure 5.14.

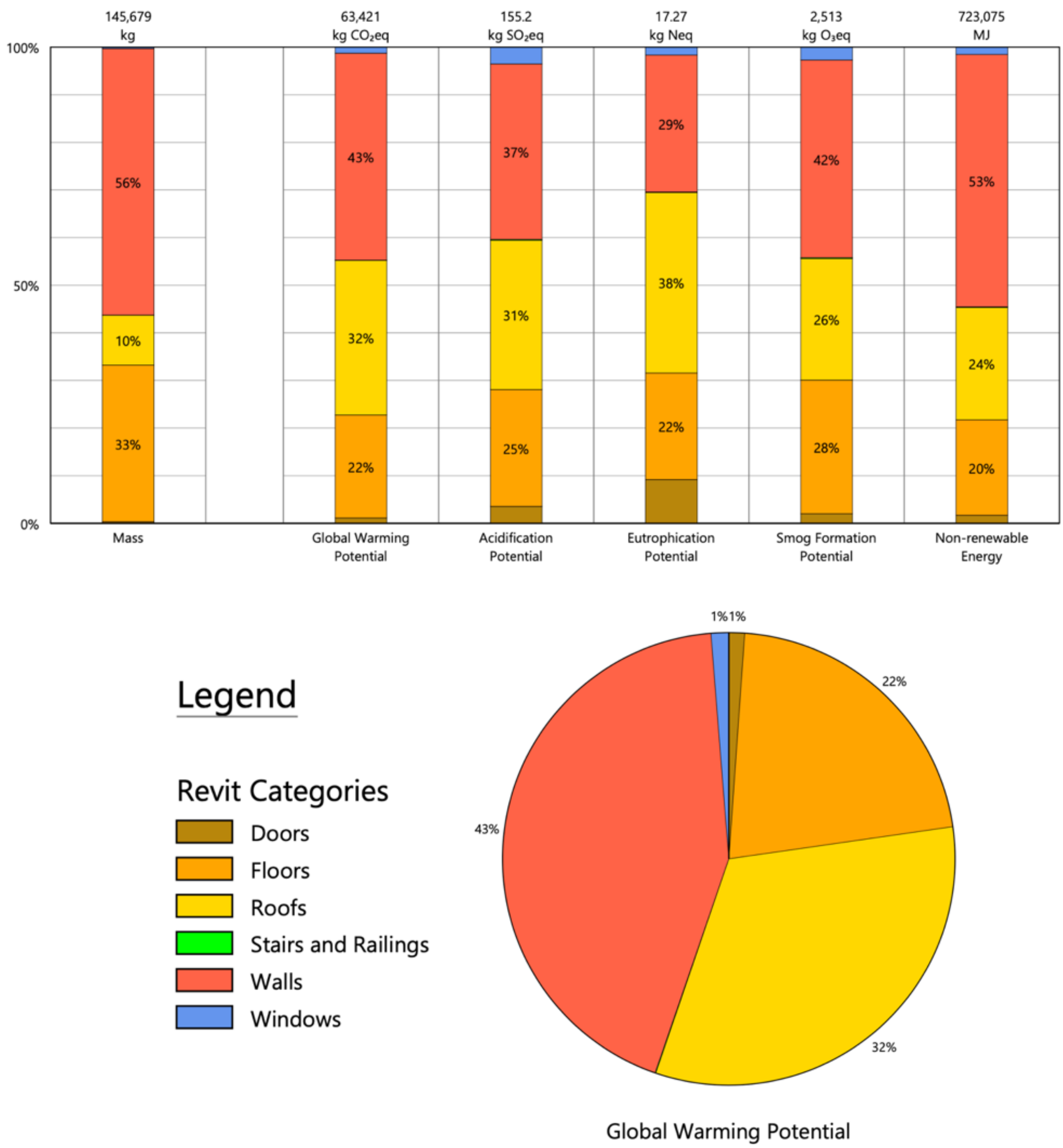


*Figure 5.14 Results per Revit category (Source: The Author)*

Having assessed and taking account of the total environmental impact based on the provided material/component data and specifications in this Tally assessment, the product stage (A1-A3) and the use stage (B2-B6) are found to have the most amount of carbon emissions as shown in the Table 5.43.

The acidification potential (AP), eutrophication potential (EP) and smog formation potential (SFP) within the use stage (B2-B6) accounts for relatively lower amount of emissions as compared to other divisions, however the total impact potential of the use stage is comparatively high (see Table 5.43). The product stage accounts for maximum amount of $CO_2$ potential as compared to the use stage.

***Table 5.43 Environmental impacts total for assessment 2 (Source: The Author)***

| | **Product Stage** | **Construction Stage** | **Use Stage** | **End of Life Stage** | **Module D** |
|---|---|---|---|---|---|
| **Environmental Impact Totals** | **[A1-A3]** | **[A4-A5]** | **[B2-B6]** | **[C2-C4]** | **[D]** |
| Global Warming (kg CO2eq) | 56,868 | 1,423 | 4,816 | 8,529 | -3,946 |
| Acidification (kg SO2eq) | 139.8 | 6.645 | 12.99 | 20.34 | -13.5 |
| Eutrophication (kg Neq) | 12.97 | 0.6862 | 0.6387 | 3.938 | -0.422 |
| Smog Formation (kg O3eq) | 2,124 | 214.0 | 187.5 | 285.1 | -136 |
| Ozone Depletion (kg CFC-11eq) | 2.486E-004 | 1.618E-010 | 4.804E-006 | 5.508E-010 | 1.658E-005 |
| Primary Energy (MJ) | 763,925 | 21,041 | 98,555 | 51,237 | -41,456 |
| Non-renewable Energy (MJ) | 682,015 | 20,380 | 86,713 | 47,910 | -40,312 |
| Renewable Energy (MJ) | 82,373 | 666.7 | 11,946 | 3,384 | -1,160 |

The components of the existing building are found to have more than half of the design life left, however, some of these components would need to be replaced in the refurbishment/re-use scenario as previously discussed.

*Table 5.44 Environmental impacts per area for assessment 2 (Source: The Author)*

| | Product Stage | Construction Stage | Use Stage | End of Life Stage | Module D |
|---|---|---|---|---|---|
| **Environmental Impact Totals** | **[A1-A3]** | **[A4-A5]** | **[B2-B6]** | **[C2-C4]** | **[D]** |
| Global Warming (kg CO2eq) | 580.3 | 14.52 | 49.14 | 87.03 | -40.3 |
| Acidification (kg SO2eq) | 1.427 | 0.06781 | 0.1325 | 0.2075 | -0.1378 |
| Eutrophication (kg Neq) | 0.1323 | 0.007002 | 0.006517 | 0.04018 | -0.004306 |
| Smog Formation (kg O3eq) | 21.67 | 2.184 | 1.914 | 2.910 | -1.39 |
| Ozone Depletion (kg CFC-11eq) | 2.537E-006 | 1.651E-012 | 4.902E-008 | 5.620E-012 | 1.692E-007 |
| Primary Energy (MJ) | 7,795 | 214.7 | 1,006 | 522.8 | -423 |
| Non-renewable Energy (MJ) | 6,959 | 208.0 | 884.8 | 488.9 | -411 |
| Renewable Energy (MJ) | 840.5 | 6.803 | 121.9 | 34.53 | -11.8 |

As shown in the Table 5.44, the environmental impacts per area accounts for higher percentage in the product and the end of life stages. Here, the higher ratio of $CO_2$ in the end of life scenario is due to the age of the building, it is a newly build structure with 95 years of remaining design life, therefore the current $CO_2$ emission would surely be lower than the future, as the building's components and materials would not be 100% efficient due to their age and lower remaining design life after around 90 years. The future $CO_2$ could be more than the Tally's predicted figures if the building is not being maintained properly. The primary renewable and non-renewable energy accounts for lower $CO_2$ in the use stage as compared to the product stage, therefore the electrical fixtures and components would not need to be replaced in the refurbishment/re-use scenario. Hence, the replacement of secondary structure would be feasible and cost effective option in the refurbishment/re-use scenario, which includes walls, floors and ceilings.

#### 5.4.2.1 Components assessed for LCA – Assessment 2

This section includes all the materials and components of the building assessed in this Tally trial and their total identified mass in kg (see Table 5.45). The end of life scope (recycle or landfill), and product scope for each of the components have already been mentioned in the previous assessment.

*Table 5.45 Components assessed for LCA – Tally Assessment 2 (Source: The Author)*

| Components | Mass |
|---|---|
| Acid-etching (for glazing) | 7.7kg |
| Adhesive, acrylic | 201.3kg |
| Aluminum extrusion, AEC - EPD | 20kg |
| Ash lumber, 2 inch | 28.6kg |
| Autoclaved aerated concrete block (AAC) | 19294.1 |
| Brick, generic | 57310.3kg |
| Cellulose insulation, blown | 675.3kg |
| Cellulose insulation, boards | 969kg |
| Coarse aggregate | 6739.4kg |
| Door frame, wood, no door | 65.4kg |
| Door, exterior, wood, solid core | 111.0kg |
| Door, interior, wood, MDF core | 81.6kg |
| EPDM, non-reinforced membrane, 60 mils, SPRI - EPD | 198.7kg |
| Expanded shale | 1347.9kg |
| Fasteners, galvanised steel | 56.4kg |
| Fasteners, stainless steel | 159.6kg |
| Fluid applied synthetic polymer air barrier | 243.8kg |
| Fluoropolymer coating, metal stock | 1.5kg |
| Galvanized steel support | 289kg |
| Glazing, double, 3 mm, laminated safety glass | 122.9kg |
| Glazing, double, insulated (air) | 354.2kg |
| Hardware, aluminum | 10.9kg |
| Hardware, stainless steel | 29.8kg |
| Lime mortar (Mortar type K) | 7354.9kg |
| Paint, exterior acrylic latex | 0.9kg |
| Paint, interior acrylic latex | 112.6kg |
| Polyethelene sheet vapor barrier (HDPE) | 27.1kg |
| Portland cement, PCA - EPD | 3931.3kg |
| Roofing tiles, concrete | 10991.5kg |
| Sand | 6664.5kg |
| Spray polyurethane foam insulation, closed cell roofing | 910.6kg |
| Stainless steel door hinge | 35.9kg |
| Steel, concrete reinforcing steel, CMC - EPD | 449.5kg |
| Steel, reinforcing rod | 130.2kg |
| Steel, sheet | 2224.4kg |
| Steel, welded wire mesh | 158.4kg |
| Structural concrete, 4001-5000 psi, 30-39% slag | 16433.3kg |
| Wall board, gypsum, natural | 3524.6kg |
| Water | 4368.1kg |

| | |
|---|---|
| **Window frame, aluminum, powder-coated, fixed, insulated** | 62.3kg |
| **Wood stain, water based** | 0.2kg |

#### 5.4.2.2 Decision for Tally Assessment 2

Following the detailed analysis in Tally of each of the major components of this commercial building, it has been observed that the components with higher remaining design life, possess more chances of being re-used in the refurbishment scenario. However, more than 80% of the components have higher design life, as they are newly installed and also, the building has been maintained at a good level. Thus, refurbishment and regular maintenance would be cost effective and favours the environmental impact factor too.

Overall, the results from the Tally LCA indicates that the economic impact factor would play a key role in the decision-making of this structure and therefore, it is recommended that the refurbishment option is more viable for this structure as it has almost 95 years of design life left, which is around 88%. Furthermore, as it is a newly designed building, each component of the structure has been designed in accordance with the latest and revised version of the British Standards (BS) code of practice, they possess a considerably higher design life as compared to the components built in the 1990's.

Therefore, based on the environmental and economic impact as the key identified decision making factors, it has been concluded that a refurbishment/re-use with the replacement of some parts of the secondary structure (non-load bearing) is the most feasible option in this second Tally assessment.

### 5.4.3 Tally Assessment 3 – Existing Design Life of an old Building

This Tally LCA is performed on existing semi-commercial building in order to find the remaining design and service life of the structure including the components and materials and also to check whether the refurbishment/re-use scenario is feasible when the structure reaches the end of its design life (EODL).

**Project Details**

- Project: Existing Building report – four-storey semi-commercial building;
- Location: South-East London;
- Gross Area: 736m$^2$;
- Building's current life: 100 years.

**On-site construction**

- 100 kWh electricity use;
- 100 kWh heating energy use;
- 1000 gallons water use.

**Operational energy**

- 100 kWh annual electricity use;
- 100 kWh annual heating energy use.

**Goal and scope of assessment**

- Existing design life of a building and LCA check for refurbishment scenario.

The subjected building in this Tally trial is a 100 years old semi-commercial building. Its construction includes reinforced concrete structure (reinforced columns and steel beams) with cavity wall (consists of concrete blocks, insulation and bricks) on the exterior boundary. The ground and first floor consists of commercial units, while the second, third and fourth floor consist of residential units. The building is considered as an old building, as it has 20 years of design and service life left. However, the building had been refurbished twice within the last 30 years, which included the replacement of internal walls, ceilings and electrical fixtures, thus many of the components and materials have more than half of the design life left. The main structure (load bearing) has not had any changes or amendments since its construction 100 years ago. Overall, the building has been highly maintained with regular service at required intervals and when needed throughout its service life.

In this case, a decision-making is required, as the building is about the reach the end of its design and service life. The Revit model is assessed in Tally for refurbishment scenario in order to check whether the refurbishment/re-use scenario would be applicable and feasible for this structure or not. Thus, the Tally life cycle assessment (LCA) conducted on this Revit model highlights the application of the key identified decision-making factors that are mainly applicable in the refurbishment scenario. As this assessment is based on the LCA, the preference is given to the environmental and social impact factors. Although, other relevant key factors in this case are also implemented, which are also applicable in the refurbishment scenario mainly.

Considering the refurbishment scenario for this semi-commercial building in Tally LCA, Figure 5.15 only highlights the maintenance and replacement stage. Whereas, other modules and stages are not relevant, as the consideration is only given to the refurbishment scenario in this Tally assessment. Thus, the refurbishment scenario is considered to have the maximum amount of environmental impact in this case and also having the maximum impact in all other emissions (see Figure 5.15).

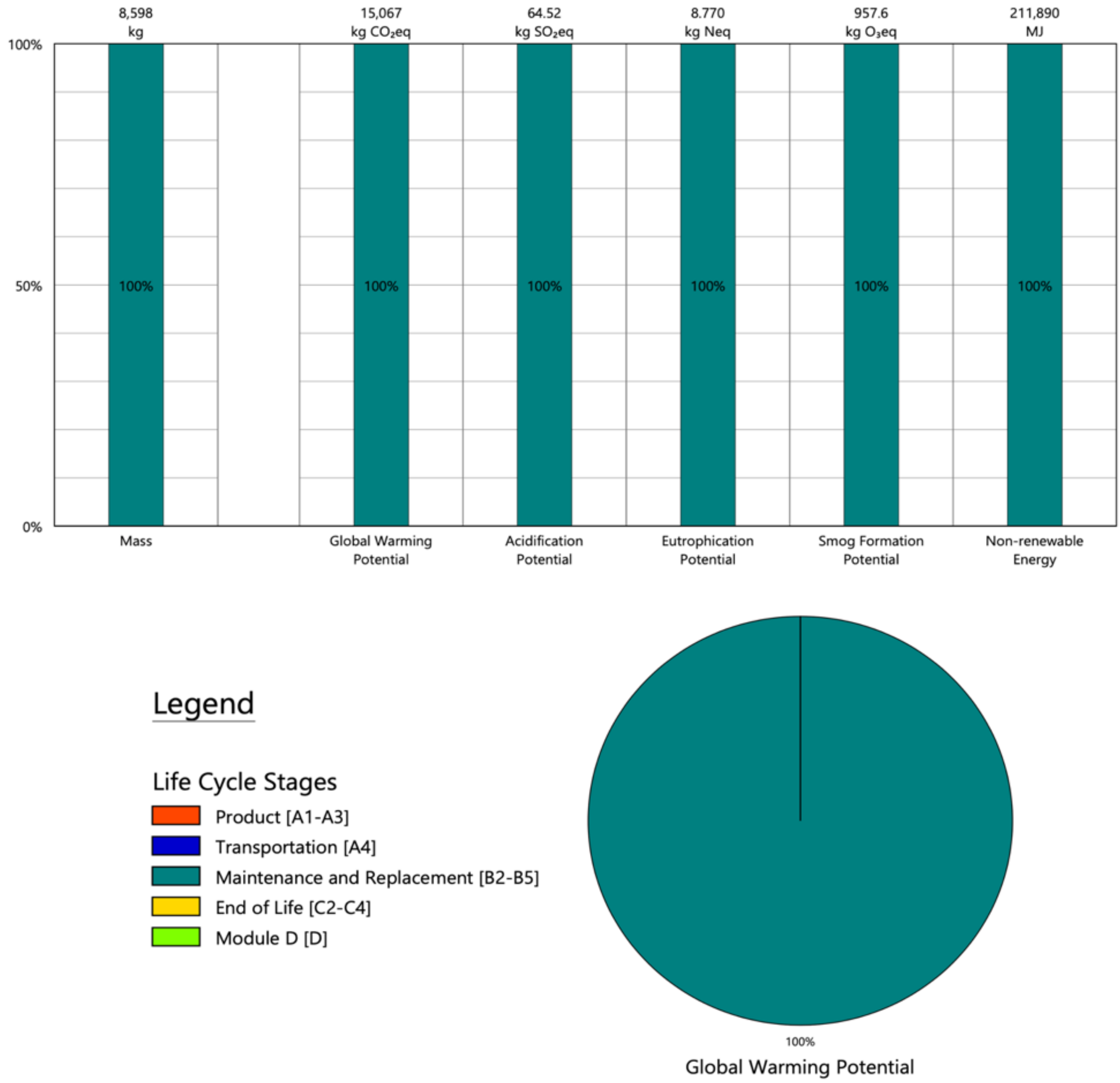


***Figure 5.15 Results per life cycle stage (Source: The Author)***

The subjected building in this Tally assessment is a stand-alone structure, located within a commercial estate in an urban area with no property sharing the party wall with this building, hence the demolition and rebuild scenario is possible in this situation, subject to approval from the LPA for such demolition and construction projects. However, the purpose of this Tally assessment is to assess the existing building for refurbishment scenario. Therefore, only the relevant key decision-making factors are considered and applied in this case. Mainly, the environmental and economic factors are applicable in order to make a decision for refurbishment scenario.

The breakdown for each of the life cycle stages of the assessed building in Figure 5.16 indicates that woods/plastics/composites, thermal and moisture protection, openings and glazing and finishes contributes the highest amount of $CO_2$ within the maintenance and replacement stage (B2-B5). Thus, these components would need to be replaced during the refurbishment process. And, the replaced components should include the materials that are environmental-friendly and cost effective too.

On the other hand, concrete, masonry and metals contribute the lowest amount of GWP. Reason being, the building had been refurbished twice in the recent past and many if these components and materials were replaced with the new ones that have a long lasting and durable life with less $CO_2$ potential.

The refurbishment and replacement of components of this building would be environmentally acceptable in this scenario. The proposed refurbishment also seems to be economically reasonable, as the components such as walls, ceilings and electrical fixtures would not need to be fully replaced.

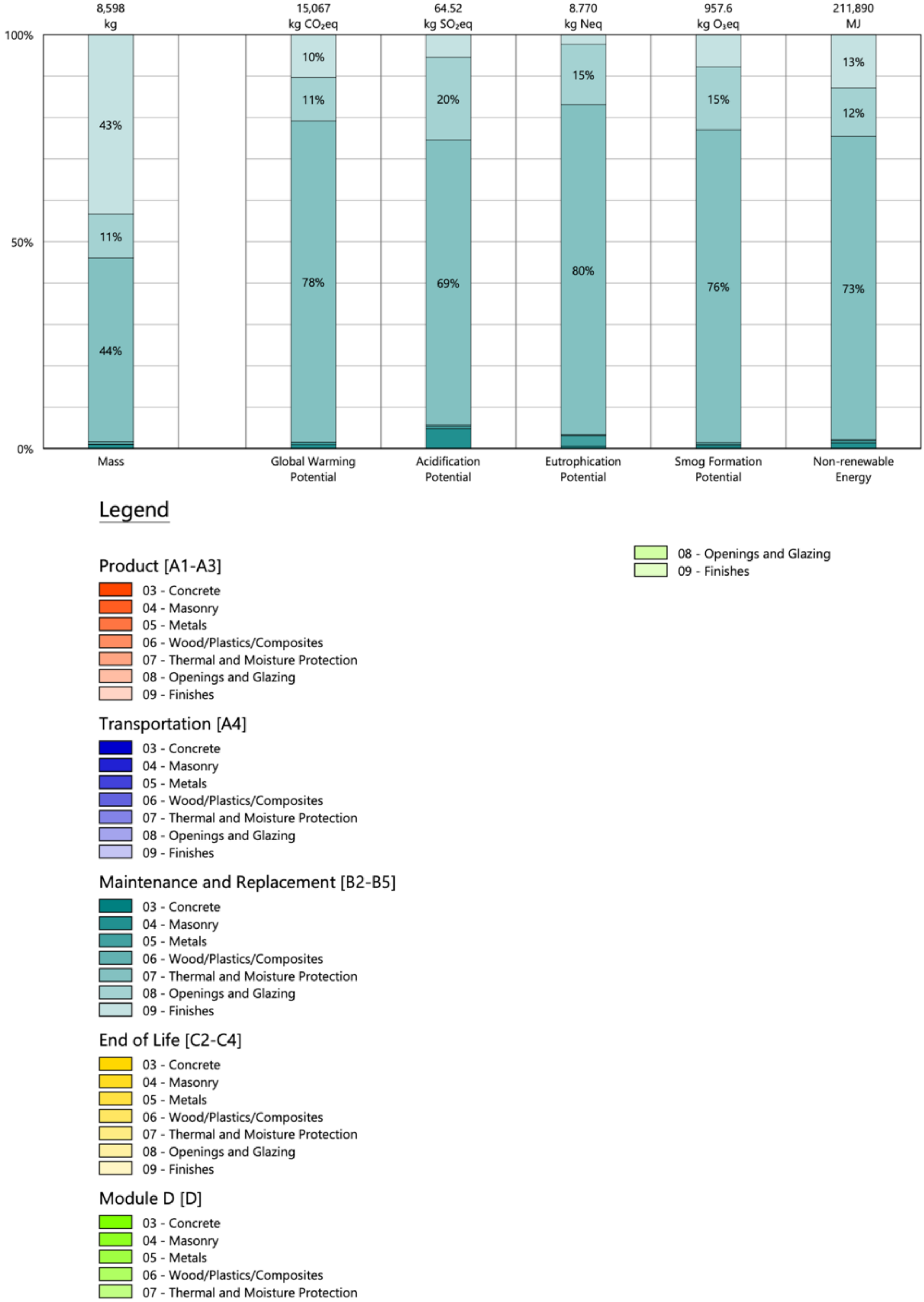


***Figure 5.16 Results per life cycle stage, itemised by material (Source: The Author)***

Thermal and moisture protection accounts for the maximum amount (78%) of $CO_2$ emissions as shown in the Figure 5.17. On the other hand, opening and glazing, and finishes accounts for second and third highest amount of $CO_2$, which is 11% and 10% respectively.

The masonry and metal division under the maintenance and replacement (B2-B5) module accounts for the lowest amount of $CO_2$ emissions as shown in Figures 5.16 and 5.17.

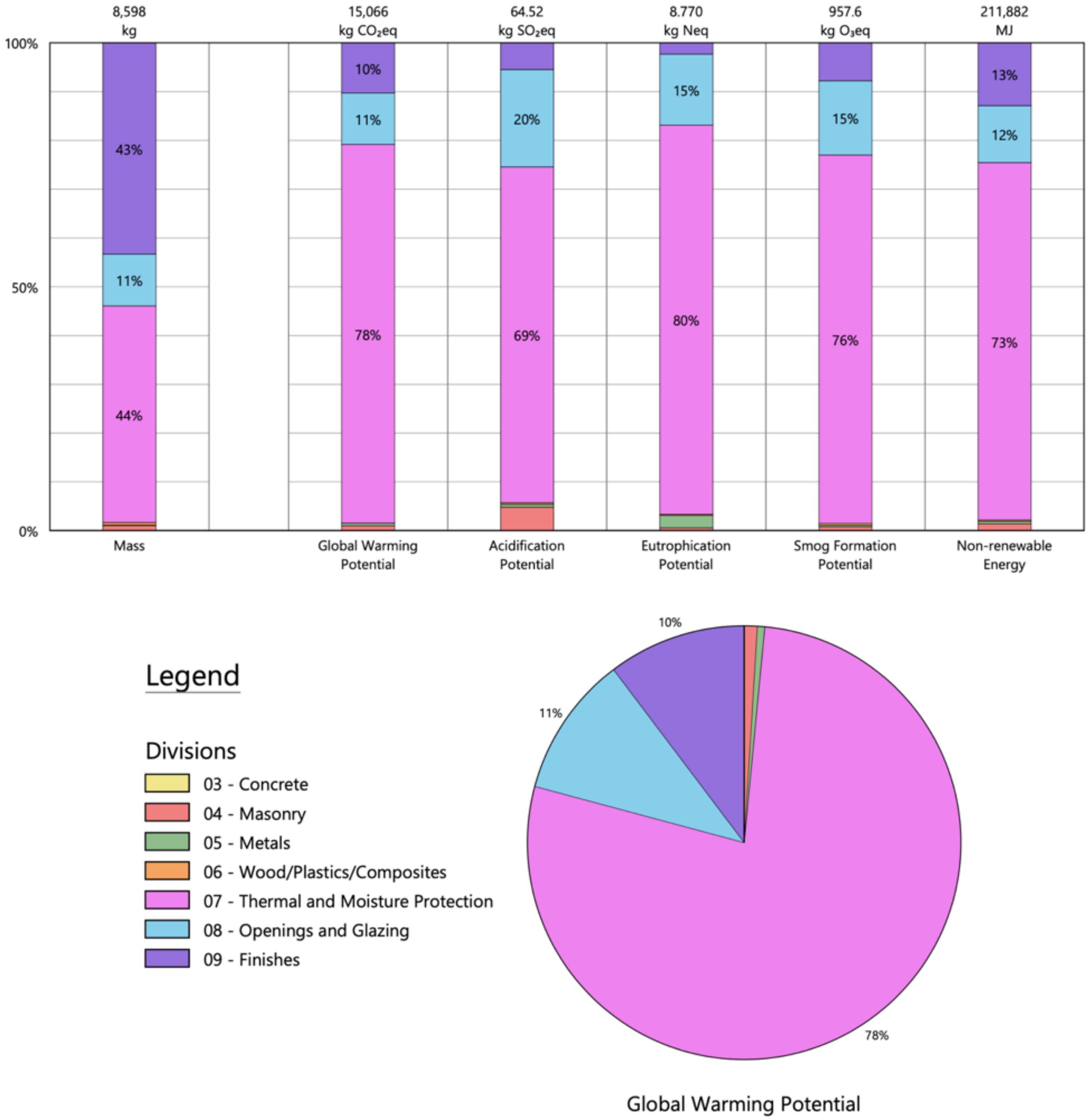


***Figure 5.17 Results per division (Source: The Author)***

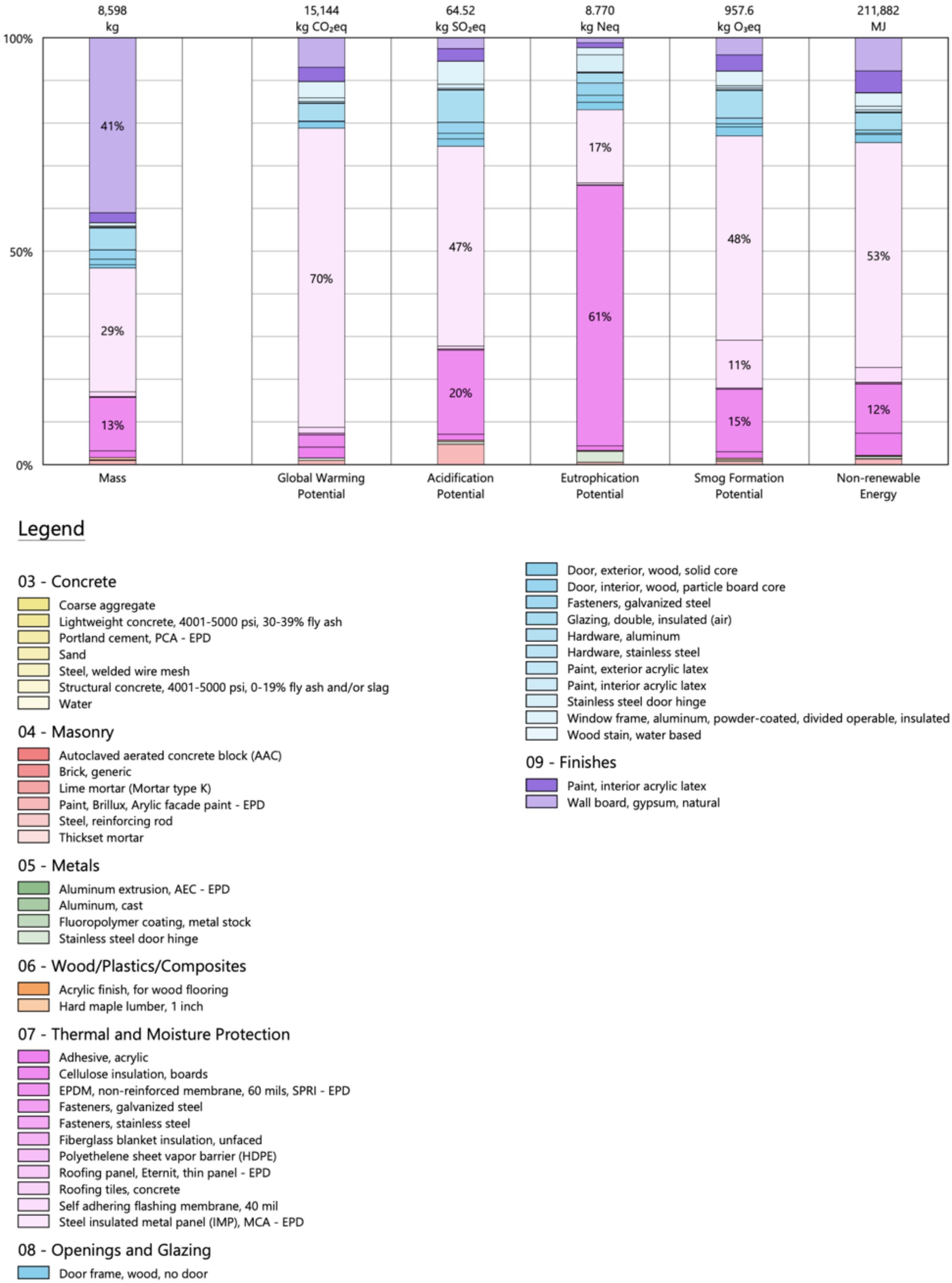


***Figure 5.18 Results per division, itemised by material (Source: The Author)***

The sub-categories of materials are listed in Figure 5.18, which highlights the results per division, obtained from the imported Revit categories in Tally. As discussed previously, the materials of the thermal and moisture layers would need to be fully replaced in the refurbishment scenario. The finishes module has the lowest percentage of $CO_2$, but it accounts for the second highest in the overall chart. Thus, this cannot be considered to have a serious impact on the overall environmental factor. But, the finishing would eventually be redone for the whole structure after the refurbishment works.

Further, from the results per Revit category (as shown in Figure 5.19), it can be seen that roof contributes to the highest amount of global warming potential (GWP) i.e. 78%. This highlights the importance that a new roof will need to be installed in the refurbishment scenario. Walls, floors accounts for only 11% and 5% respectively from the total global warming potential (GWP), whereas from the components, windows and doors account for 7% and 4% respectively (see Figure 5.19). therefore these components are negligible in terms of mass and all impact categories. Furthermore, these components can be recycled, if not needed in the refurbishment scenario.

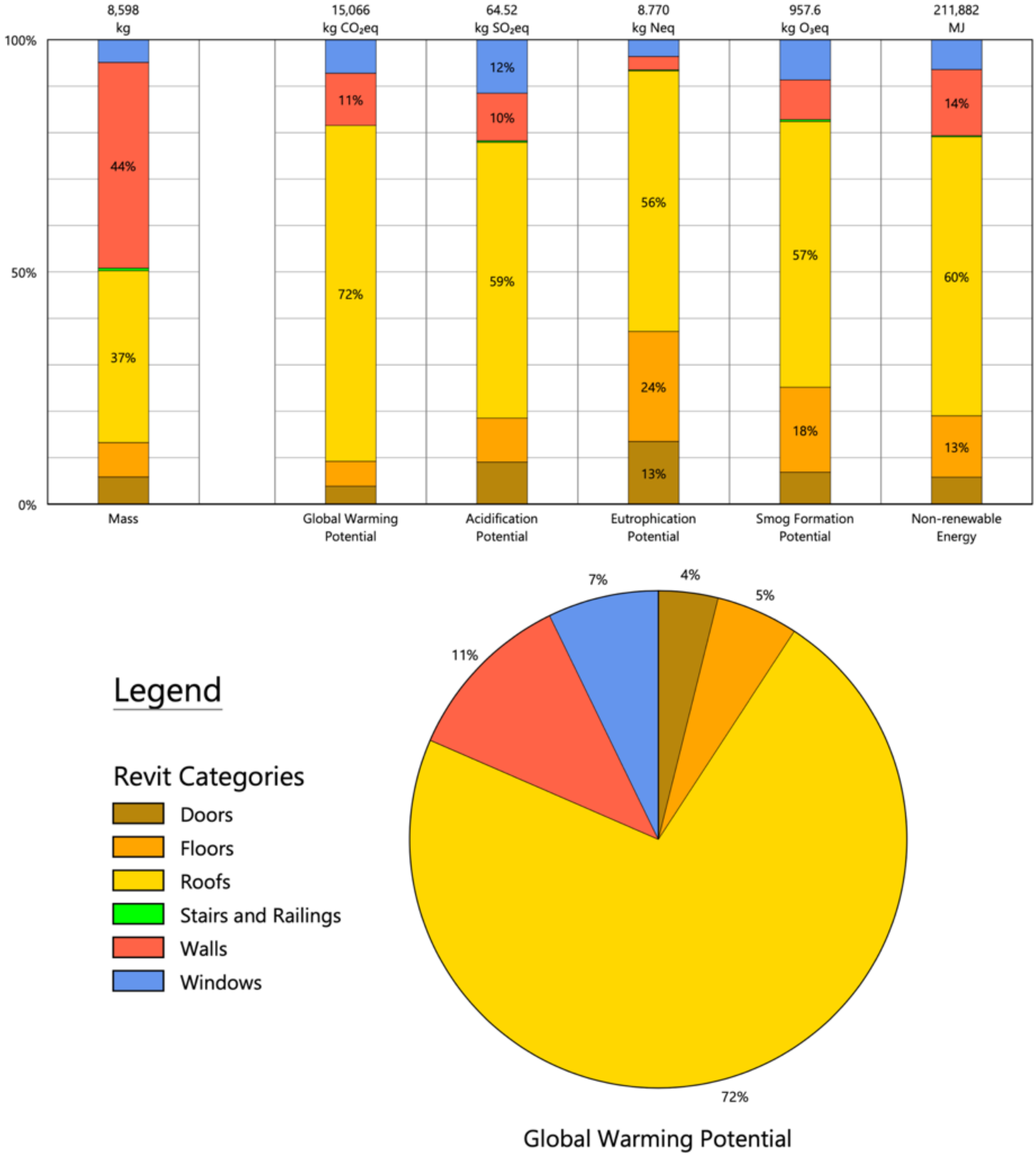


***Figure 5.19 Results per Revit category (Source: The Author)***

Having assessed and taking account of the total environmental impact based on the provided material/component data and specifications in this Tally assessment, the materials of thermal and moisture protection layer, finishes and roofs are found to have the most amount of GWP potential in the refurbishment scenario.

The global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion (OD) and smog formation potential (SFP) within the use stage (B2-B6) accounts for higher amount of emissions as compared to other divisions as shown in the Table 5.46. The product stage accounts for second highest amount of $CO_2$ potential after the use stage. However, there is a massive difference in the total and individual values of $CO_2$ emissions between these two stages. Thus, the product stage is exempted and considered to be within the lower limit of $CO_2$ emissions.

***Table 5.46 Environmental impacts total for assessment 3 (Source: The Author)***

| | **Product Stage** | **Construction Stage** | **Use Stage** | **End of Life Stage** | **Module D** |
|---|---|---|---|---|---|
| **Environmental Impact Totals** | **[A1-A3]** | **[A4-A5]** | **[B2-B6]** | **[C2-C4]** | **[D]** |
| Global Warming (kg CO2eq) | 1.806 | 0.02444 | 15,065 | 3.930E-004 | -0.8048 |
| Acidification (kg SO2eq) | 0.005544 | 1.132E-004 | 64.51 | 1.820E-006 | -0.001578 |
| Eutrophication (kg Neq) | 2.227E-004 | 9.220E-006 | 8.769 | 9.211E-008 | -6.394E-005 |
| Smog Formation (kg O3eq) | 0.0702 | 0.003742 | 957.5 | 3.608E-005 | -0.02236 |
| Ozone Depletion (kg CFC-11eq) | -7.377E-009 | 8.369E-016 | 0.001319 | 7.243E-017 | 5.678E-009 |
| Primary Energy (MJ) | 24.01 | 0.3554 | 246,476 | 0.006751 | -7.02 |
| Non-renewable Energy (MJ) | 22.58 | 0.3469 | 211,867 | 0.006304 | -7.51 |
| Renewable Energy (MJ) | 1.426 | 0.008593 | 34,693 | 4.449E-004 | 0.5187 |

*Table 5.47 Environmental impacts per area for assessment 3 (Source: The Author)*

| | Product Stage | Construction Stage | Use Stage | End of Life Stage | Module D |
|---|---|---|---|---|---|
| **Environmental Impact Totals** | **[A1-A3]** | **[A4-A5]** | **[B2-B6]** | **[C2-C4]** | **[D]** |
| Global Warming (kg CO2eq) | 0.01843 | 2.494E-004 | 153.7 | 4.010E-006 | -0.008212 |
| Acidification (kg SO2eq) | 5.657E-005 | 1.155E-006 | 0.6583 | 1.857E-008 | -1.611E-005 |
| Eutrophication (kg Neq) | 2.272E-006 | 9.408E-008 | 0.08948 | 9.399E-010 | -6.524E-007 |
| Smog Formation (kg O3eq) | 7.163E-004 | 3.818E-005 | 9.771 | 3.682E-007 | -2.281E-004 |
| Ozone Depletion (kg CFC-11eq) | -7.528E-011 | 8.540E-018 | 1.345E-005 | 7.391E-019 | 5.794E-011 |
| Primary Energy (MJ) | 0.245 | 0.003626 | 2,515 | 6.889E-005 | -0.07163 |
| Non-renewable Energy (MJ) | 0.2304 | 0.003539 | 2,162 | 6.433E-005 | -0.07665 |
| Renewable Energy (MJ) | 0.01455 | 8.769E-005 | 354.0 | 4.540E-006 | 0.005292 |

As shown in the Table 5.47, the environmental impacts per area also accounts for higher percentage in the use stage. Here, the higher ratio of $CO_2$ in the use stage is due to the age of the building, as it is an old structure with 20 years of remaining design life, therefore the current $CO_2$ emission would surely be higher as most of the building's components and materials are not 100% efficient. Although, after the refurbishment works, the $CO_2$ emissions would surely be reduced. The primary renewable and non-renewable energy also accounts for higher $CO_2$ in the use stage as compared to other stages, but still the figures are considerably small and within the allowed limit, hence the electrical fixtures and components would not need to be replaced in the refurbishment/re-use scenario.

Hence, the refurbishment/re-use scenario seems to be feasible in this case, which should include the replacement of thermal and moisture protection layers, and roofs.

#### 5.4.3.1 Components assessed for LCA – Assessment 3

This section includes all the materials and components of the building assessed in this Tally assessment and their total identified mass in kg (see Table 5.48). The end of life scope (recycle or landfill), and product scope for each of the components have already been mentioned in the first assessment.

*Table 5.48 Components assessed for LCA – Tally Assessment 3 (Source: The Author)*

| Components | Mass |
|---|---|
| **Acrylic finish, for wood flooring** | 298kg |
| **Adhesive, acrylic** | 549.7kg |
| **Aluminum extrusion, AEC - EPD** | 100.5kg |
| **Aluminum, cast** | 98.9kg |
| **Autoclaved aerated concrete block (AAC)** | 87750.9kg |
| **Brick, generic** | 675.3kg |
| **Cellulose insulation, boards** | 969kg |
| **Coarse aggregate** | 6739.4kg |
| **Door frame, wood, no door** | 65.4kg |
| **Door, exterior, wood, solid core** | 111.0kg |
| **Door, interior, wood, MDF core** | 81.6kg |
| **EPDM, non-reinforced membrane, 60 mils, SPRI - EPD** | 198.7kg |
| **Fasteners, galvanised steel** | 56.4kg |
| **Fasteners, stainless steel** | 159.6kg |
| **Fiberglass blanket insulation, unfaced** | 243.8kg |
| **Fluoropolymer coating, metal stock** | 2.5kg |
| **Glazing, double, insulated (air)** | 289kg |
| **Hard maple lumber, 1 inch** | 122.9kg |
| **Hardware, aluminum** | 50.9kg |
| **Hardware, stainless steel** | 29.8kg |
| **Lightweight concrete, 4001-5000 psi, 30-39% fly ash** | 7354.9kg |
| **Lime mortar (Mortar type K)** | 12.9kg |
| **Paint, Brillux, Arylic facade paint - EPD** | 112.6kg |
| **Paint, exterior acrylic latex** | 27.1kg |
| **Paint, interior acrylic latex** | 3931.3kg |
| **Polyethelene sheet vapor barrier (HDPE)** | 10991.5kg |
| **Portland cement, PCA - EPD** | 6664.5kg |
| **Roofing panel, Eternit, thin panel - EPD** | 910.6kg |
| **Roofing tiles, concrete** | 35.9kg |
| **Sand** | 449.5kg |
| **Self-adhering flashing membrane, 40 mil** | 130.2kg |
| **Stainless steel door hinge** | 2224.4kg |
| **Steel insulated metal panel (IMP), MCA - EPD** | 158.4kg |
| **Steel, reinforcing rod** | 16433.3kg |
| **Steel, welded wire mesh** | 3524.6kg |
| **Structural concrete, 4001-5000 psi, 0-19% fly ash and/or slag** | 4368.1kg |
| **Thickset mortar** | 62.3kg |

| | |
|---|---|
| **Wall board, gypsum, natural** | 80.2kg |
| **Window frame, aluminum, powder-coated, divided operable, insulated** | 309.1kg |
| **Wood stain, water based** | 19.8kg |

#### 5.4.3.2 Decision for Tally Assessment 3

Following the detailed analysis in Tally of each of the major components of this semi-commercial building, components with less remaining design life indicating the need for rebuilding rather than refurbishment. But, the remaining design life is still 20 years, which is further indicating that keeping the current use is also a solution. Or, as assessed by Tally that the current use is also generating higher $CO_2$ due to some of the old components and materials, so the replacement of these existing components with new components having low $CO_2$ emissions could also be a feasible solution. However, there is a cost factor that needs to be taken into account when deciding for partial refurbishment scenario, as after 20 years, the building has to be demolished anyway due to the end of its design life. Also, taking into account that around 20% of the components have lower design life and the building's current maintenance and replacement is affecting the overall environmental and economic impact factor, the partial demolition and refurbishment scenario seems to be acceptable and achievable and, it is also favouring this case.

The partial demolition and construction scenario will require the designers to demolish only the necessary part of structure and refurbish it, taking out the components and materials that are old (out of the 20% materails that have lower remaining design life) or not required and replacing these with the new components.

Overall, the results from the Tally LCA indicates that the economic impact factor would play an important role in the decision-making of this structure and therefore it is recommended that the partial demolition and refurbishment option is more viable and economically feasible for this building/structure as it has almost 20 years of design life left. Furthermore, the building has been refurbished at a high standard within the last 30 years, so many of the components and materials have more than 80% of the design life left that can be utilised for 20 more years. And the un-required new components (if any) can be recycled using the deconstruction method and used in other construction projects, where required.

These three buildings were chosen as they represent good examples of commercial buildings and residential buildings in addition to the fact that they have a variety of the most common types of building materials including bricks, masonry, concrete, steel, timber and gypsum.

Although, there is one set of results for each building type, the set of results are applicable and transferrable across all the three types of buildings, as the principles are similar in terms of the Life Cycle Analyses (LCA), remaining design life and the Life Cycle Cost (LCC) for each of the material and components of the building.

## 5.5 Validation of the Key Decision-making Factors

Now, as the key decision-making factors have been identified and applied onto existing and new buildings on Tally via Revit/BIM based model, the validation of these factors is necessary.

### 5.5.1 Experts Opinion Survey

A survey was conducted based on the experts opinion in order to validate the identified key factors. Experts from different designations and sectors of the industry took part in the survey and provided their opinion with the best of their expertise. As each these professionals have been actively working in the industry for more than 10 years, they know the insights of the industry and possess great amount of knowledge especially in the subject of waste. This was the main reason for choosing to conduct this survey and having to compare the responses of the experts with the identified factors and their application in Tally. A sample of the survey questionnaire is available in Appendix D.

- Total experts = 38;
- Age = 35-55 years;
- Experience in the industry = 10-25 years.

#### 5.5.1.1 Designation of the Experts

- Site Manager = 3;
- Construction Manager: 14;
- BIM Specialist = 5;
- Assistant Project Manager = 4;
- Project Manager = 10;
- Project Director = 2

#### 5.5.1.2 Experts responses to waste related questions

As discussed several times in the previous chapters of this project, the amount of waste generated in the last few years has been an alarming sign and steps need to be taken to resolve this issue. The reason to raise this question with experts, is to understand how they are getting affected by this and how much they are concerned about this global issue.

Though there was a mixed opinion, as 15 experts are satisfied with the measures taken by the industry in order to tackle this issue, 11 of them have the view that the current measures are not enough (see table) as the current figure still shows the fairly high amount of carbon emission within the C&D industry, which comes under the environmental impact factor. However, all experts suggest that more measures need to be taken along with more research on the topic in order to achieve the best results in the future.

Important point to consider here is that all the experts who are satisfied with the current measures, are Construction Managers. As they are on construction sites every day, managing the works, producing reports and collaborating with all the stakeholders and sub-contractors, their opinion particularly in this question takes the higher share as compared to the rest. The responses from this question gives a big boost to the importance of the environmental factor. And thus, the environmental impact factor has been given the highest priority among all other factors in this project (see figure).

#### 5.5.1.3 Experts responses to BIM related questions

As the process for the identification and application of the key decision-making factors involve the implementation of Revit/BIM, it was mandatory to ask the question about BIM.

As per the responses, all the experts have been working on BIM, a collaborative model and approach. 85% of them found BIM to be very useful and a great way to work on the project from design stage to execution through to completion. 12% have the impression of. While the remaining 3% are neither satisfied nor dissatisfied with the implementation of BIM and its uses. Surely, having the majority of 85% clearly indicates the BIM as the most useful and mandatory tool within the C&D industry.

Having familiarity with BIM and knowing the implementation process of it throughout the project, they are very keen for the decision-making model based on the key identified factors to be implemented in BIM process (see figure), so that the key factors can be a part of the collaborative model too. This will allow all the project stakeholders to work closely on each aspect of the project economically with minimum waste/reduced environmental impact and the ability to make a decision using the key factors according to their priority. An example of this process is shown in figure.

Following the responses, it has been decided to implement the validated key factors onto the relevant stage of BIM process.

#### 5.5.1.4 Comparison of the decision-making factors against the opinions of the CWM experts

In this section, the response regarding the key decision-making factors in experts opinion are listed and further evaluated. Table 5. Below highlights the total responses for each of the identified factors and compared with the Tally findings in order to check the matching percentage and to prioritise each factor based on the responses and Tally analyses.

*Table 5.49 Comparison of the decision-making factors against the opinion of the CWM experts (Source: The Author)*

| The Identified Factors | Results of Application of the Key Factors | Experts Opinion | Matching % |
|---|---|---|---|
| **1. Existing Condition** | Effective in TALLY | 87% agreed | 78% |
| **2. Age of the property** | Effective in TALLY | 95% agreed | 85% |
| **3. Remaining design life** | Effective in TALLY | 100% agreed | 96% |
| **4. Historical significance** | Not applicable in TALLY | 53% agreed | 53% |
| **5. Environmental impact** | Applicable and effective in TALLY | 100% agreed | 89% |
| **6. Maintenance and repair** | Not very effective in TALLY | 83% agreed | 89% |
| **7. Cost comparison** | Applicable and effective in Revit/BIM only | 77% agreed | 85% |
| **8. Demolition cost** | Applicable and effective in Revit/BIM only | 80% agreed | 73% |
| **9. Refurbishment cost** | Applicable and effective in Revit/BIM only | 82% agreed | 76% |
| **10. Time comparison** | Not effective in Revit neither BIM, but consideration can be given to this factor when using the developed frameworks in Chapter 4. | 53% agreed | 53% |
| **11. Material waste estimation and transportation** | Applicable in TALLY, but not very effective | 48% agreed | 58% |

Out of the responses received from the experts, it has been observed that the priority has been given to the cost and the environment as the main key factors that aid the decision of whether to refurbish or rebuild.

Given the scenario, if there is an existing building, reaching the end of its design life, then the most important factors to consider is the cost of refurbishment and rebuild, and the environmental impact. Also, as shown in the Tally trails for existing buildings, the environmental impact was the main factor in deciding the building's future. However, the cost also played an important role, but given the current situation in the world regarding the environment and the target to achieve zero carbon emission, environmental impact is considered as the most important deciding factor and weighs more than the economic impact (cost).

The collected samples in this research project are considered to be statistically significant, based on the quality of information received from the industrial experts and its relevance with Tally assessments. With the probability that more than 90% of the responses were properly addressed according to the questions asked in the survey, this accounts for significant p value to be within 0.05.

Talking about the economic impact, it is not only limited to the direct cost (refurbish or rebuild) of the building, but also includes the indirect cost such as the survey cost, procurement cost, design and consultancy cost etc. Taking account of the indirect cost, a relationship chart has been produced (as shown in Figure 5.20), which shows importance of the economic impact factor in different scenarios.

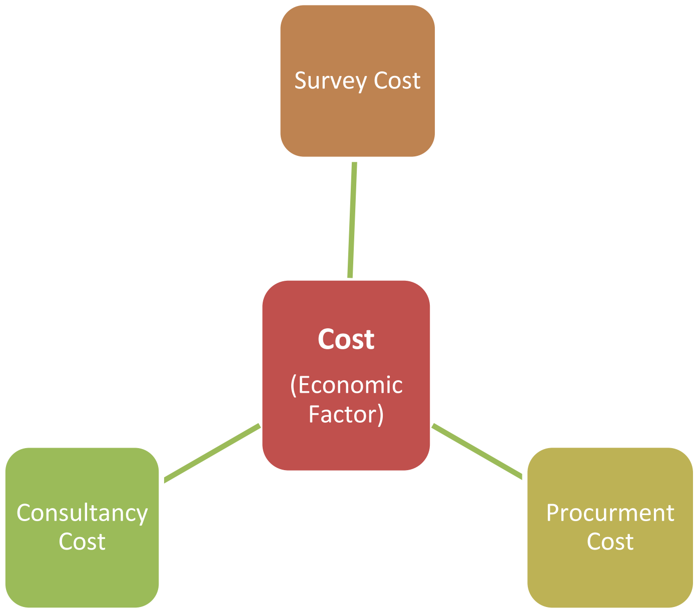


***Figure 5.20 Indirect cost relationship chart (Source: The Author)***

All of the participants of the survey also mentioned the existing condition and age of the property as other prime factors in the decision-making process (see Figure 5.21). These factors play an important role when calculating and assessing the economic and environmental impact and also have direct impact on the these factors (see Figure 5.21), as the results of the assessment of economic and environmental impact can be different if the existing condition and age of the property is property is not properly evaluated, and the final decision-making of whether to refurbish or rebuild can go extremely wrong. So, these two factors have been put first in the decision-making process.

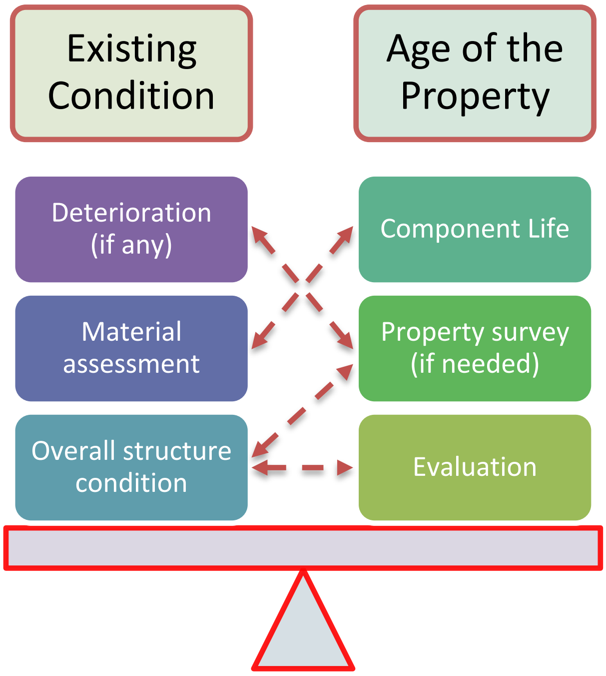


***Figure 5.21 Direct relationship chart between existing condition and age factor (Source: The Author)***

As shown in Figure 5.21, the existing condition factor consists of different stages in order to evaluate the existing condition and similarly, the age factor also consist of different steps. However, as mentioned earlier, these two factors have direct relationship and the sub-sections of each factor can make an impact onto the sub-section of another as illustrated in Figure 5.21.

Again, the cost of the refurbishment and demolition are chosen to be another key factors by the experts. Important to mention here that the overall cost is not the cost of refurbishment and the cost of demolition. The cost relationship chart can be seen in Figure 5.20. These are three different factors but have an indirect relationship (see Figure 5.22).

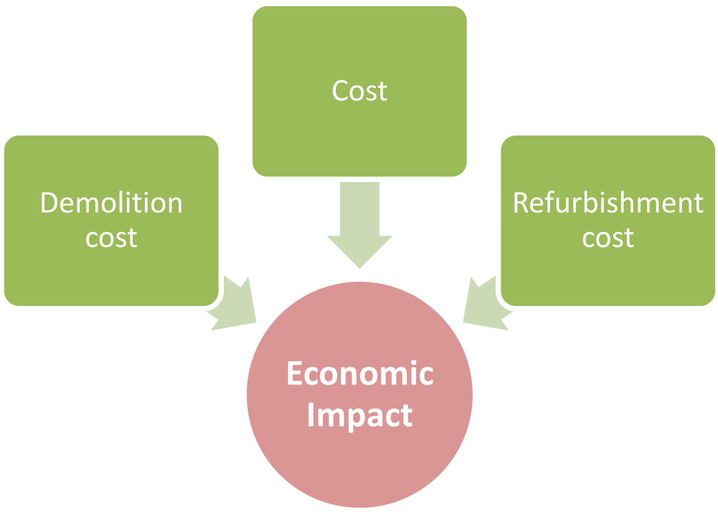


***Figure 5.22 Indirect relationship chart (Source: The Author)***

In terms of the historical significance factor, it is chosen among the lowest factors by the experts. Most of the experts do not consider this a key factor for the decision-making. Indeed, the historical significance of the property is important, but it is assumed the historical significance of the property would already be considered before it is due to go through a decision-making process. Further to this, Tally also does not have the option to assess the historical significance of the property, as it is purely based on the life cycle impact, which does not require to evaluate the historical value of the building. So, based on both the responses and the Tally results, it has been decided to keep this factor in the decision-making criteria, but it will be among the lowest weightage factors that have the least consideration value. Time comparison and material waste estimation and transportation are the other two factors that have been given the least priority by the experts.

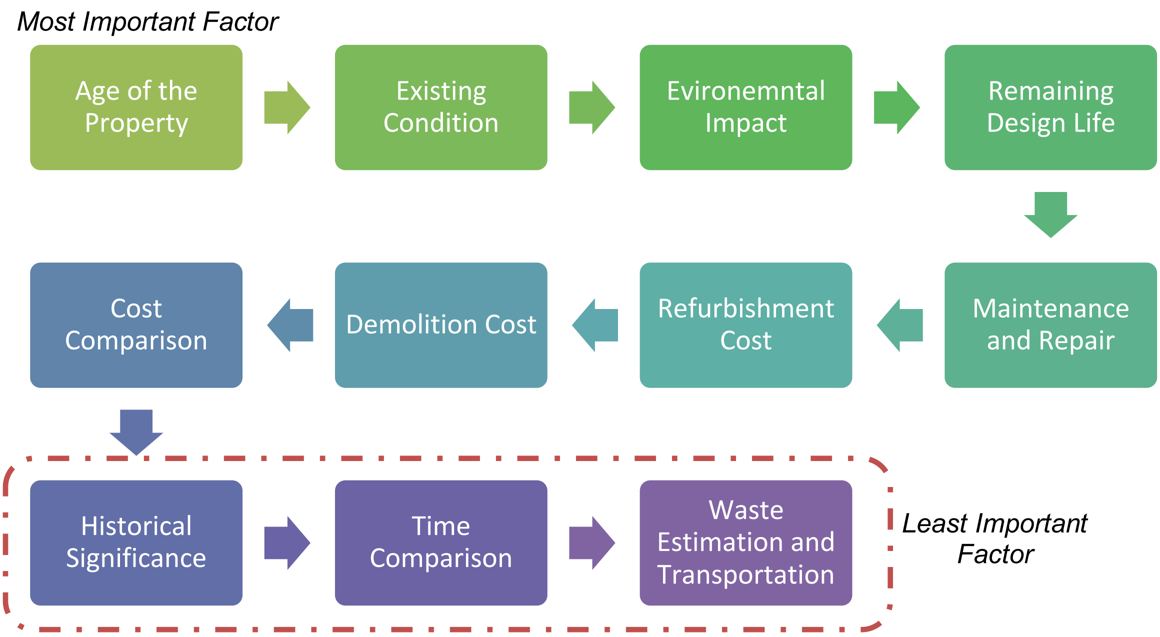


***Figure 5.23 Priority order for the key decision-making factors (Source: The Author)***

After analysing all the responses from the experts, the priority order for the key factors has been generated (see Figure 5.23), starting from the most important factor (age of the property) and ending at the least priority factor (waste estimation and transportation). The last three factors in Figure 5.23 are not considerable in all scenarios, thus they are highlighted in red. Especially, in the decision-making of a new development, these factors are not very effective and can be neglected due to their minimum impact.

Figure 5.23 shows a logical order that reflects the flow of information and their progressive analyses as thought of and structured by the Author. The sequence was generated based on the TALLY results, where material and component design life were given the priority in deciding the remaining design life of a building, and the survey questionnaire, where the experts provided their list of factors, which included the most and the least important factors that in their opinion need to be considered in the decision-making process.

Based on the experts opinion and the Tally analyses, age factor has been given the top priority in the decision-making process. During the data input in Tally, the age of the property was one of the prominent factors that showed a high level of significance. However, the matching percentage with the experts opinion is 95%, the age would still be considered the top priority factor due to its vital role in the decision-making process.

The existing condition factor takes the second priority after the age factor, as most of the experts chose this as the key factor in the decision-making process. Also, data related to existing condition of the building had to be inserted into Tally in two stages, which played another important role in the Tally analyses. The consideration to existing condition of any building is highly important in order to determine whether the building is suitable for further use or not.

Environmental impact is the next important factor in the decision-making process, as all of the experts chose this factor in their list of key decision-making factors. Also, Tally results showed that the environmental impact does play a key role in deciding the future of the building. The matching percentage of environmental impact between Tally and experts opinion was found to be at 89%.

Determination of the remaining design life is another key factor that is included in the priority order for decision-making (see Figure 5.23). All the respondents of the survey chose this factor to be considered in the decision-making strategy, and similarly, the results from Tally analyses also highlights this as the key factor.

Maintenance and repair is the fifth key factor in the priority order, where 83% of the experts considered this as another main factor. Tally results also included the maintenance and repair possibilities for each of the components in the building.

Refurbishment and demolition cost are considered to be the next factors in the priority order of the key decision-making strategy. Again, these two factors were chosen by most of the experts (as shown in Figure 5.23), and the decision from the Tally assessments also reflected these in the refurbishment and rebuilding scenarios. These factors can also be analysed in Revit for detailed decision-making.

Lastly, cost comparison is another key factor. 77% of the experts chose this factor to be considered in the decision-making strategy. Cost comparison of both refurbish and rebuild scenarios can be done in Revit, where the Revit based tools allow the user to input all the cost associated information regarding the 3D model in order to obtain the desired results.

# Chapter 6. **Discussion and Analysis**

## 6.1 Chapter Overview

In this chapter, findings from the previous chapters are discussed and elaborated. The chapter is discussed under nine broad headings. The first part addresses the difference in perception of waste minimisation strategies based on site, which further illuminates deep-rooted non-collaborative culture and practices within the construction industry. Subsequent four sections discuss findings of design, design competencies, procurement and construction strategies for engendering waste minimisation, material impact and the options for refurbishment and rebuilding, while the sixth section discusses the developed frameworks and their usage. The last section highlights the important points on the application and validation of the key decision-making factors. Preceding the culminating section is the discussion of relationship and interplay of the framework and the key identified factors.

Considering the fact that construction works are going on everywhere around the world and this is enormously affecting the environment by poor decisions and planning and various other factors, therefore this initiative of identifying the key factors for decision-making strategy will most likely help the designers, planners, managers and engineers to come up with an overall better development based decision on any existing building that is about to reach the end of its design life (EODL) or a newly proposed development that will reach the end of its design life in the future.

## 6.2 Construction Waste Management and BIM Application

In the beginning, this research project highlights the importance of construction waste management (CWM) and its application on different stages of a C&D project. In most cases, the CWM approaches, techniques and tools focus on separate project stages with overwhelming endeavours to manage waste on-site. It also highlights different modes of transportation for waste in order to assess the amount of C&D transported waste, which is found to be considerably high, as transportation includes fuel, a major contributor to the $CO_2$ emissions. Thus, a direct relation is established between the waste transportation and the on-site waste, therefore the necessary steps to reduce the on-site are necessary and this can be achieved with a decision-making strategy for the demolition and construction (C&D) projects that is based on the key identified decision-making factors.

The identification process for the key decision-making factors in this research project mainly included the background research on the CWM area, gaps in the CWM, current practices of CWM, relevant case studies, development of different sets of CWM frameworks (based on the on-site scenario with respect to design, planning, environment and economic impact), identification, evaluation and mapping of the waste causing factors, and the factors influencing at different stages of a construction project.

Within the existing waste reduction guides, there is also general acknowledgement of the causes for waste being generated in the first instance such as: poor design and specification, poor planning, poor jobsite layout, poor quality control on site and in the supply chain, and a lack of returnable packaging (Ali, et al., 2018b). Furthermore, limited efforts have been made in the past to concentrate on pre-construction waste generation related to supply chain management issues and procurement, design and tender stages (Ali, et al., 2018b). BRE (2011) called for the development of more advanced and powerful online CWM techniques and tools. Yet, there are not many research studies conducted on integrated waste minimisation or information technology (IT) related approaches, techniques and tools across all life cycle stages and phases of the C&D projects. However, implementations of some useful IT and CAD based tools have been acknowledged in the recent past, as discussed in the Chapter Two of this research project. Application of these study based approaches at an early design stage of the project would particularly be beneficial to design out waste and promote the waste-efficient/minimum-waste design strategy, since 33% of construction waste is directly influenced by the inappropriate design decision-making and multiple on-site revisions of design/plan, which contributes to more than 50% of the total on-site waste production in the C&D projects (Ali, et al., 2018b).

BIM tools and applications in Revit have been found to be very useful in this research project. The tool allows the user to access and edit the material specifications, remaining design life and data sheet of each component, predicted $CO_2$ emission for each of the components and materials (acquired from the manufacturer's data sheet for the relevant component or material), cost estimation and to create and manage all the phases of a C&D project.

Furthermore, with the proposed and revised waste hierarchy, there will be an increased efficiency in the planning and design phase with the probability of minimum waste generation during the construction phase. As stated in the first case study in Chapter Four, the revised waste hierarchy aims to eliminate the last two possibilities (least preferable stage) in the hierarchy with justifications provided within the case study. The revisions in the waste hierarchy helped in the identification of the waste causing factors through different phases of the project, where the key factors were taken into further consideration. The two case studies in Chapter Four then led to the evaluation of the key identified waste causing factors by taking account of the factors that contributes to waste in the case studies.

The strategical approach towards the identification of the key decision-making factors was taken by considering different scenarios of construction into account and developing these scenarios in the shape of different sets of frameworks. These frameworks helped in the development of the final two decision-making frameworks for existing and new structures in the second part of Chapter Four. These frameworks also aim to help the designers/stakeholders in order to come up with a waste efficient design for any construction project. The developed frameworks were used to highlight and identify the key factors in Chapter Five that aid the decision of whether to refurbish/re-use or rebuild/recycle an existing structure that reaches the end of deign life or a newly build design that requires a decision-making at the end of its design life.

## 6.3 Tally LCA

Tally produced highly detailed reports in Excel and PDF format for each of the Tally assessments in Chapter Five. Each report includes visual and numerical representations of the results based on the LCA stages, material categories and sub-categories, design life of a component and material, structure type, and the Revit families. Furthermore, total LCA results for LCA modules and impact categories, calculated material mass, calculation methodology, a glossary of LCA terminology and LCA metadata are also included in the reports generated by Tally. These details are included within the Tally LCA section of Chapter Three.

As Revit BIM software is not able to conduct the Life Cycle Assessment (LCA) by itself, It requires LCA add-in tools that work collaboratively with the Revit model to process an LCA study. In short, Revit BIM model is the source of geometrical and semantic data for the LCA process. The LCA process and its results were produced, reported and shared digitally. However, the end-product, i.e. the building, is physical, yet some of the phases and deliveries, such as LCA for each of the buildings, were carried out digitally. Through this study, a joint value and responsibility are obtained in order to deliver a result that the tools cannot deliver by themselves.

Furthermore, there are major differences in between the traditional and BIM-based LCA processes. The used LCA add-in tool (Tally) in this research was also taken as an example to state these differences. However, the traditional LCA process was not used in this research project and the obtained differences were determined based only on the modern BIM-based LCA plug-in tool (Tally), and it may differ from other LCA add-in tools and the users. In addition to that, future possibilities and recommendations to develop the current status of BIM-based LCA tools and their efficiency are also suggested in Chapter Seven.

Interoperability enables transferring and exchanging data between software (IEEE, 1990). Since interoperability is the backbone of BIM-based LCA, the BIM-based LCA tools can provide a higher level of efficiency and practicality in many ways compared to the traditional LCA tools and processes (Anton & Diaz, 2014). The first notable difference of the BIM-based LCA process from the traditional LCA process is the ability to automate the data extraction operation, which is one of the most promising benefits of BIM-based LCA process. Traditional LCA process requires manual data entry (Anton & Diaz, 2014), yet in BIM-based LCA process, geometrical and semantic component data are extracted to LCA tools through open standards. During the manual data entry in traditional LCA processes, it is likely to lose data and spend more time (Anton & Diaz, 2014). Whereas, in the BIM based LCA via Tally plug-in, the data was extracted from the BIM model in form of IFC open standard format and no data loss was detected. Therefore, possibility to incorrect data entry in BIM based LCA process is eliminated through automated data extraction based on interoperability of software. It was also found that the time required for automated data entry is almost zero. Thus, smoother, more accurate and complete data entry were obtained in BIM-based LCA process in this research project as compared to the traditional LCA process used in the past studies.

A BIM-based LCA process provides the user to execute better and early decision-making process (Malmqvist, et al., 2011). In traditional LCA process, the LCA results are obtained mostly when the design is finalised, but it has been observed through various researches that LCA process can be brought forward to start at early-design phase with integration to BIM models (Malmqvist, et al., 2011). It adds a great deal of value to the decision-making process. Based on the empirical study with add-in tools, it is possible to make comparisons and estimations based on the LCA values through the design process starting from an early-design phase in contrast to traditional LCA process (Malmqvist, et al., 2011). Selected BIM-based LCA tools in this research project allowed the user to run LCA process simultaneously even though the CAD design/model of the existing building is not complete. Thus, more accurate and well-structured decisions can be taken, and the possible environmental impacts are minimised starting from the early design phase.

### 6.3.1 LCA Results and Material Impact

The buildings selected for the Tally LCA study in Chapter Five were a mix of new and old buildings, some of that had been repaired and maintained couple of times during their design and service life. Even where the old structures were retained, the interiors of the buildings were refurbished to some extent, with the replacement of plasterboard/gypsum walls and ceiling boards and frames/structures, floors (non-load bearing), windows, doors, and modern bathroom and kitchen facilities, usually located in a newly-built extension. Total of three buildings in the LCA study were assessed that includes a residential house/dwelling, six-storey commercial and a four-storey semi-commercial building. Table 6.1 summarises the details of these buildings along with the decision-making based on the key identified factors.

***Table 6.1 Summary of details and decision-making for the Tally assessed buildings (Source: The Author)***

| **Project** | **Scope** | **Area / Size ($m^2$)** | **Construction Type** | **LCA and Decision-making** |
|---|---|---|---|---|
| Two-storey residential house | To assess the current material condition of the existing building and make a decision of whether to refurbish/re-use or rebuild/recycle. | 212 | Reinforced concrete foundation, ground and timber upper floor, cavity wall (brick, block and thermal insulation), rendered brick lower/common (upper), gypsum and timber frame partition walls and tiled roof. | Refurbishment – based on the economic and environmental impact factors. |
| Six-storey commercial building | To assess the current condition of a 25 year old building and make a decision of whether to refurbish or rebuild. | 788 | Reinforced concrete structure (reinforced columns and steel beams) with cavity wall (consists of concrete blocks, insulation and bricks) on the exterior boundary. | Refurbishment – based on the economic and environmental impact factors. |
| Four-storey semi-commercial building | To assess the condition of a 100 year old building and make a decision for the refurbishment/re-use scenario. | 736 | Reinforced concrete structure (reinforced columns and steel beams) with cavity wall (consists of concrete blocks, insulation and bricks) on the exterior boundary. | Partial demolition and refurbishment – decision based on the existing condition and past refurbishments to the building. |

Based on the building material quantities, specifications/data (imported into Tally plug-in from Revit CAD model) and improved impact factors, results were acquired for each component and material assembly. Overall, Tally findings for all three assessments show that structural components have the largest impact for each category, with a median contribution of 40%. However, materials in masonry and, thermal and moisture protection layers also have significant impacts for many of the categories, with maximum contributions of 35% and 66% respectively. These results showed the hotspot areas within material impacts, which can provide building designers with insight when it comes to material selection; focusing on choosing more sustainable structural materials that have the potential to drastically decrease the overall building material impacts with lower $CO_2$ emissions.

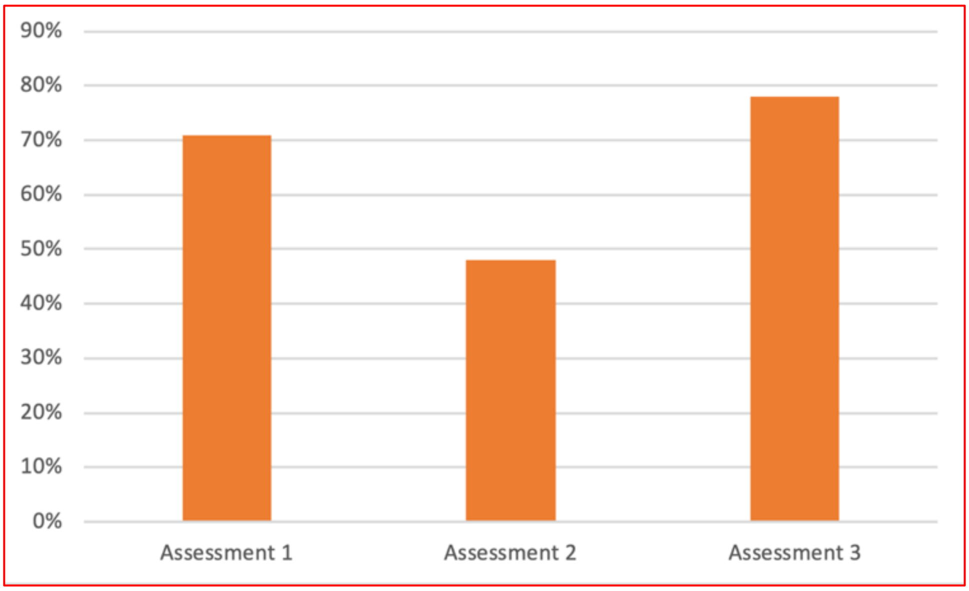


***Figure 6.1 Comparative analysis of thermal and moisture protection layers (Source: The Author)***

The comparison of the environmental impact of thermal and moisture protection layers in all three assessments reveal that the partial refurbishment and rebuild scenario accounts for higher percentage (see Figure 6.1). Even though, this scenario does not require all the components and materials to be removed or demolished, the existing materials already accounts for such percentage $CO_2$ emissions, therefore this scenario accounts for higher percentage. The probability of considering this scenario in such developments is high as this attracts the owner's interest when looking at the economic factor. Thus, in order to balance this situation, the replacement of existing components and materials with higher $CO_2$ emissions would be beneficial in both economic and environmental aspects.

Similarly, with the opening and glazing components, the third LCA assessment accounts for the most amount of expected GWP, which is 85% (see Figure 6.2). Therefore, it is clear that the components with higher $CO_2$ would need to be replaced with the new components. In terms of the social impact, the replacement of these components would not have a big impact, as the building is located within a commercial estate and no property is sharing the party wall with this structure. LCA of Tally trails one and two accounts for lower impact in the opening and glazing , which is 15% and 0% respectively. Such low percentages are expected because the buildings in these assessments account for relatively lower quantities for glazing. Also, the components of the buildings are comparatively new in these assessments. Here, the main consideration is the age of the building as one of the key identified decision-making factors, where the building in the third Tally assessment is the oldest amongst other assessed buildings and hence, it takes the priority in the age factor and the decision to partially refurbish/re-use and rebuild/recycle it.

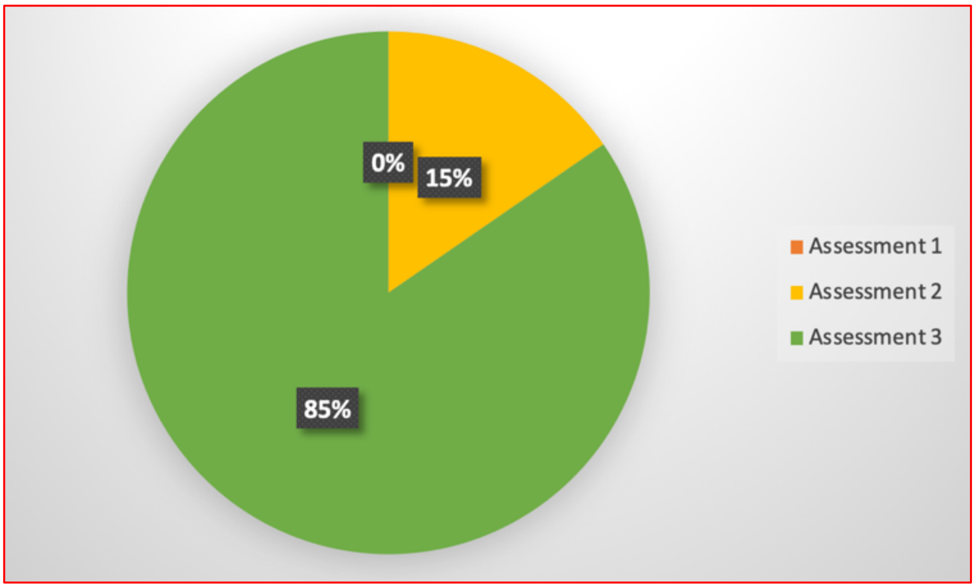


***Figure 6.2 Comparative analysis of openings and glazings (Source: The Author)***

The results also reveal that majority of the energy and associated $CO_2$ emissions were embedded within the structure of the buildings. This means that consideration should be given to the refurbish/re-use scenario for most of the existing buildings in order to reduce the environmental and economic impacts, as in the rebuild and new construction scenario, these impacts would account for higher percentages. Moreover, refurbish/re-use scenario requires considerably less energy than demolition of existing buildings, manufacture, transport, and installation of new materials. It also conserves the embodied energy in the existing buildings.

### 6.3.2 Recycling and Re-use Scope of Primary Materials

Out of the total material waste in the Tally Life Cycle Assessments (LCA), many of the materials are recyclable, where each material can be transported to the recycling plant for recycling. Following are some of the main materials that can be recovered for re-use recycling purpose:

- **Concrete and bricks –** These are some of the most commonly used and recycled materials. For recycling, many waste recyclers crush the concrete and brick waste, and use it in all-weather applications (such as low grade roads/highways) and in pavement sub-bases (such as roads and non-structural applications) as a substitute for virgin crushed rock. Bricks are often presented as 'mixed masonry' or 'builders rubble' mixed with concrete and, like source-separated concrete, this waste is relatively simple to process, with similar end markets for concrete.

- **Plasterboard –** Most plasterboard recovery often made through arrangements between the builder or construction company and the material manufacturer or supplier. Many plasterboard manufacturers regularly support the recovery of clean products from the construction sites and also support companies or top tier contractors that purchase their materials in bulk quantities. Plasterboard is regarded as a contaminant material when presented with other construction waste streams.

- **Steel –** Steel waste can be easily recycled in the UK, as well as in the EU and also, there is a good market for the recycled steel locally and internationally. Even in a combined waste stream, steel can be easily recovered from other waste materials using relatively inexpensive magnets.

- **Timber –** Timbers and woods are heavily recycled and re-used in the UK. Timber waste in construction is normally re-used in smaller jobs or recycled. Also, there is a high-value market for the re-use of quality hardwood timber, with prices over £1000/$m^3$ for some high-grade British timbers, although the volume of recovered material is relatively low. A significant source of salvageable hardwood is 'infrastructure timber', such as power poles and railway sleepers, for which there is strong demand in landscaping applications.

## 6.4 When is Refurbishment the Better Option?

Choosing refurbishment over rebuilding seems to be a feasible and economical option in most construction projects. Though, in this research project, the rebuilding option was also found to be suitable in some scenarios, where the overall condition of the existing structure is not good or the building is nearing the end of its design life. Thus, the probability of choosing refurbishment over rebuilding is considerably higher in terms of economic, environmental and social stability and therefore, all these measures contributes towards the sustainable development.

Achieving sustainability via refurbishment need not be difficult, expensive or environmentally affective, but does require an understanding of the inter-relationships between the environment, costs, associated risks and benefits as discussed. Also, there is no one-size-fits-all strategy, as so much depends upon a particular building's existing structure condition, remaining design life and possibilities for the proposed development with respect to planning and building control purposes (see Figures 4.18 and 4.19). However, the decision-making frameworks for the existing and new buildings are developed based on thorough research and case studies, a framework for determining the level of refurbishment that a building may require in order to raise it to an acceptable standard/condition is required and hence, it has been proposed in the Table 6.2 (GVA Grimley, 2010). This further lead to the requirement of the level of refurbishment works, therefore the examples of the degree of intervention are also suggested for each level of refurbishment works in the Table 6.3.

***Table 6.2 Estimated environmental impact over 60 year period – comparisons of refurbishment and new build (Source: modified from GVA Grimley, 2010)***

| Level of refurbishment | Examples of degree of intervention |
|---|---|
| ***Level 1 – Tune up and minor refurbishment*** | Carry out required health checks on building management system and controls, revise layout to improve daylight and flexibility, low energy options on replacement. Recommissioning of building services. Also, check for damaged components and materials for replacement, if necessary. |
| ***Level 2 – Intermediate refurbishment*** | All Level 1 works plus: renew lighting and control system, remove false ceilings to expose thermal mass and reinstall new false ceilings. |
| ***Level 3 – Major refurbishment*** | Replacement of most of the major components and services, floor finishes, raised floors and internal wall (non-load bearing). Installation of external solar control in order to improve the environmental impact (if possible and required by the owner). |
| ***Level 4 – Complete refurbishment*** | Only sub-structure, superstructure and floor structure retained. Structural and facade alterations. Possible relocation of cores and risers. Complete reinstallation of the internal components and materials such as partition walls (non-load bearing), electrical wiring and components, plumbing, doors, windows and false ceilings etc. |
| ***Level 5 – Demolition*** | Consider demolition and rebuild. |

The first stage when considering the available options for refurbishment/re-use should be to undertake an assessment of the performance of the existing building. During the assessment, particular attention should be given to energy use, occupier or owner satisfaction, operational efficiency, the condition of internal fittings (including load bearing and non-load bearing walls) and the external structure of the building (GVA Grimley, 2010). Comparing the achieved results against benchmarks will highlight areas for improvements to be made.

BIM-based development appraisal techniques, incorporating the life-cycle costing (LCC) methods can then be used to estimate the commercial viability of a range of potential refurbishment options for the building/structure, from basic and minor refurbishment through to complete internal refurbishment. Such analysis tools are included within the Revit BIM and similar/relevant CAD packages with more advance features added in the latest versions of the software.

***Table 6.3 Establishing the level of refurbishment required (Source: modified from GVA Grimley, 2010)***

| | | Building Condition | | | |
|---|---|---|---|---|---|
| Building Performance / Existing Condition | | **Excellent** | **Good** | **Poor** | **Very Poor** |
| | **Excellent** | Maintain | Level 1 | Level 2 | Level 3 |
| | **Good** | Level 1 | Level 2 | Level 3 | Level 3 |
| | **Poor** | Level 2 | Level 3 | Level 3 | Level 4 |
| | **Very Poor** | Level 3 | Level 3 | Level 4 | Level 5 |

The proposed criteria for the level of refurbishment works has been listed the Table 6.3, where level 1 means minor refurbishment works required, whereas level 4 demands for major refurbishment works. Level 5 demands for total demolition of the existing and rebuilding of completely new structure. As discussed, level 5 works are only required when the existing structure reaches the end of design and service life, however the components that have at least 20% of the design life remaining can be removed safely using the deconstruction method.

Hence, the refurbishment is a better option when the building or a structure has a considerable design life remaining with good history of regular and acceptable level of maintenance works and an overall expectation of less environmental, social and economic impact from the refurbishment works.

## 6.5 Risks and Technical Challenges of Refurbishment

Although, there may be numerous cost-saving opportunities from the refurbishment/re-use scenario, there may also be substantial risks and technological barriers to overcome each with potentially significant cost implications (GVA Grimley, 2010). Once again, each case is unique and has different aspects, but there are common areas of refurbishment/re-use risk that include the following:

**Existing Structure –** Constraints arising from the condition of the existing building fabric, form and orientation including the unpredictability of the effects of demolition and temporary works on the retained fabric. Physical constraints include slab-to-slab and ceiling-to-floor height limitations, limited riser capacity, and plant room space. The redistribution of services and means of escape may also be problematic (GVA Grimley, 2010). There is likely to be a need to improve the performance of the building fabric to provide improved thermal insulation and control of glare, while optimising the use of natural light in office space particularly.

**Contingency Requirement –** A higher level of contingency may be required especially for the increased risk of unforeseen costs associated with refurbishment work and also, mechanisms will be required to deal with any unexpected difficulties (GVA Grimley, 2010). Having a contingency plan in any of the construction or demolition project is considered to be a good practice within the C&D industry. Many of the top tier contractors and designers have this plan in place prior to the commencement of the construction phase, however this practice should be implemented as mandatory for all the construction companies, including SME companies too. Contingency plan also helps in the reduction of unexpected waste.

**Safety Issues –** Consideration should be given to the unexpected occurrence of hazardous materials, such as asbestos and the possibility of complex design, planning and sequencing of the construction programme, which may require expert risk assessment and management. This would impact the economical factor, but it is also beneficial in the longer run, thus the cost can be compromised to some extent in such complex cases.

**Procurement –** The elevated risks and technical challenges of refurbishment mean contractors with specialist expertise may be required, further raising costs associated with the procurement process.

## 6.6 Strategic Approach towards Achieving Sustainability in the Refurbishment of Commercial Buildings

Deciding on the most economically sustainable path requires a balancing of the costs, risks and benefits of carrying out the work. At the initial concept and design phases of a project, a key consideration should be that to achieve economic and environmental sustainability, however the finished product must benefit the economic performance of the occupiers as well as the owners.

The design must facilitate the occupier's drive to maximise productivity through high levels of workspace efficiency. Office space should be created with a high level of in-built flexibility with regard to space planning, IT infrastructure and services allowing optimal occupational densities to be achieved (GVA Grimley, 2010).

When assessing the commercial viability of a potential refurbishment project it is important to understand the costs, risks and benefits to the investor over the projected holding period. In order to achieve this, life cycle costing (LCC) should be incorporated into the standard development appraisal process to evaluate the various development options available. Life cycle costing (LCC) involves estimating the present value of the total cost of the proposed development project over its entire operating life (including initial capital cost, occupation costs, operating costs and the cost or benefit of the eventual disposal at the end of its life).

The key variables for consideration when comparing the life cycle costs (LCC) of refurbishment/re-use with rebuilding/redevelopment will include the extent of construction works, the discount rate applied, tax allowances, the proposed building design life and the nature and condition of the existing building.

For commercial owners, the decision of whether to refurbish/re-use or demolish and rebuild/redevelop will primarily depend on the commercial viability of the options available and the need to maximise the economic performance of a building for both owner and occupier (GVA Grimley, 2010). In many instances, the refurbishment of office space offers advantages over new build, which can facilitate the achievement of economic, social and environmental sustainability.

Furthermore, there is a proposed approach, which splits the refurbishment process into four phases: preparation, design, construction and use. Although, $CO_2$ focused principles can be applied to wider concepts of environmental sustainability:

1. At the preparation phase, there should be a commitment from key stakeholders to deliver an environmentally sustainable building. This vision should be set and fully incorporated into the development brief. The carbon footprint of the existing building should be established, which will enable the setting of targets for carbon ($CO_2$) reduction. A dedicated budget should be set for low-carbon elements with a 'carbon champion' appointed to ensure the original vision is kept (GVA Grimley, 2010). An experienced design team should be selected with the power to implement solutions to achieve sustainability.
2. At the design phase, reducing heating, cooling and lighting loads while improving recycling, waste management and water conservation should all be key considerations. A wide range of options should be explored utilising both energy modelling data analysis and whole life costing (WLC) appraisals, where possible. Budgets should be carefully managed and the final design to be approved and signed-off by the client (GVA Grimley, 2010). $CO_2$ Emissions target should be included in procurement arrangements for the construction phase.
3. The construction phase requires effective project management to focus on sustainability and careful selection of contractors with experience in sustainable refurbishment. Site workers should be encouraged to understand the importance of energy efficiency with the construction process consistently monitored against

objectives. Energy monitoring equipment built into the project will allow the tracking of performance within the completed building.

4. In the period following refurbishment, knowledge of the improvements made should be conveyed to the occupants of the building as using new efficient equipment effectively is vital. Building Energy Management Systems should be carefully designed, and the building operators should understand how to correctly operate new plant, systems and controls (GVA Grimley, 2010). Post-occupancy evaluations will help to ensure improvements are functioning correctly. In-use energy consumption should be monitored with results used to highlight potential areas for further improvements. Finally, the environmental sustainability features of the refurbished building should be clearly communicated to stakeholders.

The costs of delivering an environmentally sustainable office need not be high. A recent IPF report found that for offices, $CO_2$ emissions can be reduced by approximately 25% at no additional cost to the market standard (GVA Grimley, 2010). Additional expenditure of just 5% was found to be capable of reducing baseline emissions by approximately 50% for older offices, presenting huge potential to cheaply reduce $CO_2$ emissions through refurbishment (GVA Grimley, 2010).

## 6.7 Can a Refurbished Building attain the same Level of Environmental Sustainability as the New-Build?

It has been widely observed in this research project that one of the principal advantages of refurbishment/re-use over demolition and new-build is the potential to reduce resource consumption through the re-use of structural elements, building materials and services. However, the existing structure can be a burden, placing constraints on what can be achieved.

Identifying the features of existing buildings, which can be exploited should be a key consideration when assessing the refurbishment/re-use potential of office space or other commercial buildings. Again, each case will be unique and has different aspects, but there are several common areas where the environmental sustainability rating of a refurbishment project can be significantly enhanced, and the desired results can be achieved by taking account of the following steps:

**Embodied Energy –** Embodied energy can be defined as the total primary energy consumed during resource extraction, transportation, manufacturing and fabrication/construction of a building. One of the key advantages of refurbishment is that it is an opportunity to conserve embodied energy. It is important to remember that at existing levels, the operational energy use of a building is likely to significantly outweigh the amount of embodied energy in its construction, although this balance is shifting.

**Location and Orientation –** In a refurbishment project, early consideration of location and orientation can mitigate some of the burden placed on mechanical services to control the internal environment. For example, through the use of passive design strategies such as natural lighting and ventilation, although constraints will be set by the footprint of the existing building (GVA Grimley, 2010). For example, broad floorplates with cellular offices may mean that natural ventilation is not a viable option. Also, the location factor has been identified as one of the key factors in the decision-making process in this research project, therefore as this step has already been considered in the early stages of the decision-making process, the documentation will be in place when considering this step in the refurbishment/re-use scenario again.

**Re-use of Structure –** A significant reduction in the overall level of embodied energy requirements of a development project can be achieved through the re-use of building facades, structures and other features, where possible and applicable. This can be reflected in the market through voluntary environmental assessment schemes (GVA Grimley, 2010). For example, BREEAM credits are awarded where at least 50% of the new building's total facade comprises re-used facade and at least 80% by mass of the re-used facade comprises in-situ re-used material.

**Re-use of Building Materials and Land –** The energy rating of a building can be improved through the re-use of building components and materials. BREEAM credits are available when at least 80% of an existing primary structure (structural floors, columns, beams, load-bearing walls and foundations where required for structural use by a new building) is re-used without significant strengthening or alteration works (where the mass of new material is equal to or greater than 50% of the total mass of the re-used structure) and where the re-used structure comprises at least 50% of the structural volume (GVA Grimley, 2010).

BREEAM credits will also be awarded where the site has been previously built upon or used for industrial purposes within the last 50 years (GVA Grimley, 2010). In addition, credits will be awarded where the site has no, or very limited existing site ecology: this would apply in a refurbishment or on contaminated land or brownfield that has been derelict/unoccupied for less than one year.

## 6.8 The Wider Benefits of Refurbishment/Re-use

In contrast with the negative and wider problems generated by demolition, refurbishment in all but the most extreme cases is both cheaper and less damaging to the local environment than demolition and new build (Power, 2008). Refurbishment offers many clear benefits that include:

- It preserves the basic structure of the property, and retains existing infrastructure in an existing built environment;
- The renewal of a single house has an immediate effect on neighbouring properties because it provides a clear signal that the neighbourhood is worth investing in (Power, 2008);
- Upgrading is far quicker, environmentally and economically feasible than demolition and rebuilding of a completely new structure, because in most cases, it involves adaptation of the existing structure and layout of a house rather than starting from scratch and affecting the local environment and neighbouring properties as in the new build scenario;
- It is far less disruptive to local residents, because even where major work is undertaken, residents can usually stay, and the area services continue to operate unless a dangerous structure is involved in the refurbishment works. If residents have to move out temporarily, it is normally for months rather than years, but there is a minimum possibility of such situation in the refurbishment works;
- It involves a shorter and more continuous building process since most of the work can happen under cover in weatherproof conditions in most cases. New build involves many months of exposure to all weathers while building the foundations and main structure;
- Refurbishment has a positive impact on the wider neighbourhood, sending a signal that renewal and reinvestment will ensure the long-term value and stability of an area. This in turn generates other investments and broader upgrading possibilities, especially within the commercial sector;
- Older existing neighbourhoods and homes require constant upgrading. Refurbishment has a positive effect on street conditions, social mixing, service quality, local transport and schools, since it adds value and attractiveness to the surroundings (Power, 2008);
- Planning applications for most of the refurbishment projects are approved easily with minimum or no changes required by the Local Planning Authority (LPA), as the refurbishment does not require major structural changes to the building that could result into severe social and environmental impacts.

## 6.9 When is it more Environmentally Sustainable to Refurbish rather than Rebuild?

As witnessed in all the Tally assessments performed in this research project, refurbishment/re-use scenario has always been found to be more environmentally sustainable than demolition and rebuilding. Though, there has been a fine balance between the economic and environmental factors that may also result in refurbishment not being the feasible option in some cases.

In terms of the environmental sustainability, it can be seen in Tally's first and second assessment that the refurbishment was more preferred option for the building as there was a significant design life left in both assessments. Also, the refurbishment/re-use scenario was more economical in terms of planning, design, time frame for the required works and the material procurement. Thus, it is more environmentally sustainable to refurbish/re-use than rebuild/recycle in the following conditions:

- When the building/structure has more than 50% of the design life remaining with no regular major maintenance of the components and materials at required intervals;
- When the components (non-load bearing) or materials of the building have been previously maintained and replaced at regular and required intervals along with the building/structure (load bearing) having more than 30% of the design life remaining;
- When the building/structure has more than 20% of the design life remaining but there is no change of use required by the client and the purpose of the property remains the same after the refurbishment works. This option is more applicable and feasible in the commercial sector;
- When the property is sharing the party wall with any of the neighbouring properties, as this will most likely have a massive impact on the local residents as well as the local environment;
- When the overall global warming potential (GWP) of the comparative life cycle assessment (LCA) accounts for significantly lower percentage as compared to the rebuild/recycle scenario.

As discussed previously and taking account of the different scenarios for refurbish/re-use and rebuild/recycle, it is clear that the economic and environmental factors have majors roles in the decision-making process. However, all other key identified factors are directly linked with these two factors and can be counted as sub categories is some cases.

## 6.10 When is it more Environmentally Sustainable to Rebuild rather than Refurbish?

As previously discussed, refurbishment/re-use is the preferred option in most cases, although there are some cases where the rebuilding is more convenient, feasible and environmentally sustainable than refurbishment. Such cases require immense amount of detailed working in order to plan out all the phases including the deconstruction of the components from the existing building (if required), demolition of the existing building/structure, design and planning of new development, procurement, waste planning and management, execution of construction and hand over etc. In this research project, demolition and rebuild is found to be the least preferred option, however the key decision-masking factors are identified in order to make the best possible decision, which would either favours the refurbishment/re-use, rebuilding/recycle or partial demolition and refurbishment scenario.

In terms of the environmental sustainability, it can be seen in Tally's third assessment that partial demolition and refurbishment was more preferred option for the building as there was no such design life left in the assessed building, however it had major refurbishments twice within the past 30 years, which included changes and replacement of many of the major components and materials. Also, the partial demolition and refurbishment scenario was more economical in terms of planning, design, time frame for the required works and the material procurement. Thus, it is more environmentally sustainable to rebuild/recycle than refurbish/re-use in the following conditions:

- When the overall global warming potential (GWP) of the comparative life cycle assessment (LCA) accounts for significantly lower percentage as compared to the refurbish/re-use scenario;
- When the building/structure has less than 20% of the design life remaining and a change of use is also required by the client and the proposed use of the building/property is expected to be different after the required works are carried out. This option is more applicable and feasible in both commercial and residential sectors;
- When the property is not sharing the party wall with any of the neighbouring properties, as this will allow the designer and contractor to easily deconstruct or demolish the existing structure without having a negative impact on the local residents, buildings as well as the overall local environment;
- When the existing building is weak, structurally un-safe and shows clear sign of defects and, wear and tear from different sides of the structure. This would certainly require the building to be demolished.

Similar research into this question was carried out for the DTI/BRE in 2002, which resulted in the development of a model, named ‘Office Scorer’, which allows comparisons to be made between the environmental and economic impacts of refurbishment/re-use with rebuilding/redevelopment (GVA Grimley, 2010), where the model produces an ‘ecopoints’ score for the life of a given development project. The score is derived from the estimated effects of development on resource use, air, soil and water pollution in addition to the impacts of waste and effects of transport. To place ecopoints into context, a score of 100 represents the environmental impact of one UK citizen per year.

In the example outlined below (see Table 6.4), the impact of four hypothetical office development or commercial projects is compared (GVA Grimley, 2010). The results show that, assuming the characteristics of the final development are the same, the main influence on the ecopoints score is the extent of the development works to be carried out.

However, if adjustments are made to the specification of the final product, for example the types of cooling, ventilation and heating systems incorporated, the resultant environmental impact score of complete redevelopment can be less than refurbishment (GVA Grimley, 2010).

This simple demonstration shows how ultimately the answer to the question lies in identifying and understanding the contribution certain characteristics of the existing building can make via refurbishment and balancing these against the advantages of new-build.

***Table 6.4 Estimated environmental impact over 60 year period – comparisons of refurbishment and new-build (Source: modified from GVA Grimley, 2010)***

| **Refurbishment / Re-use** | | | **Rebuilding / Redevelopment** | |
|---|---|---|---|---|
| | ***Minor*** | ***Major*** | ***New Build*** | ***New Build**** |
| ***Total ecopoints for building*** | 9.160 | 9.506 | 10.887 | 9.474 |
| ***Ecopoints per ft²*** | 2.47 | 2.56 | 2.93 | 2.55 |
| ***Ecopoints per person*** | 32.05 | 33.26 | 38.09 | 33.14 |

Consider the pavement related findings reported in Chapter 4, Section 4.6. Regarding highway pavements, once the condition of the pavement is established, then a suitable method to repair or recycle would be considered. The decision to repair a pavement in critical condition but not failed condition depends on the type of the pavement and the nature and the extent of the defects of the pavement. For example, in flexible and rigid pavement, a crack of the pavement will require suitable sealant and sometimes load transfer devices for such crack. If the crack is wide-spread and of a certain width, then that may necessitates a complete recycling and rebuilding of the pavement as explained in Chapter 4, Section 4.6. Similarly, for flexible pavement with certain rut depth and cracking, the condition criteria and relevant actions to repair or recycle, which are explained in Chapter 4, Section 4.6 would be applied.

Considering the increasing importance and urgency of climate condition and the required climate action, it is equally important how the pavements are designed and maintained to avoid or delay the appearance of defects on the pavement and to make sure that the life service of the pavement is increased, its maintenance need is reduced, and the material used and the technique applied is sustainable.

It is important to recycle the materials of the failed pavement layers and to re-use materials from demolished buildings in the foundation layers of the pavement with emphasis in reducing the energy and $CO_2$ used in the design of the new pavement and in the repair and refurbishment of the existing pavements. For example, for a failed concrete pavement, the application of the “Crack and Seat” technique of the failed concrete layers is more cost effective and environmentally friendly approach to re-use the existing failed pavement materials, which only then needs to overlay the cracked and seated concrete slabs with flexible surfacing or concrete surfacing layer.

As for the flexible pavement recycling technique, the “Cold in-place Recycling” is more environmental friendly approach as it requires no heating energy and thus less $CO_2$ emissions, although it requires more research to improve its strength and durability compared with “Hot in-place Recycling”, which needs the heating of the recycled materials before application into the road pavement.

The most important aspect here is to have good pavement design and specifications with emphasis on sustainability coupled with efficient and sustainable pavement management system.

# Chapter 7. **Conclusions and Recommendations for Future Work**

## 7.1 Chapter Overview

This chapter concludes the study by summarising the whole research project and the outcomes of data collection, identification, implementation and analyses. The next section provides a holistic summary of the study, covering the goal, research design, data collection and data analytical techniques adopted in this research project. This is then followed by key findings of the study, which is presented in line with the aim and objectives of the study as earlier presented in the first chapter. Implications of the study for theory and practice, as well as its limitation, are presented before culminating this chapter with recommendations for future research within this area.

## 7.2 Conclusions

As stated earlier in this research project, the construction industry contributes the highest portion of waste to landfill, and it consumes a large portion of mineral resources excavated from nature (Anink, et al., 1996). Moreover, it contains harmful substances that jeopardise human wellbeing and the surrounding natural environment. In an effort to safeguard the environment and to enhance the sustainability of the construction sector, numerous nations around the world have formulated different rules and initiatives to reduce C&D waste. Due to negative environmental impacts of waste generation, waste intensiveness of the industry has remained a major concern for the global sustainability agenda (Anderson & Thornback, 2012). These facts led to determine the root cause of the issue with thorough research on the subject, that further developed with the idea of identification of the key factors that would help in deciding whether to refurbish or rebuild.

In order to identify the key decision-making factors that aid the decision of whether to refurbish or rebuild, this research investigated design, procurement, waste management and construction strategies for minimising waste in C&D projects and also conducted a thorough review on some of the past published research and journals on the relevant subject. It is significant to mention again that the theory behind the identification of the decision-making factors was to have the minimum waste outcome from the building that is due to be considered for either refurbishment or redevelopment. Also, the economic and social factors play an important role in the decision-making process. Apart from investigation and identification of the key factors for construction waste mitigation, the study also considers interrelationship between stages of projects' lifecycle. This is as evidence suggests that activities carried out at earlier stage are capable of engendering occurrences at later stages of the dynamic construction processes. The issue of the management of C&D waste is rather complicated. Not only should this issue attract the attention of the competent management authorities, but also general citizens should draw their attention to it and play their part, where possible.

In order to achieve the aim of the study, various methods of data collection and analyses were used in the study, however the Revit/BIM based models and their life cycle assessments in Tally played major role in the validation of the key identified decision-making factors. Following the doctrines of critical realism philosophy, this research combined quantitative approach at intensive and extensive stages respectively. At an early stage of the study, multiple data were collected through systematic literature review and reviews of the past researches within the relevant scope. The online and offline collected data and investigation on design, materials procurement, waste management and construction processes facilitated in understanding the relationship between the construction and demolition waste. Further, in Chapter 4, some case studies were performed, where the real site waste data was collected from three high rise construction sites in order to investigate the dynamic relationship and interplay among the waste management strategies that produces waste. The case studies were also used to establish the extent by which the various strategies were adopted as well as the overall waste efficiency of the project and also to figure out the importance of economic factor within this case study, an approximate figure and amount of material waste was calculated. The outcomes from the case studies lead to the development of different sets of framework based on waste minimisation strategy and the key decision-making factors were identified based on those frameworks. After, three analyses of the life cycle assessment (LCA) were carried out on different CAD models via Tally for the application of the key factors. The analysed models included residential, semi-commercial and commercial buildings. These factors (with the implementation of the decision-making frameworks for existing and new buildings) are also aimed to help designers, engineers and all relevant stakeholders to work collaboratively and produce a waste efficient design for any new development project.

The key identified factors were also used to develop a survey questionnaire, which was pilot tested and sent to construction professionals including Project Directors, Project Managers, Project Engineers, Construction Managers and Planners, BIM Specialists Waste Managers and Designers, to add their valuable opinion based on their 10+ years of expertise in order to validate the key identified factors. The survey mainly included questions related to waste, BIM, utilisation of BIM in waste management, key factors for decision-making and importance for each of the identified key factors in the decision-making process. Through this process, 38 responses were received, which were used for further analyses, including reliability of the factors, descriptive statistics and multiple variation of analyses. These sets of statistical analyses helped in establishing and re-organising the critical success factors that aid the decision of whether to refurbish/reuse or rebuild/recycle an existing building and also applicable on new building, when it reaches the end of design life (EODL). The opinion from the experts also facilitated in ranking each of the key factors based on its importance over other identified factors.

All in all, identification of the key decision-making factors have been the main area of focus in this research, along with their validation.

In terms of the relevant UK policies and legislations, the need to meet the demands of both the Government and occupiers will force the owners of property to re-assess the environmental and social sustainability of their office portfolios. Increasingly, existing buildings that do not reach the ever changing standards required will need to be refurbished if they are to remain attractive to both occupiers and investors (GVA Grimley, 2010).

Deciding on the most economically sustainable path requires a balancing of the costs, risks and benefits of carrying out the work (GVA Grimley, 2010). As part of the development appraisal process, life cycle costing (LCC) should be incorporated to evaluate various development options from basic refurbishment through to complete redevelopment (GVA Grimley, 2010). Application of the key identified factors in this scenario surely having more weight on the economic factor, however there is a need to have a fine balance between all the key factors when deciding the future of a building of such kind.

The industry has a long way to go towards cutting $CO_2$ emissions but there is much that can be achieved via refurbishment. Thus, taking account of the key factors in such scenarios, it is possible to attain a high level of environmental sustainability through simple, low-cost improvements and, where redevelopment is not viable, refurbishment should be a priority for investors and developers.

In a perfect world, sustainable rebuilding/redevelopment would, in most cases, be preferable to refurbishment as limits are not set by the numerous constraints and risks associated with the existing buildings/structures. But this fact cannot be avoided that in many cases, new-build is not financially and socially viable, particularly in the UK's city centres (GVA Grimley, 2010). Doing nothing is increasingly not an option and refurbishment is emerging as a means of achieving economic, social and environmental sustainability.

### 7.2.1 Refurbish/Re-use

As discussed in the chapter 6, The criteria for the refurbishment/re-use is based on the existing condition of the building with respect to its future proposed use. However, in terms of the Tally findings and the experts opinions, it is highly recommended to assess the current condition via modern techniques that include laser scanning, surveys and CAD programmes etc. The experts have clearly given priority to the refurbishment/re-use option, with the condition of having less environmental and economic impact in the refurbishment/re-use scenario. The Tally results also indicates the refurbishment as the better option as it generates less $CO_2$ and is also economically and environmentally feasible. But, as discussed previously, this may not be the case in all scenarios especially when an existing or old building reaches or is about to reach the end of its design life (EODL). In this case, rebuilding is the most suitable option, however it would be required to have the waste efficient design and proper planning of all other aspects with the less expectation of building and material waste.

Following on from the experts opinion, many of them also believed that the amount of waste in the coming days is likely to be increased, regardless of the current and ongoing research on this subject, this is because the level of construction activities have been accounted for a massive surge in the past and recent years and there can only be measures or new guided policies by the government to prevent the generation of waste, which is generally not followed by the small medium-sized (SME) enterprises.

### 7.2.2 Demolish/Rebuild

The case for planned large-scale demolition for energy reasons is greatly weakened when there is a consideration for embodied energy as well as the energy in-use. There are many unclear areas of information such as exact embodied energy values, the costs, the direct energy impact of demolition and its wider environmental impact. Refurbishment is possible in most circumstances as shown and experienced in the Tally assessments in this research project. It sets in train a virtuous circle of renewal with wide benefits for social, economic and local environmental conditions, thereby reducing pressures to sprawl as people try to escape bad neighbourhoods.

Highly selective demolition, a ‘scalpel’ approach to existing areas, can remove dangerous and un-savable properties, whereas planned government-supported demolition invariably targets whole streets, blocks, estates or areas. Both the wider arguments in this research project and concrete evidences support a focus on refurbishment rather than large-scale demolition.

Even with the highest feasible level of demolition, the existing stock would remain the dominant energy challenge in the built environment far into the future. Higher incentives through policy reform could reduce energy use within a short time frame, and could achieve a significant reduction of carbon emissions from buildings in the near furture. Upgrading of the existing stock to reduce $CO_2$ emissions cheaply, quickly and easily would be invaluable in shaping future policies.

There are gaps in the scientific evidence base around the issues that have been discussed from the previously conducted researches and case studies. Further work is needed on the wider economic and specifically environmental impacts of demolition, new build, refurbishment, density, materials and other issues to clarify the arguments put forward in this research project.

In short, the demolition and rebuild has to be the last resort/option for any decision-making process, as this will promote the environment, social and economic factors. Therefore, the identified key decision-making factors played an important role in assessing the existing condition of the building in order to make a decision that is in the best interest of economic, environmental and social stability while achieving the overall sustainability within the C&D industry.

### 7.2.3 Summary of Key Conclusions

This section summarises the key conclusions of this research project. The key conclusions are:

- To consider the option for refurbishment when an existing building or its components have more than half of the life left;
- If the building has reached the end of design life, but the components still have considerably good life left and are in re-usable condition, then the partial deconstruction of the building needs to be done, up to a stage when it is feasible, convenient and safe to remove the useful components. An economic feasibility is required to make a decision and on this task, which will identify whether the deconstruction is a viable option or not;
- To consider the option for demolition when the building has less than 30% of the design life left and less than 20% of the components are in re-usable condition. As in this case, the deconstruction of building for the removal of very few components is not feasible and would impose a negative impact on the economic and environmental factors;
- Partial refurbish and demolition option should be considered on the decision-making of buildings that are complex in design or if the structure has been greatly

maintained with high standard service and refurbishment at regular and required intervals.

- Un-recyclable waste from the demolished or refurbished building could be transported to the nearest highway construction site to use it for the sub-base layer of the highway. Economic and environmental feasibility would be required for this process such as waste transportation cost and $CO_2$ emission.
- It is clear that the key factors identified in this research project support the decision-making on whether to refurbish/re-use or demolish/rebuild and as evident by comparison with the corresponding opinions of the experts in the construction industry.
- The findings of these factors reduce the environmental impact of the construction by minimising the construction waste and the promotion of refurbishment and re-use as suitable.
- The three buildings analysed in this research project (including the use of TALLY plug-in for Revit/BIM software) were chosen as they represent good examples of commercial buildings and residential buildings in addition to the fact that they have a variety of the most common types of building materials including bricks, masonry, concrete, steel, timber and gypsum. Although, there is one set of results for each building type, the set of results are applicable and transferrable across all the three types of buildings, as the principles are similar in terms of the Life Cycle Analyses (LCA), remaining design life and the Life Cycle Cost (LCC) for each of the material and components of the building.

## 7.3 Recommendations for Future Work

As seen in the chapter four and five of this research project, the key factors were identified through different developed frameworks that are partly based on REVIT (BIM) software and mainly based on the commonly used practices within the industry, the future revisions to these identified factors could be purely computer based and in a better form such as the application of Artificial Intelligence (AI) technology into a BIM based framework within a CAD software. The revised factors could be named as AI Decision-making Framework for existing and new developments. Furthermore, this idea is to not restrict this framework to a one specific software, rather making it workable for and integrated in all industrial CAD software packages. At this stage, this can be done by introducing a plug-in for the CAD software packages. Not only this will benefit the industry but will also contribute towards the better environment and improved economy.

The inclusion of each decision-making factor within the framework is based on research including past papers, journals on relevant subject and industrial experts opinion. The proposed decision-making framework will achieve minimum waste or waste efficient design, less environmental impact and improved cost savings.

### 7.3.1 Artificial Intelligence Integration into BIM Model

Since this research was carried out within the UK, future research could investigate generalisability of findings from this study to other countries as more research and improved revisions with validation of the identified key factors would further reduce the construction waste and designers and planners will be able to have a better, precise and well informed decision on any construction project. Based on LEAN philosophy, non-material sources of construction waste could be investigated and integrated into BIM. Thus, future research could also extend the scope of this study beyond the developed frameworks and key decision-making factors to reduce construction waste, such as the introduction of Artificial Intelligence (AI) with BIM integration. In the same way, the scope of future studies could be extended to cover civil engineering and infrastructure projects. Future research could also go beyond just construction waste to consider prediction of excavation, operational, and demolition waste and based on the prediction, an AI based decision-making strategy could be applied.

BIM software companies have already begun to use artificial intelligence to improve the efficiency and potential of their programmes (Myers, 2020). BIM software can now use machine learning to learn from data and detect patterns and from this, make independent decisions on how to automate and improve the model building process.

BIM software collects tons of data, which AI uses to explore the possibilities of each aspect of a construction project and find the best solution, which is far quicker than a human mind. Not only does this make processes quicker, but it reduces the risk of human error which can improve safety on sites (Myers, 2020).

It is much likely  that there will be much more AI-assisted BIM in the future within the industry over the next decade. Artificial intelligence has shown that the inventors and researchers now have the capacity to push BIM to the next level, to make further progress in the industry.

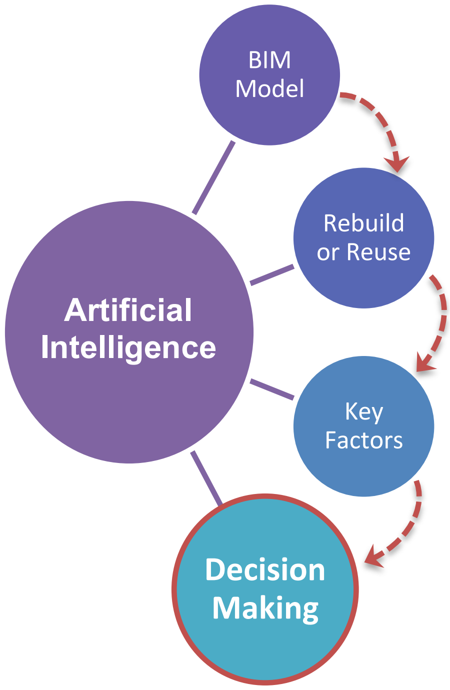


***Figure 7.1 AI Integrated BIM model for decision-making (Source: The Author)***

As shown in Figure 7.1, the proposed model for the AI integrated BIM model would let the designers to decide the future of the building by simply entering the properties of the building components and then an AI would generate the results based the key decision-making factors. Productivity has always been an issue in construction and as a result, the industry has developed at a much slower pace than any other. It's starting to seem like artificial intelligence AI could be the answer to the barriers, the industry has faced in the past.

### 7.3.2 How is AI making BIM Systems more Efficient?

#### 7.3.2.1 Safety and risk mitigation

It's commonly known that construction is an accident-prone industry; one in five worker deaths are construction-related. In recent years, BIM software has improved on-site safety, making it easier to put extra safety measures in place before a project is carried out.

AI assisted BIM can take this to the next level, predicting on-site incidents before they may even happen (Myers, 2020). Through machine learning, BIM software now has the ability to analyse construction projects from an image alone and identify risks such as workers at a height, slip, trip and fall hazards.

#### 7.3.2.2 Building design

Artificial intelligence allows a user to input a design criteria or set of "rules" into a system so the machine can create the most viable output based on the user needs. In terms of

BIM, this can be used to create site footprints, floor plan designs and more. These plans are all linked to one another too, which means if the user change the measurements in the site footprint during the process, his machine will know to make the necessary adjustments across all areas of the design to ensure the highest accuracy throughout the project (Leach, 2019).

#### 7.3.2.3 Continuously updating

Systems that utilise AI are always learning from past and ongoing projects. This means that they are able to update on an almost daily basis, delivering the most efficient and effective information to construction workers as soon as possible (Leach, 2019). This will help to develop and grow the industry and help to find new design solutions quicker and allow these to be shared across the board.

#### 7.3.2.4 Improved productivity

The construction industry has been suffering in recent years due to low productivity levels. In the construction industry which makes up 7% of the global workforce, productivity has grown by just 1% in the past 20 years (Myers, 2020).

More investment into construction technology in recent years has brought about the development of AI assisted BIM, which has made processes across the board more efficient (Myers, 2020). This new technology has helped eliminate inefficiencies that were slowing things down, minimising mistakes and improving the speed of project completion. But whilst we have already come a long way, there’s still much more potential for BIM software that AI will soon unlock.

### 7.3.3 BIM-based Waste Statistics Tool

As stated earlier in this research project, the case studies and data used for framework development are limited in some areas, future research could develop BIM-based waste statistics tool. This is to integrate waste data record into federated BIM models. Similarly, the waste data for every construction project in the UK could be stored appropriately within the scope of waste management route allocated within the BIM-based tool. Achieving this would enable more accurate prediction of C&D waste along other dimensions. Integrating waste related data into BIM-based tool would provide huge opportunities for developing a structured knowledge base for waste management and would enable a standard schema for construction waste analytics.

### 7.3.4 Integration of BIM into Augmented Reality

Another area of future research could be integration of BIM-based waste management capability with immersive technologies such as Augmented Reality (AR) and Virtual Reality (VR). Achieving this would help to visualise virtual building material in real world, and how these materials and building practices could influence waste generation. AR particularly overlays digital information over the real-world environment using a piece of head-mounted display like Google Glass and Microsoft HoloLens. As such, these technologies could help to visualise and simulate waste management activities during building construction, site planning, building maintenance, transportation route planning, and hazardous waste management.

The Autodesk plugin (Tally LCA) used in this study could lead to the development of a complementary plugin for Autodesk Revit, which could integrate AI technology within the software. This will enable waste generation to be visualised vis-à-vis building project timeline and construction sequence and the life of an existing building to be monitored within the consideration of all the validated key factors according to their priority. Achieving this will enable building operators to simulate waste generation and to plan for waste collection activities effectively.

If time and resources allow, the opinion of the owner, developer and their consultant would be useful to include in the survey of the experts opinion to further support the developed decision-making factors.

### 7.3.5 Summary of Key Recommendations

In summary, the key recommendations are:

- The implementation of the decision-making framework for existing and new buildings into BIM model could be a game changer within the construction and demolition industry. This idea can be converted into reality with the creation of a plug-in tool for Revit or other BIM software.

- The key decision-making factors should be incorporated in the BIM integrated Artificial Intelligence (AI) technology in the future, as this will allow the modern technology to process all the data, implement BIM model, run LCA analyses, comply with the key decision-making criteria come up with a decision of whether to refurbish or rebuild.

- The recycling of highway waste should be utilised in the sub-base, capping or base of new highway.

- The survey of the construction expert opinions would be more improved if the opinions of the owners of the buildings are included. During the time of the survey, it was not possible to get hold of the owners of these buildings despite a lot of effort and attempts to contact them.

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# Appendix A – Maintenance level and service life of structures

***Table 1 Maintenance level (source: British Standard BS 7543, 2003)***

| Level | Description | Scope | Examples |
|---|---|---|---|
| **1** | Repair only. | Maintenance restricted to restoring items to their original function after failure. | Replacement of jammed valves; re-glazing of broken windows. |
| **2** | Scheduled maintenance plus repair. | Maintenance work carried out to a predetermined interval of time, number of operations, regular cycles etc. | Five yearly external joinery painting cycle. Five yearly recoating of roof membrane with solar reflective paint. |
| **3** | Condition based maintenance plus repair. | Maintenance carried out as a result of knowledge of an item's condition. [The condition having been reported through a systematic inspection (procedure)]. | Five yearly inspection of historic churches etc. leading to planned maintenance. |

***Table 2 Criticality of service life of structures and elements of structures (Source: Kelly, 2007)***

| | |
|---|---|
| **High criticality** | Lifelong: durability failure would cause cessation of function or major disruption and unacceptably high costs during remedial work. |
| **Medium criticality** | Efficiency of operation reduced, but remedial work or replacement can be done during normal working hours at acceptable cost. |
| **Low criticality** | Not critical. Maintenance and remedial work or replacement can be done without inconvenience and for an acceptable cost. |

***Table 3 Design service life table (Source: Kelly, 2007)***

| Component | Category | Minimum lifetime |
|---|---|---|
| Timber frame | Life-long Maintainable | 60 years |
| Windows (PVC-U) | Replaceable Maintainable | 25 years |
| Concrete frame | Life-long | 60 years |
| Roof tiles | Replaceable Maintainable | 50 years |

# Appendix B – Estimated design service life for regulation (*EDSL-R*)

## Assessment Form

***Table 4 Estimated design life assessment form (Source: Kelly, 2007)***

| **Element:** | **Structural**<br>Please tick: | **Non-Structural**<br>Please tick: |
|---|---|---|
| **Description:** | | |
| Reference service life (RSLC): (Years) | | |
| Factor: scale 0.8 to 1.2 (1.0 the nominal value for normal levels of quality, design and exposure) | | |

| | **Factor** | **Explanation** |
|---|---|---|
| **A: quality of materials** | | |
| **D: environmental exposure (internal and/or external)** | | |
| **Estimated design service life for regulation (EDSL – R) = RSLC x A x D = ____________years** | | |
| **Notes:** | | |

## Factoring Information

The factoring system is based on the following details. A nominal value of 1 should be entered if :

- the information provided does not have a positive or negative effect on the overall design service life of the building.
- information relating to the factor is unknown or cannot be adequately assessed.

The factoring approach is based on a certain amount of judgement by the applicant. The following table gives guidance on how to determine which factor to apply. The assessor can also apply a factor of, for example, 1.05 if this is considered more acceptable (Kelly, 2007). The factor applied should be justified in the assessment form set out above.

***Table 5 Factoring system (Source: Kelly, 2007)***

| **Factor** | **Description** |
|---|---|
| 0.8 | Presents a significant adverse effect on the lifetime of the material or component. |
| 0.9 | Presents an adverse effect on the lifetime of the material or component. |
| 1.0 | Presents no effect on the lifetime of the material or component. |
| 1.1 | Presents additional benefit to the lifetime of the material or component. |
| 1.2 | Presents increased benefit to the lifetime of the material or component. |

# Appendix C – Embodied energy of common building materials

***Table 6** **Embodied energy intensities for different types of building materials (Source: modified from Chau, et al., 2015)***

| Type of building material | Embodied energy intensities (MJ/kg) |
|---|---|
| Aluminum | 155.0–227.0 |
| Bitumen and asphalt | 2.6–44.1 |
| Bricks and blocks | 0.9–4.6 |
| Concrete | 0.50–1.6 |
| Galvanized steel | 35.8–39 |
| Glass | 15.0–18.0 |
| Stone, gravel and aggregate | 0.3–1.0 |
| Purified fly ash (PFA) | <0.1 |
| Paint | 20.0–81.5 |
| Plaster, render and screed | 1.4–1.8 |
| Plastic, rubber and polymer | 67.5–116.0 |
| Plywood | 8.5–15.0 |
| Precast concrete element | 2.0 |
| Reinforcing bar and structural steel | 9.9–35.0 |
| Stainless steel | 51.5–56.7 |
| Thermal and acoustic insulation | 3.0–45.0 |
| Ceramic and tile | 0.8–11.1 |

***Table 7 $CO_2$-equivalent emission values for different types of materials (Source: modified from Chau, et al., 2015)***

| Type of building material | CO2-eq emission value (in kgCO2-eq/kg) |
|---|---|
| Concrete | 0.05–5.15 |
| Steel bar | 1.03–3.51 |
| Stainless steel | 3.38 |
| Plywood mold | 0.61 |
| Cement | 0.32 |
| Copper | 1.81–3.02 |
| Brass | 2.34 |
| Cast iron | 2.34 |
| Limestone | 0.019–0.37 |
| Brick | 1.13 |
| Polyethylene | 1.58 |
| Glass | 1.06–1.50 |
| Tile | 0.74–6.78 |
| Aluminum | 8.24–11.4 |
| Bitumen and asphalt | 0.045–0.48 |
| Bricks and blocks | 0.20–0.23 |
| Galvanised steel | 2.82 |
| Glass | 0.85 |
| Stone, gravel and aggregate | 0.016–0.056 |
| Purified fly ash (PFA) | 0.01 |
| Paint | 2.95–3.56 |
| Plaster, render and screed | 0.12–0.16 |
| Plastic, rubber and polymer | 2.2–16.2 |
| Precast concrete element | 0.22 |
| Reinforcing bar and structural steel | 1.72–2.82 |
| Stainless steel | 6.15 |
| Thermal and acoustic insulation | 0.15–1.86 |
| Ceramic and tile | 0.43–0.65 |
| Plywood | 0.75–1.35 |

# Appendix D – Application of Revit/BIM Software

## Introduction

Revit is a building information modeling (BIM) software that helps constructions companies, structural engineers, architects and mechanical, electrical and plumbing (MEP) service providers manage designing, 3D visualisation, analysis and other construction operations. This software allows the user to create or import a CAD model into Revit platform. The model can either be two-dimensional (2D) or three-dimensional (3D). Revit is an Autodesk's product and is free for students studying in a higher educational institute in order to pursue their careers.

Revit includes communication management tools, which lets teams share files, simultaneously work on projects and add notes or annotations on designs in a shared workspace to facilitate collaboration across multiple departments. Its main features include process design and documentation, 2D sheets import/export, construction coordination, fabrication management and more. Additionally, engineers can generate a variety of model-based designs such as elevations, floor plans and 3D views.

## Revit Layout and Relevant Tools

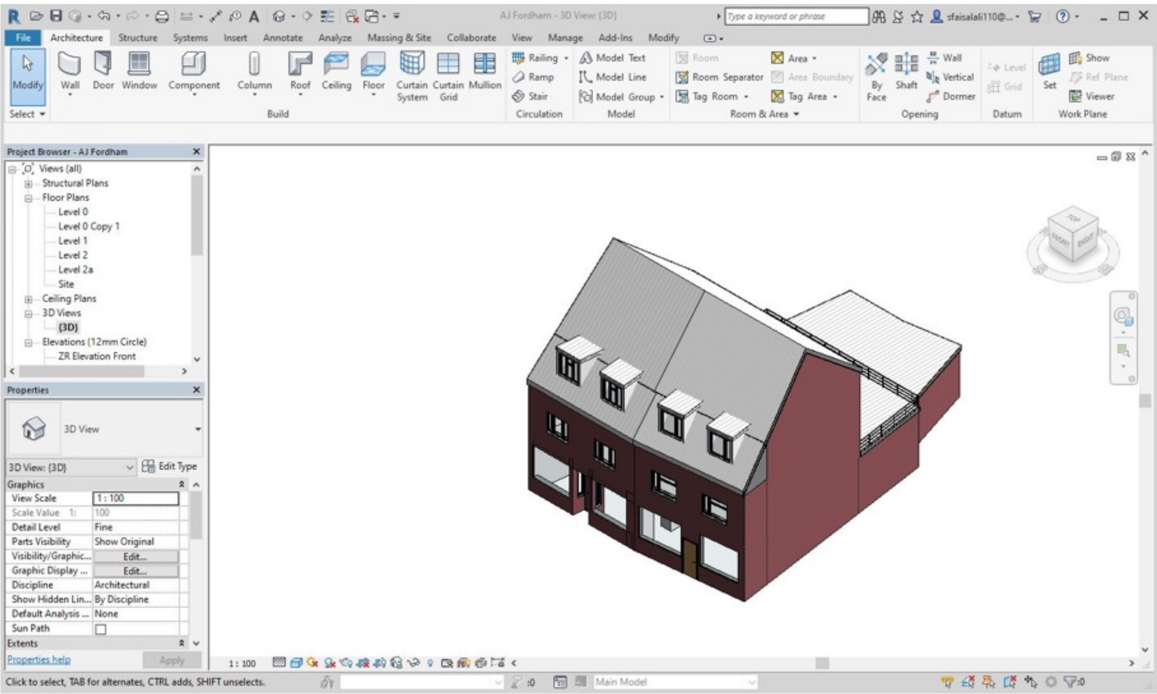



***Figure 1 Revit model layout (Source: The Author)***

Figure 1 shows a 3D model on the Revit layout. The model can either be created or imported by using the provided sets of tools within this package. To assess the building into this package, it was first imported to the Revit layout as shown in Figure 1.

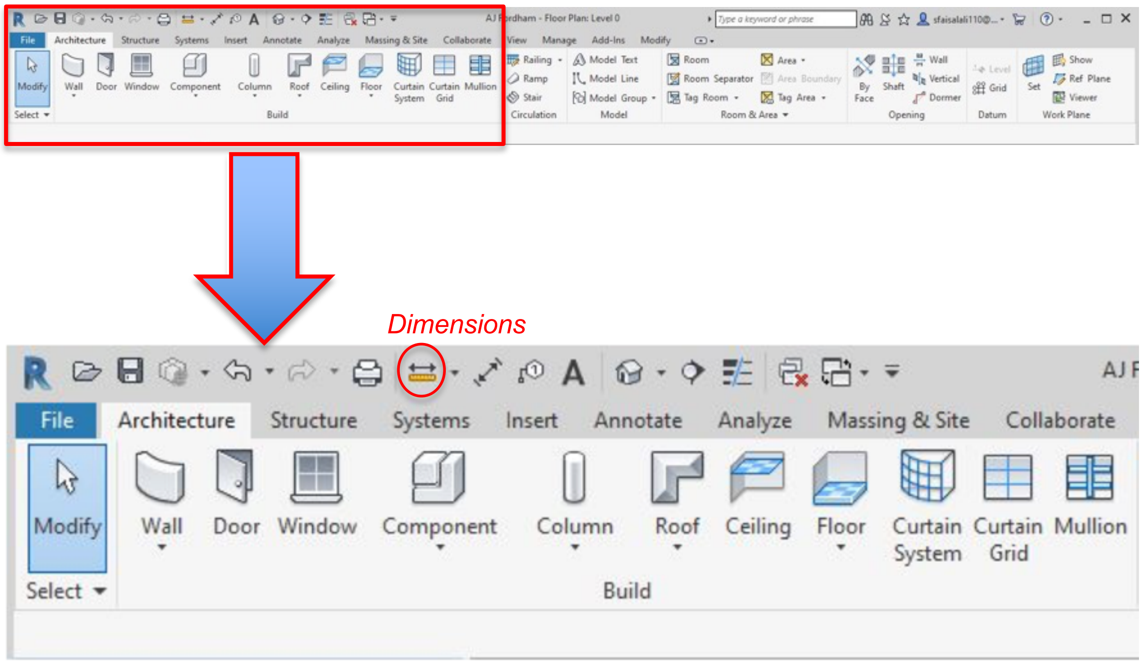



***Figure 2 Revit menu bar (Source: The Author)***

Once imported, the building was first checked for its correct dimensional values and by using the dimensions icon in the menu bar as shown in Figure 2. Also, there are building tools provided within the menu bar such as wall, door, component, column and roof etc. (see Figure 2).

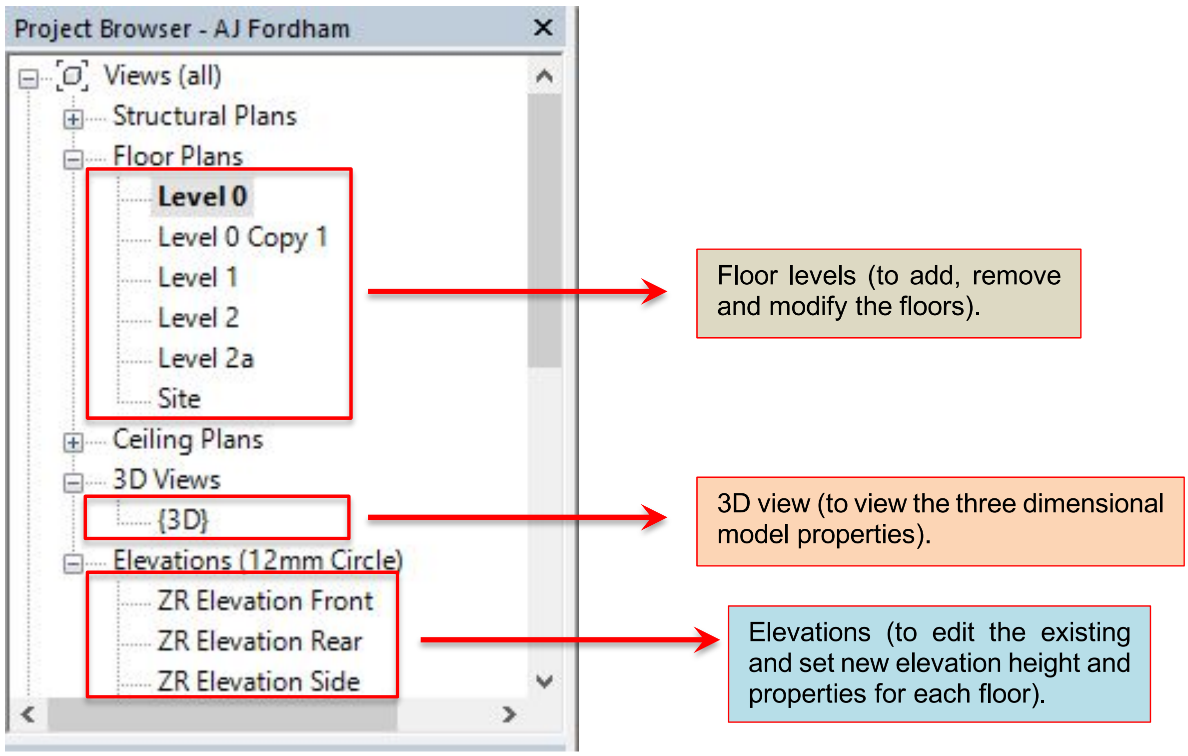



***Figure 3 Project browser (Source: The Author)***

Then on the left hand side of the Revit layout, is the project browser (see Figure 3), which helps in creating and editing the floors for the 3D model. This tool was utilised to create the additional floors and modify the existing floors of the imported building for Tally LCA analysis.

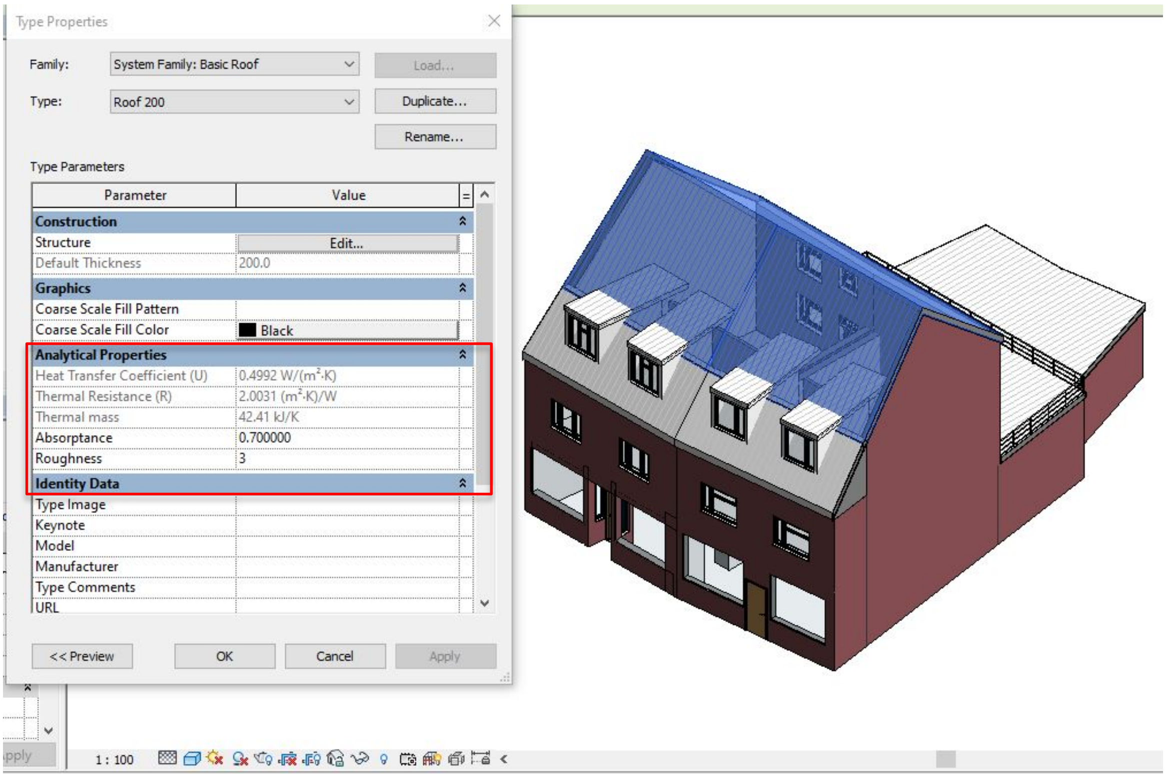



***Figure 4 Model selection (Source: The Author)***

Each component of a Revit model can be edited from the properties bar (see Figure 4). Similarly, the properties of components of the imported model were also revised in accordance with the required needs for Tally life cycle assessment. Also, the thermal properties can be seen for each material component from the same properties bar as shown in Figure 4, highlighted in red box under the 'Analytical Properties' section. The thermal properties are very important as these are used and analysed by Tally in order to generate the environmental assessment of the model. This shows how much of carbon emission has been in the past or will be generated in the future by the model. Mainly, the $CO_2$ emissions and the overall global warming potentials (GWP) are generated in the Tally report from the imported thermal properties of each of the materials used in Revit model. A component comprises of different materials such as a door, it comprises of a wood, steel or iron handle, glazing/glass and polyvinyl chloride (PVC) etc., therefore the components of a Revit model comprises of different variety of materials with different thermal properties and the design life, so the bottom line is that a component does not have a fixed design life, instead it depends on the property of each material that is installed within that particular component.

Similarly, in the case of this research project, each component of a building has been evaluated in a precise manner in Tally with the aim to achieve the maximum accuracy with respect to remaining design life of each component and the possibility of future $CO_2$ emissions in terms of the application of the key identified factors.

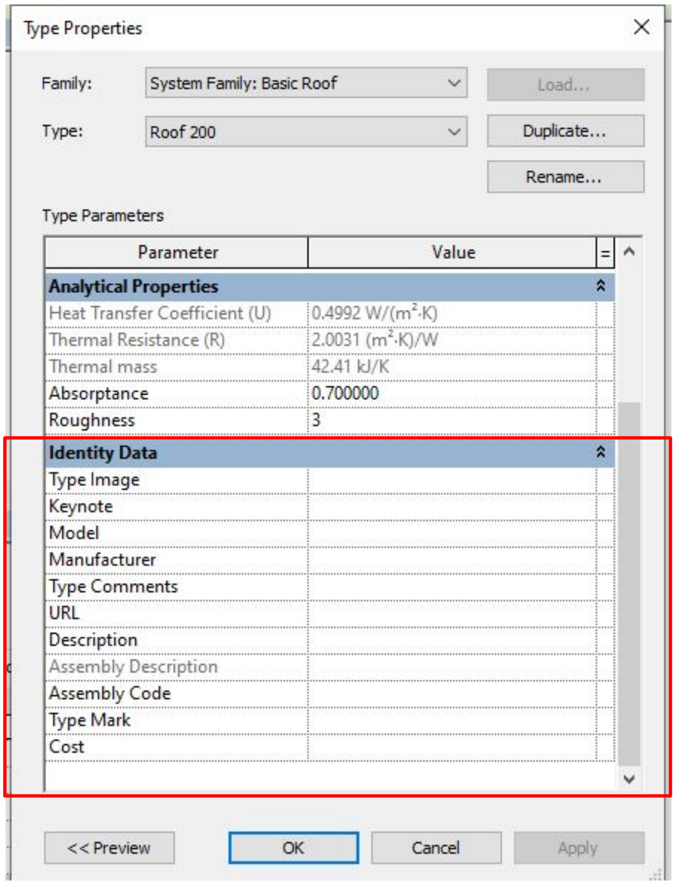



***Figure 5 Material properties (Source: The Author)***

In addition the thermal properties of the materials, important information and values of each of the components can also be input in the relevant section of the material properties (called Identity Data) by scrolling the cursor in the downward direction (see Figure 5). The important values within this section (highlighted in red box in Figure 5) include model no., manufacturer, component description, assembly code and the cost. The values for each of the models used in this research project for Tally analysis were imported from the data sheet of each of the components. The data sheet for every building component is easily accessible from the manufacturer's website portal, as these are also required for planning and building control purposes of a structure by the Local Planning Authority (LPA).

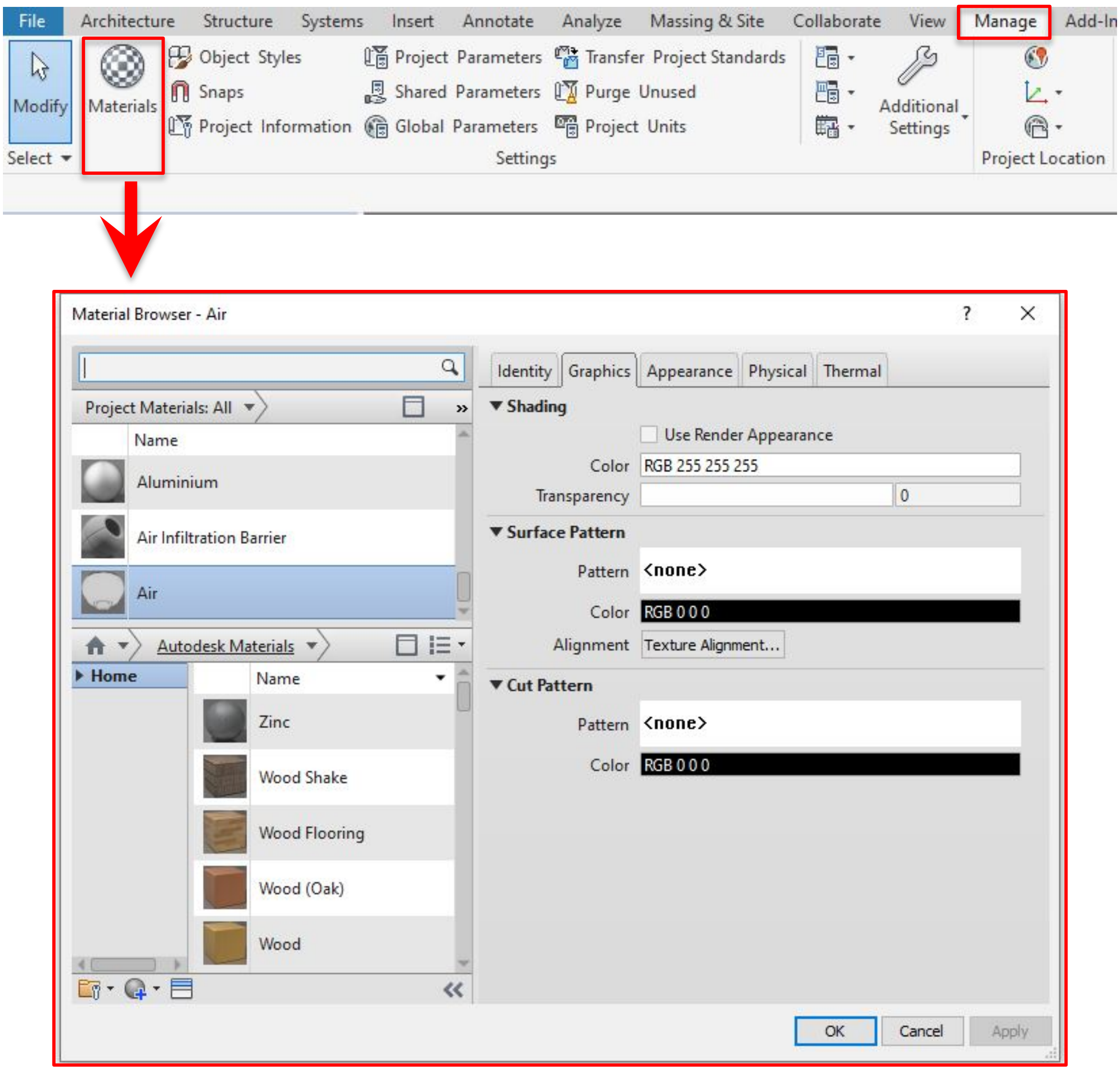



***Figure 6 Manage material editor tool (Source: The Author)***

The imported model also required adjustments to some materials, therefore the full material editor tool was used in Revit. The tool was accessed by clicking the ‘manage’ option in the menu bar and then selected ‘materials’, which resulted in the opening of a new window called ‘Material Browser’, as shown in Figure 6. This tool let the user to modify the existing material with addition to render properties (realistic model) and import new image file to replace with the existing material. Also, the user can create new material or component from this tool with random properties. In this study, this tool was used to modify the material type with updated render properties and image file to match with the existing building’s layout.

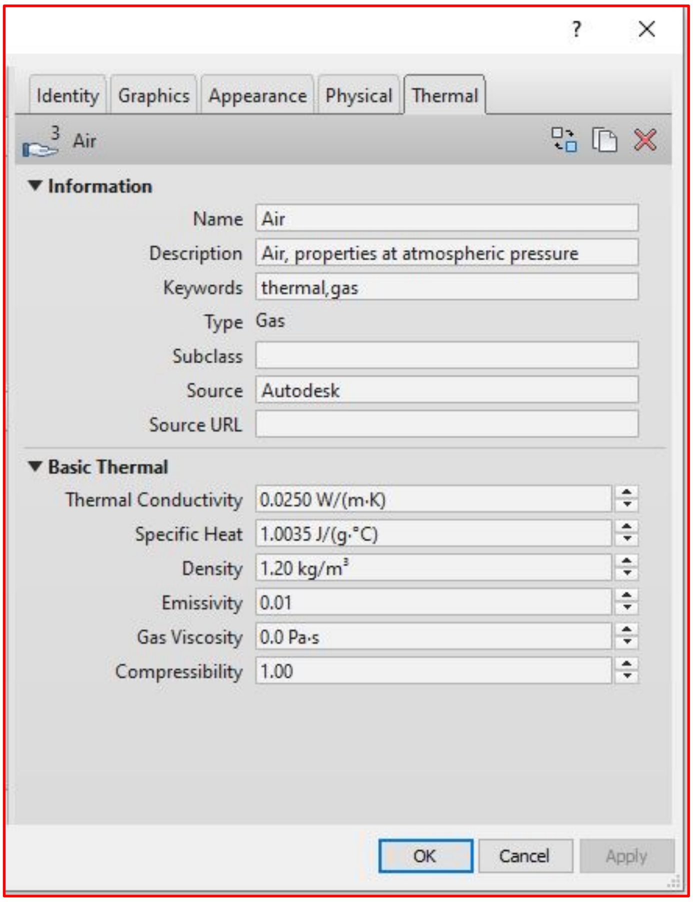



***Figure 7 Materials – Thermal properties (Source: The Author)***

Within the same window of 'material browser', the thermal properties of that particular material can also be accessed and edited as shown in Figure 7. Again, these values are available on the manufacturer's website for each of the materials. Hence, material properties can be accessed and modified from two different options in Revit. However, the second option (manage material tool) has more tools and editors as compared to the first one. For the purpose of having correct material properties, especially thermal properties, it is required to use the right set of provided tools. Using wrong material properties can result in the desired outcomes to be totally wrong and invalid, which would then require to edit and re-enter the material properties in Revit and assess the model again in Tally.

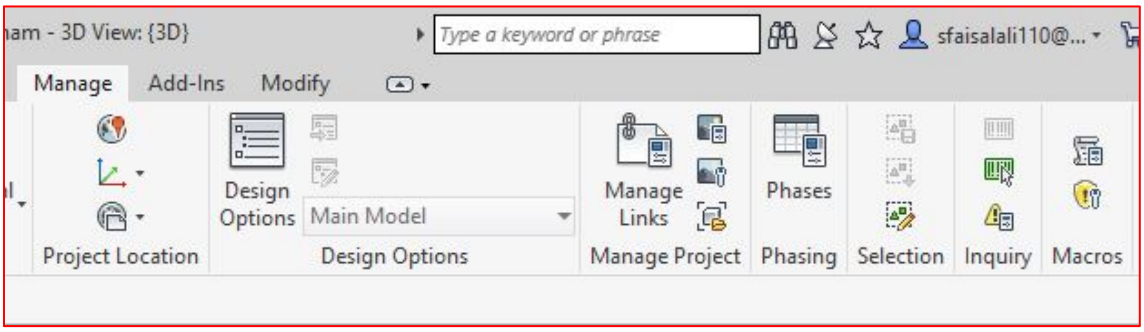



***Figure 8 Revit model phases (Source: The Author)***

Following the adjustments to the materials and components, phasing was required. Phasing is the step where different section of a model can highlighted and marked with new or old/existing construction phase (see Figure 8 and 9). Tally has the capability to detect phases of a Revit model. Phasing was necessary in the trailed models used in this research project, as the imported Revit models did not consist full details for phasing. Thus it had to be done manually within the package.

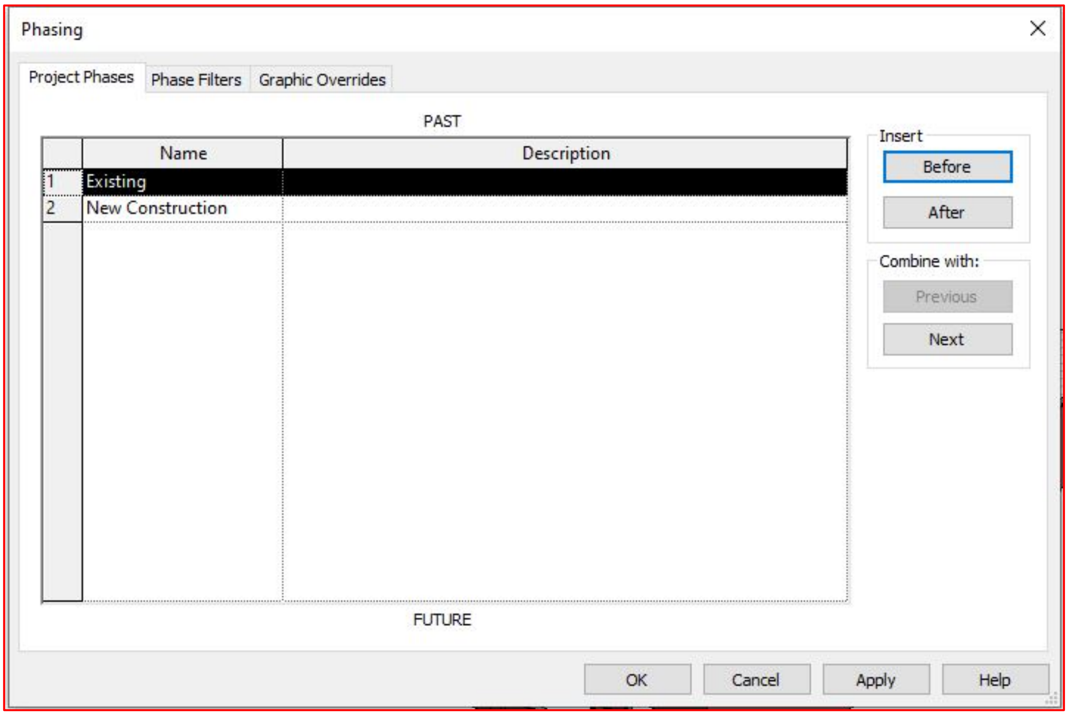
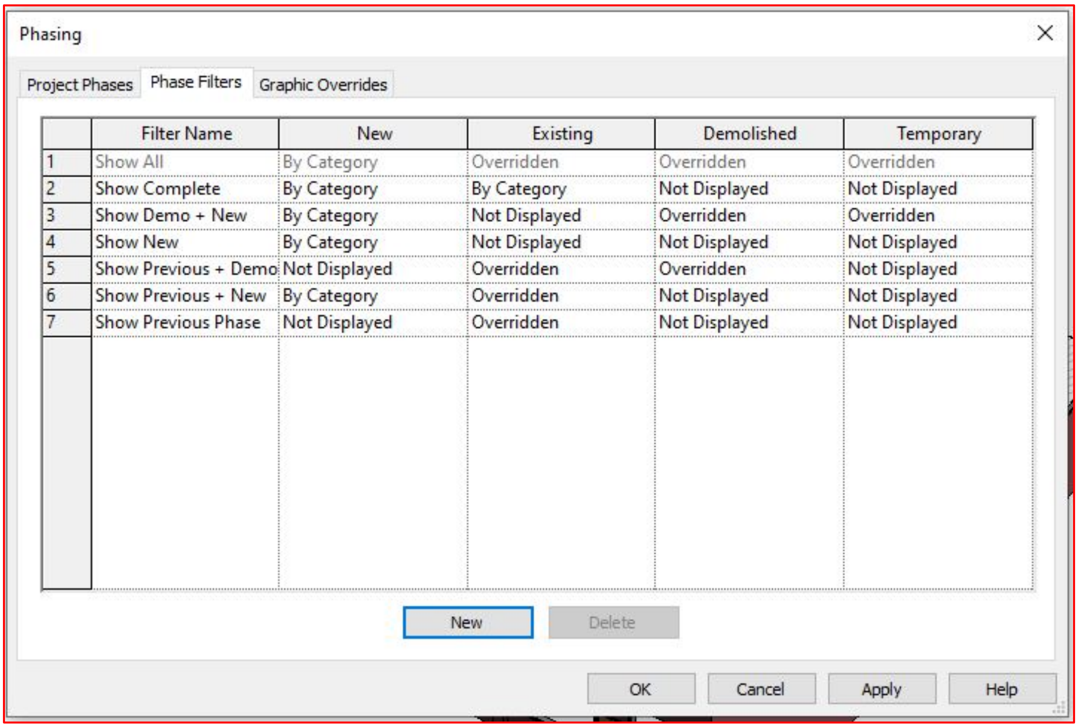



***Figure 9 Project phases (Source: The Author)***




| | Filter Name | New | Existing | Demolished | Temporary |
|---|---|---|---|---|---|
| 1 | Show All | By Category | Overridden | Overridden | Overridden |
| 2 | Show Complete | By Category | By Category | Not Displayed | Not Displayed |
| 3 | Show Demo + New | By Category | Not Displayed | Overridden | Overridden |
| 4 | Show New | By Category | Not Displayed | Not Displayed | Not Displayed |
| 5 | Show Previous + Demo | Not Displayed | Overridden | Overridden | Not Displayed |
| 6 | Show Previous + New | By Category | Overridden | Not Displayed | Not Displayed |
| 7 | Show Previous Phase | Not Displayed | Overridden | Not Displayed | Not Displayed |

***Figure 10 Phase filters (Source: The Author)***

As seen in Figure 9, there are three main sections for phasing of the a model; project phases, phase filters and graphic overrides. Each section has its own importance in terms of adding details to the model. However, the first section holds the upmost importance, it determines each component of the model whether as new build or existing. The rest two sections (as shown in Figure 10 and 11) are mainly for filtering, detailing and highlighting the marked components within the Revit model just to make every component of different construction look different than others.

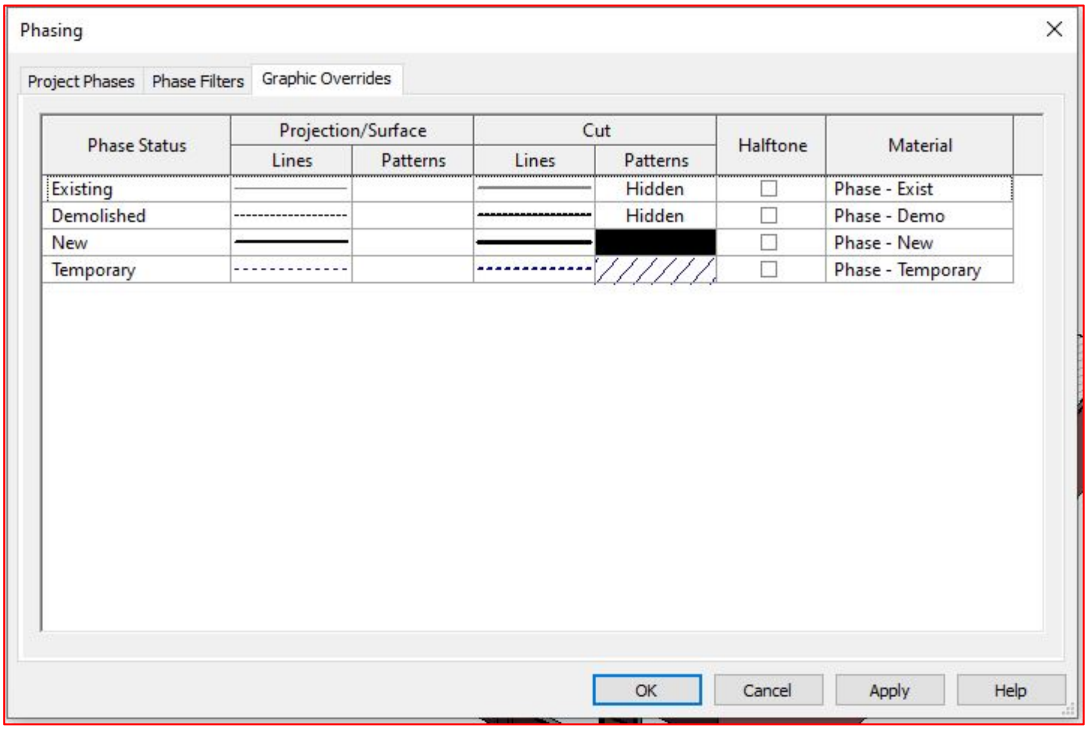


***Figure 11 Phases – Graphic overrides (Source: The Author)***

After assigning materials and components of imported Revit model into relevant categories by phasing, the model was ready to be imported in Tally within Revit via plug-in tool.

# Appendix E – TALLY's LCA Calculation Methodology

The calculation methodology used in Tally is based on the following input values collected from the building:

1. Life cycle stages;
2. Environmental impact categories.

## Life Cycle Stages

The following describes the scope and system boundaries used to define each stage of the life cycle of a building or building product, from raw material acquisition to final disposal. For products listed in Tally as Environmental Product Declarations (EPD), the full life cycle impacts are included, even if the published EPD only includes the Product stage [A1-A3].

**Product [EN 15978 A1 - A3] -** This encompasses the full manufacturing stage, including raw material extraction and processing, intermediate transportation, and final manufacturing and assembly (Tally TM, 2014). The product stage scope is listed for each entry, detailing any specific inclusions or exclusions that fall outside of the cradle to gate scope. Infrastructure (buildings and machinery) required for the manufacturing and assembly of building materials are not included and are considered outside the scope of assessment.

**Transportation [EN 15978 A4] -** This counts transportation from the manufacturer to the building site during the construction stage and can be modified by the modeler.

**Construction Installation [EN 15978 A5] (Optional) -** This includes the anticipated or measured energy and water consumed on-site during the construction installation process, as specified by the modeler (Tally TM, 2014).

**Maintenance and Replacement [EN 15978 B2-B5] -** This encompasses the replacement of materials in accordance with their expected service life. This includes the end of life treatment of the existing products as well as the cradle to gate manufacturing and transportation to site of the replacement products. The service life is specified separately for each product. Refurbishment of materials marked as existing or salvaged by the modeler is also included.

**Operational Energy [EN 15978 B6] (Optional) -** This is based on the anticipated or measured energy and natural gas consumed at the building site over the lifetime of the building, as indicated by the modeler.

**End of Life [EN 15978 C2-C4] -** This includes the relevant material collection rates for recycling, processing requirements for recycled materials, incineration rates, and landfilling rates. The impacts associated with landfilling are based on average material properties, such as plastic waste, biodegradable waste, or inert material. Stage C2 encompasses the transport from the construction site to end-of-life treatment based on national averages. Stages C3-C4 account for waste processing and disposal, i.e., impacts associated with landfilling or incineration.

**Module D [EN 15978 D]** - This accounts for reuse potentials that fall beyond the system boundary, such as energy recovery and recycling of materials. Along with processing requirements, the recycling of materials is modeled using an avoided burden approach, where the burden of primary material production is allocated to the subsequent life cycle based on the quantity of recovered secondary material. Incineration of materials includes credit for average US energy recovery rates.

## Environmental Impact Categories

A characterisation scheme translates all emissions and fuel use associated with the reference flow into quantities of categorised environmental impact. As the degree that the emissions will result in environmental harm depends on regional ecosystem conditions and the location in which they occur, the results are reported as impact potential. Potential impacts are reported in kilograms of equivalent relative contribution (eq) of an emission commonly associated with that form of environmental impact (e.g. kg $CO_2$eq).

The following list provides a description of environmental impact categories reported according to the TRACI 2.1 characterisation scheme, the environmental impact model developed by the US EPA to quantify environmental impact risk associated with emissions to the environment in the United States. TRACI is the standard environmental impact reporting format for LCA in North America. Impacts associated with land use change and fresh water depletion are not included in TRACI 2.1. For more information on TRACI 2.1, reference Bare 2010, EPA 2012, and Guinée 2001. For further description of measurement of environmental impacts in LCA, see Simonen 2014.

**Acidification Potential (AP) kg $SO_2$eq -** A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion ($H^+$) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline, and the deterioration of building materials.

**Eutrophication Potential (EP) kg Neq -** A measure of the impacts of excessively high levels of macronutrients, the most important of which are nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems, increased biomass production may lead to depressed oxygen levels caused by the additional consumption of oxygen in biomass decomposition.

**Global Warming Potential (GWP) kg CO2eq -** A measure of greenhouse gas emissions, such as carbon dioxide and methane (Tally TM, 2014). These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may, in turn, have adverse impacts on ecosystem health, human health, and material welfare.

**Ozone Depletion Potential (ODP) kg CFC-11eq -** A measure of air emissions that contribute to the depletion of the stratospheric ozone layer. Depletion of the ozone leads to higher levels of UVB ultraviolet rays reaching the earth's surface with detrimental effects on humans and plants. As these impacts tend to be very small, ODP impacts can be difficult to calculate and are prone to a larger margin of error than the other impact categories.

**Smog Formation Potential (SFP) kg O3eq -** A measure of ground level ozone, caused by various chemical reactions between nitrogen oxides (NOx) and volatile organic compounds (VOCs) in sunlight. Human health effects can result in a variety of respiratory issues, including increasing symptoms of bronchitis, asthma, and emphysema. Permanent lung damage may result from prolonged exposure to ozone. Ecological impacts include damage to various ecosystems and crop damage.

**Primary Energy Demand (PED) MJ (lower heating value) -** A measure of the total amount of primary energy extracted from the earth. PED tracks energy resource use, not the environmental impacts associated with the resource use. PED is expressed in energy demand from non-renewable resources and from renewable resources. Efficiencies in energy conversion (e.g. power, heat, steam, etc.) are taken into account when calculating this result (Tally TM, 2014).

**Non-Renewable Energy Demand MJ (lower heating value) -** A measure of the energy extracted from non-renewable resources (e.g. petroleum, natural gas, etc.) contributing to the PED. Non-renewable resources are those that cannot be regenerated within a human time scale. Efficiencies in energy conversion (e.g. power, heat, steam, etc.) are taken into account when calculating this result.

**Renewable Energy Demand MJ (lower heating value) -** A measure of the energy extracted from renewable resources (e.g. hydropower, wind energy, solar power, etc.) contributing to the PED (Tally TM, 2014). Efficiencies in energy conversion (e.g. power, heat, steam, etc.) are taken into account when calculating this result.

## TALLY's LCI DATA

### END-OF-LIFE [C2-C4]

A Life Cycle Inventory (LCI) is a compilation and quantification of inputs and outputs for the reference unit. The following LCI provides a summary of all energy, construction, transportation, and material inputs present in the study. Materials are listed in alphabetical order along with a list of all Revit families and Tally entries in which they occur, along with any notes and system boundaries accompanying their database entries. Each entry lists the detailed scope for the LCI data sources used from the GaBi LCI database and identifies the LCI data source.

For LCI data sourced from an Environmental Product Declaration (EPD), the product manufacturer, EPD identification number, and Program Operator are listed. Where the LCI source does not provide data for all life cycle stages, default North American average values are used. This is of particular importance for European EPD sources, as EPD data are generally only provided for the product stage, and North American average values are used for the remaining life cycle stages.

Where specific quantities are associated with a data entry, such as user inputs, energy values, or material mass, the quantity is listed on the same line as the title of the entry.

Specific end-of-life scenarios are detailed for each entry based on the US construction and demolition waste treatment methods and rates in the 2016 WARM Model by the US Environmental Protection Agency except where otherwise specified. Heterogeneous assemblies are modeled using the appropriate methodologies for the component materials (Tally TM, 2014).

1. **End-of-Life Landfill**

- **Scope:** Materials for which no recycling or incineration rates are known, no recycling occurs within the US at a commercial scale, or which are unable to be recycled are landfilled. This includes glass, drywall, insulation, and plastics. The solids contents of coatings, sealants, and paints are assumed to go to landfill, while the solvents or water evaporate during installation. Where the landfill contains biodegradable material, the energy recovered from landfill gas utilisation is reflected as a credit in Module D.

- **LCI Source:** US: Glass/inert on landfill ts (2017) US: Biodegradable waste on landfill, post-consumer ts (2017) US: Plastic waste on landfill, post-consumer ts (2017).

2. **Concrete End-of-Life**

- **Scope:** Concrete (or other masonry products) are recycled into aggregate or general fill material or they are landfilled. It is assumed that 55% of the concrete is recycled. Module D accounts for both the credit associated with off-setting the production aggregate and the burden of the grinding energy required for processing.
- **LCI Source:** US: Diesel mix at refinery ts (2014) GLO: Fork lifter (diesel consumption) ts (2016) EU - 28 Gravel 2/32 ts (2017) US: Glass/inert on landfill ts (2017).

3. **Metals End-of-Life**

- **Scope:** Metal products are modeled using the avoided burden approach. The recycling rate at end of life is used to determine how much secondary metal can be recovered after having subtracted any scrap input into manufacturing (net scrap). Net scrap results in an environmental credit in Module D for the corresponding share of the primary burden that can be allocated to the subsequent product system using secondary material as an input. If the value in Module D reflects an environmental burden, then the original product (A1-A3) contains more secondary material than is recovered.
- **LCI Source:** Aluminum - RNA: Primary Aluminum Ingot AA/ts (2010) Aluminum - RNA: Secondary Aluminum Ingot AA/ts (2010) Brass - GLO: Zinc mix ts (2012) Brass - GLO: Copper (99.99% cathode) ICA (2013) Brass - EU-28: Brass (CuZn20) ts (2017) Copper - DE: Recycling potential copper sheet ts (2016) Steel - GLO: Value of scrap worldsteel (2014) Zinc - GLO: Special high grade zinc IZA (2012).

4. **Wood End-of-Life**

- **Scope:** End of Life waste treatment methods and rates for wood are based on the 2014 Municipal Solid Waste and Construction Demolition Wood Waste Generation and Recovery in the United States report by Dovetail Partners, Inc. It is assumed that 65.5% of wood is sent to landfill, 17.5% to incineration, and 17.5% to recovery.
- **LCI Source:** US: Untreated wood in waste incineration plant ts (2017) US: Wood product (OSB, particle board) waste in waste incineration plant ts (2017)

US: Wood products (OSB, particle board) on landfill, post-consumer ts (2017)
US: Untreated wood on landfill, post-consumer ts (2017) RNA: Softwood lumber CORRIM (2011).

# Appendix F – Sample and Raw Data of Experts opinion survey questionnaire

1. Age group. *

   *Mark only one oval.*

   - 18-24
   - 25-35
   - 36-45
   - 46-50
   - <50

2. Which of the following is the most relevant to your job role? *

   *Mark only one oval.*

   - Engineer
   - Building Surveyor
   - Quantity Surveyor
   - BIM Specialist
   - HSE
   - Supervisor
   - Assistant Manager
   - Site Manager
   - Construction Manager
   - Project Manager
   - Project Director
   - Other: ____________________

3. How many years have you worked within the construction Industry in a professional role?

   *Mark only one oval.*

   - 1-10 years
   - 10-15 years
   - 16-25 years
   - 26-35 years
   - More than 35 years

4. How satisfied are you with the average amount of waste (100 - 120 million tonnes) generated every year from the Construction and Demolition (C&D) industry? i.e. is it too much waste generated or is it reasonable/sustainable?

*Mark only one oval.*

- ◯ Very satisfied
- ◯ Somewhat satisfied
- ◯ Neither satisfied nor dis-satisfied
- ◯ Not satisfied
- ◯ Strongly dis-satisfied
- ◯ Other: ____________________

5. When is the C&D waste scheduled to be collected from your site? *

*Mark only one oval.*

- ◯ Daily
- ◯ Weekly
- ◯ Every two weeks
- ◯ Monthly
- ◯ Other: ____________________

6. Which material produces the maximum amount of waste on site? *

*Check all that apply.*

- ☐ Plasterboard / gypsum
- ☐ Wood / timber
- ☐ Concrete
- ☐ Insulation
- ☐ Metal
- ☐ Iron
- ☐ Plastic
- ☐ PVC
- ☐ Electrical wires
- ☐ Tiles / ceramic
- ☐ Stones
- ☐ Sand / clay

Other: ☐ ____________________

7. In your opinion, can the waste be further reduced by introducing new training schemes for effective was management?

   *Mark only one oval.*

   - Yes
   - No
   - Other: ____________________

8. In your opinion, should there be new policies introduced in order to reduce the waste generation from C&D projects?

   *Mark only one oval.*

   - Yes
   - No
   - Other: ____________________

9. In your opinion, is BIM a useful tool for managing and reducing C&D waste? *

   *Mark only one oval.*

   - Yes
   - No
   - Other: ____________________

10. Following on from the previous question, how useful is BIM for waste efficient design of a newly constructed building? Please explain in detail.

11. Based on your experience, how has the implementation of BIM benefited your company/organisation? (if you have never used BIM, please go to Question 12).
*Check all that apply*

- ☐ Improved efficiency
- ☐ Improved collaboration within the supply chain
- ☐ Reduced costs
- ☐ Improved client relations
- ☐ Reduced accidents
- ☐ Improved resource allocations
- ☐ Ability to explore "what if" scenario's
- ☐ Reduction of waste
- ☐ BIM didn't make any tangible difference to the running of the project.
- ☐ BIM was only used because it was a client requirement.
- ☐ Overall the use of BIM was a negative experience.

Other: ☐ ____________________

12. How is the C&D waste disposal used and utilised at a particular building site? Please explain in detail.

____________________
____________________
____________________
____________________
____________________

13. In your opinion, which phase of construction contributes to the maximum amount of the total waste? *
*Check all that apply.*

- ☐ Slab construction
- ☐ Reinforcement
- ☐ Construction of concrete structure
- ☐ Dry lining / internal partition walls
- ☐ Ceiling works
- ☐ Electrical works
- ☐ Plumbing works
- ☐ Roofing
- ☐ Carpentry (doors, skirtings, frames etc.)
- ☐ Flooring
- ☐ HVAC works

Other: ☐ ____________________

14. In your opinion, which area on site (construction area, storage, etc.) generates the most amount of waste and why? Please explain in detail.

15. In your opinion, how effective is the site waste management plan (SWMP)? Please rate on a scale of 1 to 10.

*Mark only one oval.*

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Not at all effective | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Extremely effective |

16. In your opinion, should there be the fuel-efficient vehicles introduced to transport the waste in order to reduce the CO2 emission and why?

*Mark only one oval.*

- Yes
- No
- Other: ______

17. From your experience, do you think that in some instances, useful material (that could be reused) are al being dumped into the waste?

*Mark only one oval.*

- Yes
- No
- Other: ______

18. Do you reuse any amount of waste/material waste during construction or demolition?

*Mark only one oval.*

- Yes
- No
- Other: ______

19. In your opinion, is the recycling of construction waste significant in financial terms and why?
*Mark only one oval.*

- Yes
- No
- Other: ____________________

20. In your opinion, should there be an approved methodology for identifying cost savings, specifically in waste reduction? *
*Mark only one oval.*

- Yes
- No
- Other: ____________________

21. In your opinion, which is the most recommended and powerful CAD software with advance BIM tool/technology and why?

____________________
____________________
____________________
____________________
____________________

22. In your opinion, does BIM plays a vital role in the reduction of waste from any C&D project? *
*Mark only one oval.*

- Yes
- No
- Other: ____________________

23. In your opinion, can BIM be economically useful in identifying the useful material and avoid it being dumped into waste? Please explain in detail. *

*Mark only one oval.*

- Yes
- No
- Other: ____________________

24. Do you think that the introduction of a new BIM integrated framework will be useful in the reduction of waste and why? *

*Mark only one oval.*

- Yes
- No
- Other: ____________________

25. Overall, where do you see BIM within the future of C&D industry?

26. Please list the key factors that can be used by experts to decide on whether to demolish or refurbish/reuse an existing building. *

27. Please select as many from the following identified factors, that in your opinion, are the key factors for decision-making. *

*Check all that apply.*

- [ ] Existing condition of the building
- [ ] Age of the building
- [ ] Remaining design life
- [ ] Historical significance
- [ ] Environmental impact
- [ ] Maintenance and repair
- [ ] Cost comparison
- [ ] Demolition cost
- [ ] Refurbishment cost
- [ ] Time comparison
- [ ] Material waste estimation and transportation

Other: [ ] ______________________

28. In your opinion, who will benefit the most from the key factors for the decision-making?*

*Check all that apply.*

- [ ] Client
- [ ] Stakeholders
- [ ] Designers
- [ ] Contractors
- [ ] Surveyors

Other: [ ] ______________________

29. Would you like to receive feedback on the results of this survey? *

*Mark only one oval.*

( ) Yes

( ) No

30. If you selected "Yes" please provide your contact details below: