Safak Muslu

Tony Gee and Partners LLP

A Designer Toolkit to integrating Circular Economy Principles to UK Infrastructure

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Contents

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1. Glossary

Term	Definition
Reinforced Concrete	Concrete in which steel is embedded in such a manner that the two materials act together.
Universal Column (UC)	Structural steel. typically formed of 2 flanges and a web forming a 'H' shape section.
Continuous flight auger (CFA) Piles	Piles are drilled and concreted in one continuous operation. Reinforcement is placed into the wet concrete after casting.
Circular Hollow Section (CHS)	Structural steel. Described as a Circular hollow section.
Ekki Mat	Hardwood Timber planks used typically for supporting cranes for heavy lifting.
Engineering Granular Fill	Manmade crushed rock or gravel.
Pre-cast concrete panel	Reinforced Concrete beam made offsite and transported and installed on site.
Timber panel	Softwood Timber planks.
King Post Wall	Comprised of reinforced concrete or timber panels spanning between UC Sections. Concrete bored piles embedded into ground.
Contiguous Pile Wall	Series of individual vertical Reinforced Concrete P**iles.**
Reinforced Concrete Gravity Wall	Vertical supported retaining wall formed of a base and stem created an 'L' shaped structure.
Modular Design	Design that is constructed with standardized units or dimensions for flexibility and variety.
In-situ	Also means 'on-site' or 'locally'.

2. Introduction

Circular Economy in construction is a concept that aims to reverse the current 'take – make – waste' model and incentivise value driven, recovery and regenerative thinking into the design and management of the built environment.

This report investigates the impact of Circular Economy principles to promote sustainable development into the design and management of infrastructure projects in the UK. Engineers today have a lack of practical tools to measure the principles of a Circular Economy related to construction. Focusing on the Circular Economy of solutions will lead to designing out waste and pollution, integrating a closed-loop approach that utilises the products value and enables the regeneration of natural systems.

This report will undertake the following:

- Review the existing body of research and frameworks developed in academia and by policymakers for the integration of Circular Economy practice in infrastructure projects. This will focus on the analysis of the whole life cycle of infrastructure and considers practical tools that enable consultancies to integrate the key principles.
- Propose a new qualitative assessment toolkit that aids decision-makers to integrate Circular Economy thinking to infrastructure projects. This includes the incorporation of practical monitoring mechanisms that maximise recoverability and reusability of the project over the entire life cycle. The proposed assessment tool will be trialled on active and completed projects in the highways and railways sector, to analyse the impact on the project and determine missed opportunities for improving resource efficiency through Circular Economy integration.

The primary advantages of improved Circularity in infrastructure projects will be discussed, including significant reduction in the environmental impact, improved resource efficiency and enhanced socio-economic value of the project. However, it will be shown that the lack of knowledge of Circular Economy and synergy amongst contractors, clients, suppliers, and consultants is the leading hindrance for improved Circularity in infrastructure.

Providing engineers with a greater awareness and technical support regarding Circular economic principles can lead to improved preservation of natural capital by limiting the use of finite resources and associated Greenhouse Gas Emissions. Combined with the present shift in behavioural patterns and technology within the industry, Circular economic thinking will encourage engineers to deliver infrastructure that incorporates the values of sustainable development.

2.1. Aims

The aim of this research is to provide a basis of information that will encourage early-stage integration of Circular Economy to infrastructure projects. An assessment tool is developed for design engineers to incorporate the principles of Circularity by integrating key features into the design that improves the efficiency of disassembly and reinstating construction materials back into the built environment domain. By abiding to the guidelines proposed in the assessment, as well as the future considerations discussed in the report, it is envisaged that Circular Economy in infrastructure is fulfilled to meet the greater goals of sustainable development.

2.2. Objectives

Based on the aim outlined above, the following are the objectives set out for this research:

- Outline the definition and principles of Circular Economy in the construction industry and how it will play an imperative role in upholding the goals of sustainable development is outlined;
- Understand the history of Circular Economy and how its emergence has evolved over the last 50 years.
- Determine the benefits of Circular Economy and the limiting factors that have prevented the full fruition within the built environment.
- Outline the industry-wide enablers that will ensure the transition towards Circular Economy practice.
- Discuss various case studies that highlight the benefits of Circular Economy.
- Outline the keyways that design engineers can be involved in incorporating Circular Economy to a project focusing on the concept of 'Design for Disassembly and Reuse'.
- Develop a design for disassembly checklist to encourage Circular Economy-based decision-making tool, focusing primarily on maximising the efficiency of disassembly and incorporating back into the built environment.
- Trial the toolkit on two permanent and temporary works projects and discuss the results by determining the benefits and limitations of the assessment method;
- Summarise of how Circular Economy can be incorporated into construction industry and discussing a range of required actions to enable an industry and business wide change in implementing Circular Economy principles into the construction industry. In addition, summarise the key observations made in the toolkit results and suggest future works required to improve the assessment.

2.3. Methodology: how the research was undertaken

This paper is segmented into three key sections:

- An initial literature review to contextualise Circular Economy in infrastructure as a distinct and adolescent concept that aims to welcome new initiatives that promote environmental, economic, and social security and prosperity;
- A qualitative assessment of the results from the trialling of the design for disassembly toolkit developed in this research for enabling design engineers to follow guidelines to design materials and construction elements for disassembly and reuse. The section will gauge the effectiveness of the decision-making tool and learn its benefits and limitations; and
- Concluding remarks on the envisaged future for Circular Economy and its role in satisfying the needs for an infrastructure industry that promotes the values of sustainable development. Outline the effectiveness.

3. Defining Sustainable Development

Sustainable Development is a term used broadly throughout all spectrums of industry across the world but is mainly the driving force for remedying the significant issues facing the human population and the natural environment. The aim of sustainable development is to ensure the long-term stability of the economy, society, and environment to preserve resources for future generations. The first widely adopted:

'meeting the needs of today without compromising the ability of future generations to meet their own needs (Brundtland Commission, 1987)'

Sustainable development has continuously evolved in definition and application. At present, it is defined by three co-dependent features (Figure 1), referred to as the three pillars of sustainability:

- Social
- Economic
- Environmental

The broad aim of sustainable development in today's world is to ensure 'economic development that is socially inclusive and environmentally sustainable' (BRE, 2019). The term is driven by two key concepts:

- The needs, especially the essential needs of the world's poor; and
- Limitations that prevent the state of technology and social construct advancing beyond the environments capability to fuel it.

Figure 1 represents a simplified illustration of how all three aspects are equally balanced and intertwined to meet the goals of sustainable development.

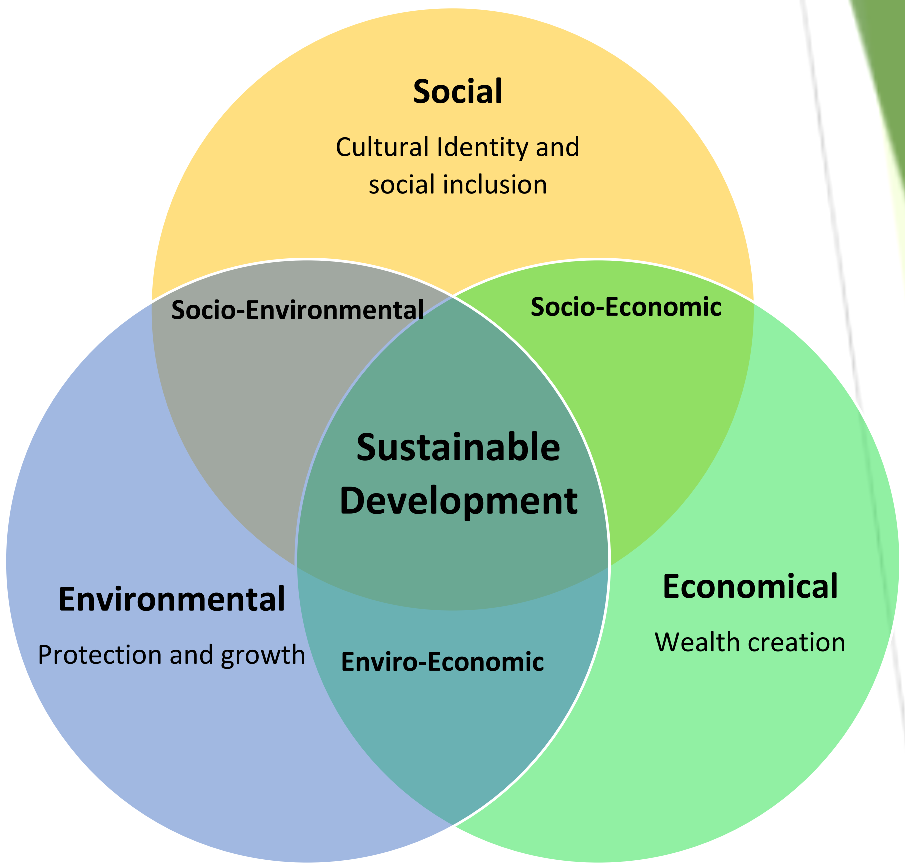


Figure 1. Outline of the three pillars of sustainable development and the interactions between the three to form sustainable development (United Nation, 2020).

3.1. Sustainable Development Goals

In 2015, all UN states came together to formulate the '2030 Agenda for Sustainable Development'. The purpose of this was to create a shared blueprint for all UN members to follow and maintain the long-term social, economic, and environmental stability of the world. What followed was the '17 UN Sustainable Development Goals 2015' (see Figure 2) which provides targets for what should be achieved in the next 15 years. The emphasis is on a "global partnership" involving collaboration between governments, the Major Groups (Women, Children & Youth, Indigenous Peoples, NGOs, Local Authorities, Workers and Trade Unions, Business and Industry, Scientific and Technological Community and Farmers), and other stakeholders to take action in ending poverty, improve health and education, reduce inequality, and stimulate growth in the economy – all while promoting renewable energy and actively preserving natural resources.

Figure 2. Outline of the 17 Sustainable Development Goals 2015 developed by the UN (Mckinsey Center for Business and Environment, 2018)

4. Sustainable Development in Infrastructure

Infrastructure plays a critical role in Sustainable Development. Its influence is rooted in the range of major sectors such as transport, energy, and water management that all ensure the functionality of society is maintained. Infrastructures role in delivering the three pillars of sustainable development is exemplified, but not exclusive to, by the following case studies:

- Economic: In 2013, the failure of the Dawlish sea wall in the south-west of England, which was destroyed during a storm, cost the UK economy approximately £1.2 billion as it supports a critical route for transport connection to the south-west of England (The Resiliance Shift, 2018).
- Environmental: Infrastructure is accountable for 16% of the UK's annual carbon emissions, and responsible for 37% attributable to the material and energy required to build, maintain, and operate infrastructure (BusinessGreen, 2020).
- Social: Infrastructure can be a tool for unlocking social mobility. In recent years, nations such as Sudan and Tanzania have introduced solar power in schools which enabled an increase in completion rates at primary and secondary schools from less than 50% to almost 100% (The Resiliance Shift, 2018).

By concentrating on the goals of Sustainable Development, the goal of building resilient infrastructure can be achieved. Infrastructure investment in the UK's commitment to Sustainable development continues to gain momentum. This is exemplified by the National Infrastructure Delivery Plan (NIDP) which outlines £483 billion of investment in over 600 infrastructure projects and programmes. There will be increased pressure on the local availability of construction materials and associated logistical pinch points. The following outlines the key objectives that are outlined in the NIDP to ensure infrastructure upholds sustainable development goals (Spencer, 2016):

- Keep resources in use for as long as possible.
- Extract maximum value from resources while in use.
- Recover and regenerate products and materials at the end of design life.
- Keep products, components and materials at their highest utility.

4.1. Challenges hindering Sustainable Development in Infrastructure

4.1.1. The Current 'take-make-waste' Model

The industry currently embraces a severely entrenched and long-practiced linear approach of 'take-make-waste' model. This entails the extraction of materials, harnessing them to manufacture a product or service, and capitalising on the product by selling it to consumers. It is then discarded when the design life is reached or is no longer fit for purpose.

In 2010, 65 billion tonnes of raw material entered the market, which is expected to rise to 82 billion by 2020. Figure 3 illustrates the current 'take-make-waste' model.

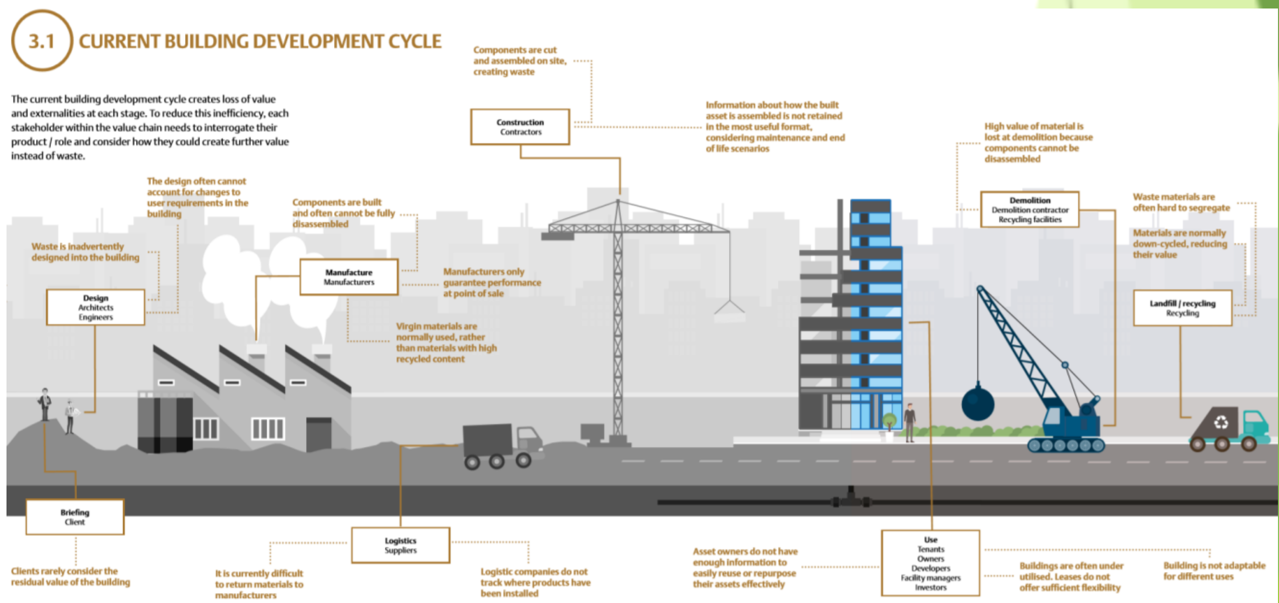


Figure 3. Current 'take-make-waste' model used in the construction industry (CE100, 2019)

4.1.2. Construction waste in infrastructure

One of the main detriments of infrastructure in the UK is its contribution to construction waste. Research conducted by the Department for Environmental Food & Rural Affairs (DEFRA) (Service, 2020) to understand the UK waste estimates and outlined key findings:

- The UK generated 221 million tonnes of waste in 2016, with England responsible for 85% of the UK total.
- The UK is also estimated to generated 41.1 million tonnes of commercial and industrial waste in 2016. In 2018, this dropped to 37.2 million tonnes.

The construction industry accounts for 60% of UK materials use (Council, 2020). Subsequently, under the C Waste Framework Directive, a target of 70% recovery of non-hazardous construction and demolition waste by 2020 was set (Service, 2020). Research conducted by DEFRA shows that the rate of recovery (generation vs recovery) between 2010 and 2016 has remained consistently at 91%. In 2016, the two largest waste materials that comprise the waste generation in the UK were mineral wastes and soils (27% and 27% respectively).

In the EU (pre-Brexit), construction, and demolition accounted for 25% of all waste generated (Thromark, 2017). The pattern of losses in material value is also seen in the USA, where only 20-30% of all construction material is recycled or re-used. This stems from the fact that buildings are designed and built in a way that is difficult to breakdown (Guide, 2020). This means that the materials used in a building are irretrievable, subsequently diminishing the value of materials after the asset owners have no use of it. Moreover, data collected from the Environmental Agency (EA) in the UK show that increases in landfill waste have largely been due to materials from soils and stone waste. Indeed, in 2016, soils made up 55% of the tonnage received by landfill sites.

Thus far, some steps have been have taken to reduce the quantity of waste produced from construction. For example, of all the waste treatment methods, recycling and other recovery was the most common form of treatment in the UK, accounting for 104 million tonnes (49%) in 2016.

4.1.3. Resource Scarcity

With global population and consumption rates increasing, an overbearing pressure is being exerted on the natural world. As well as being a dominant contributor to waste, the UK construction sector is one the greatest consumers of material. The continued consumption of material made from finite sources has subsequently caused rising prices of resources. Between 2019 and 2023, it is forecasted by the RICS that construction material cost is expected to rise by approximately 21%. The versatile nature of construction steel prices is highlighted by the figure below, which shows a sharp increase after the 2008 recession.

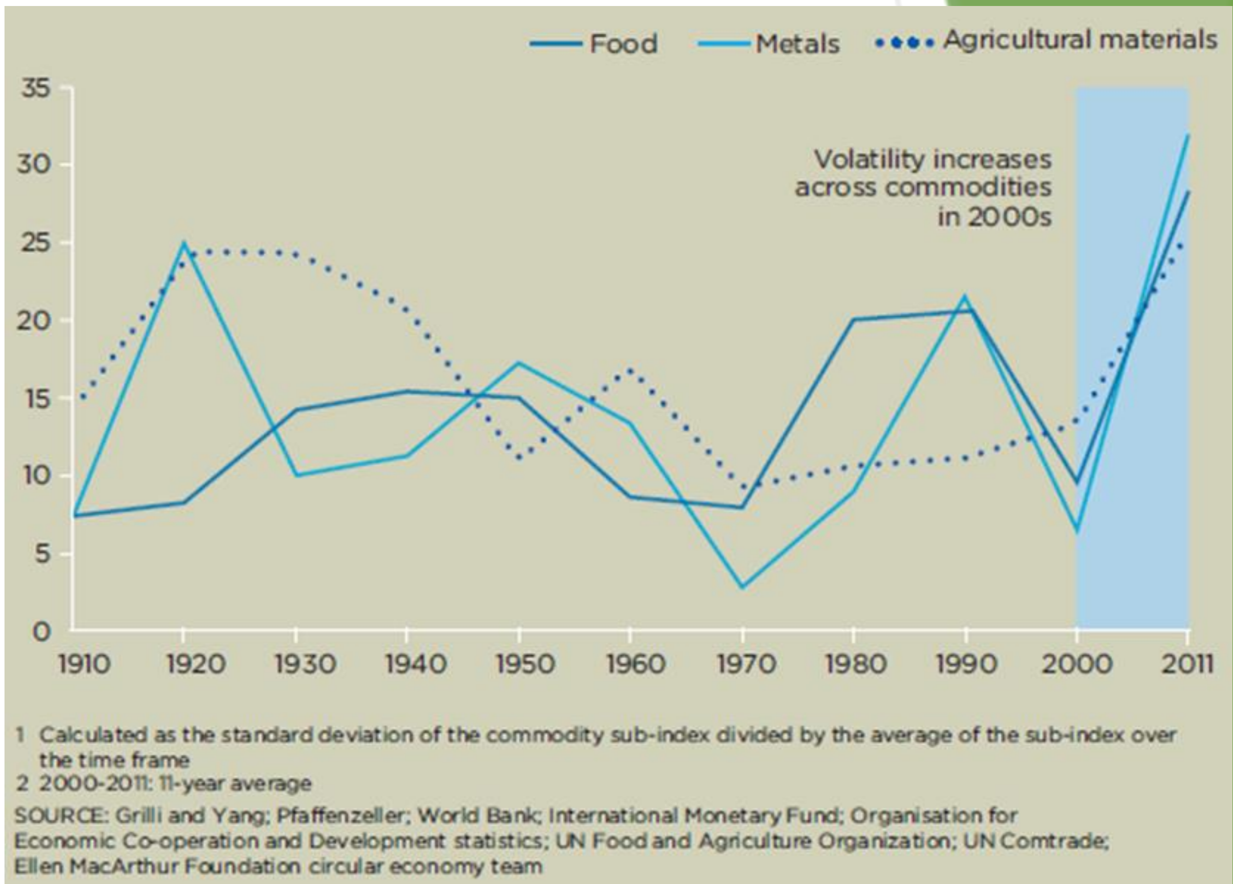


Figure 4. Graph produced by the Ellen MacArthur Foundation highlighting the drastic rise in metals since 2011 (Ellen MacArthur Foundation, 2015)

A survey undertaken by the UK Construction Group (UKCG) showed that 77% of respondents, which included over 300 contractors and suppliers, said that the rising prices of resources was highly important and 70% said that resource scarcity was the main driving force for this (UKCG, 2017). This highlights that there is genuine concern that price and availability of resources is going to harm the construction industry. By finding a way to improve the value of disused, excavated and demolished material, the strain of increased cost of resources may be reduced.

4.1.4. Rising Population

As resources become scarcer, the issue of population growth becomes propelled. Indeed, it is projected that the world population will reach 9.8 billion by 2050 with the population growing by roughly 83 million people a year (United Nation, 2020). Running parallel with this, it is estimated that urban zones are expected to house close to 66% of the world's population by 2050. The construction of a city is enormously resource intensive and constructing the necessary infrastructure to facilitate this will be even more so (Capacity4dev, 2020). The motivation to steer towards a more Circular approach to resource management in construction is ever more critical to handle to pressures of rising population and urbanisation.

4.1.5. CO2 Emissions

Infrastructure plays a key role in materialising the concerns surrounding carbon emissions. While delivering over £500 billion worth of infrastructure investment between 2016 and 2030, there are now active steps being taken to reduce the greenhouse gases in order to uphold the governments legal pledge to reduce carbon emissions by 80% in 2050. As noted previously, the UK Infrastructure industry accounts for 16 % of total carbon emissions.

A main source of this contribution to CO_2 emissions is concrete. The use of concrete constitutes a predominant amount of material used in the construction of infrastructure, with the production and transportation of concrete contributing to 5% of the total CO_2 emissions in the world (Chemistry World, 2008).

Cement is a vital ingredient in concrete. However, the process of creating cement is energy intensive with associated carbon emissions. In 1990, the carbon dioxide emission attributed to the production of cement in the United Kingdom was 13.8 million metric tonnes. Although this number has reduced to 7.4 million metric tonnes in 2013, it is still considerably high and is exemplary of the large quantity of material produced that is damaging to the world's ecosystem (N.Sonnichsen, 2020).

The current model of production and management of resources in infrastructure seeks to promote short-term consumption and is directing the planet towards an unsustainable paradigm. Many of the concerns that jeopardise the long-term and sustainable development of infrastructure can be remedied by derailing towards a new 'system of resources where reduction, reuse and recycling of elements prevails' (Acconia, 2020).

5. The Solution: Circular Economy

It is vital that the industry begins to move away from the current 'take-make-dispose' approach that extracts virgin materials and creates new products which are used potentially once for a single purpose and disposed once their original purpose expires. Infrastructure must start to think about extending the longevity of the materials it produces and deploy a Circular approach to resource management to minimise the strain that waste disposal has imposed on society.

The noticeable increase of risk and higher resource price and supply disruption, rising urban population and damage to the environment has spurred the need for a new model: Circular Economy.

The purpose of this section is to discuss Circular Economy. It will outline the defining principles of Circular Economy and how it can be, and in some respect already is, incorporated in infrastructure and construction to meet the greater need of sustainable development. The following Figure outlines the framework that connects the three pillars of Sustainable Development to the key principles of Circular Economy as shown in Figure 5.

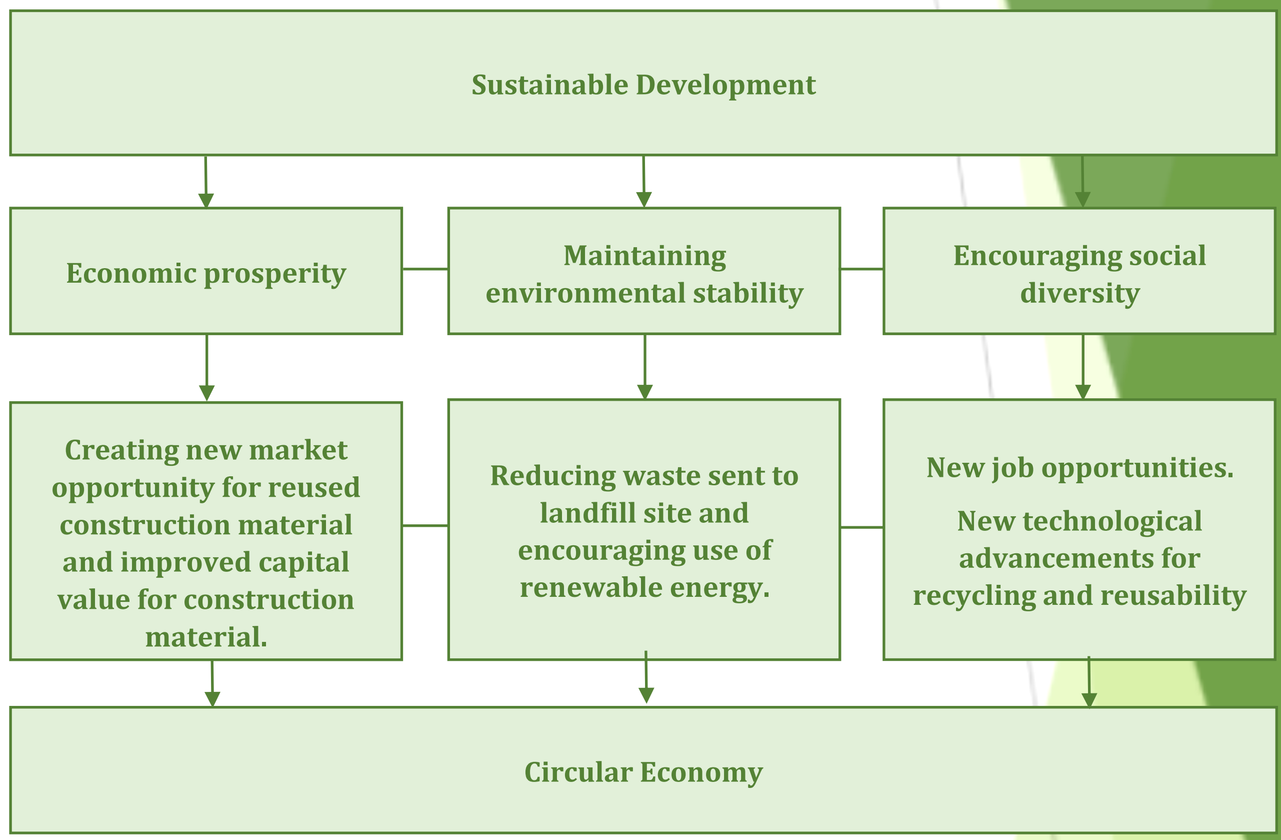


Figure 5. Outline of connection between the goals of Sustainable Development and Circular Economy.

5.1. Definition of Circular Economy

As defined by the Ellen Macarthur Foundation, who have spear headed the concept for several years, Circular Economy is:

> *'one that is restorative and regenerative by design, and which aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles'.*

Other definitions also include 'industrial economy in which material flow keep circulating at a high rate without entering the biosphere unless they are biological nutrients' (Kalmykova, 2018). Others, such as Linder and Willionader defines a Circular business model as one 'in which the conceptual logic for value creation is based on utilising the economic value retained in products after use in the production of new offerings' (Lewandowski, 2015).

Circular Economy is a concept that aims to replace the linear 'take-make-waste' model that has long been the source of problems in the construction industry. It aims to replace this existing method with a new, sustainable, regenerative approach that encourages reuse, sharing, repair, refurbishment, remanufacturing and recycling to create a closed-loop system. Figure 6 outlines a simplified comparison of the two models.

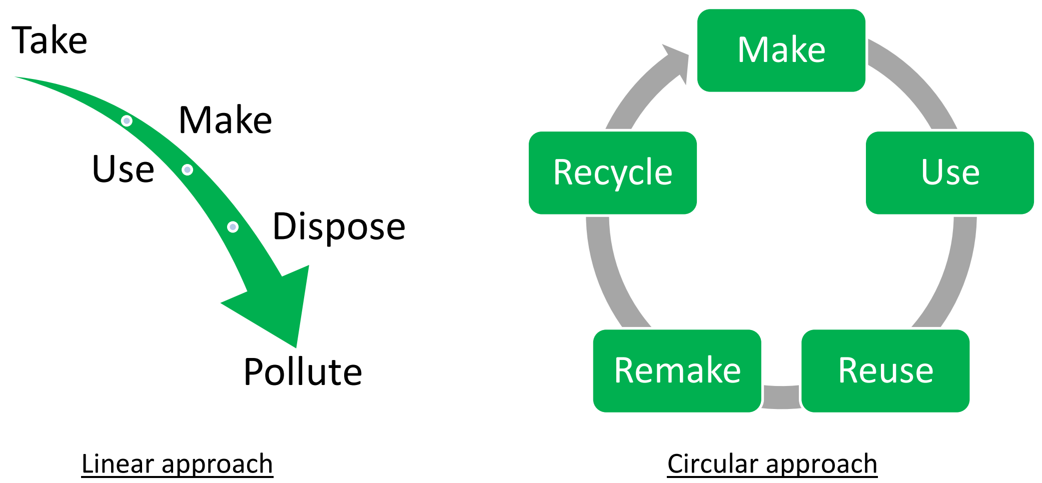


Figure 6. Comparison of the 'take-make-waste' model that is used currently in infrastructure and the proposed 'Circular' approach.

A useful conceptualisation of Circular Economy in relation to sustainability is that it is an idea used to describe a zero-waste industrial economy that profits from two types of material inputs: biological and technical. From a sustainable development perspective, the integration of Circular Economy into infrastructure looks to improve the worlds capacity to grow in the long-term (Lewandowski, 2015). The concept of Circular Economy is founded on three main principles (see Figure 7). The principle 'design out waste and pollution' is built on the premise that waste does not exist, and encourages the process of dissemble and reuse, which sets it apart from recycling.

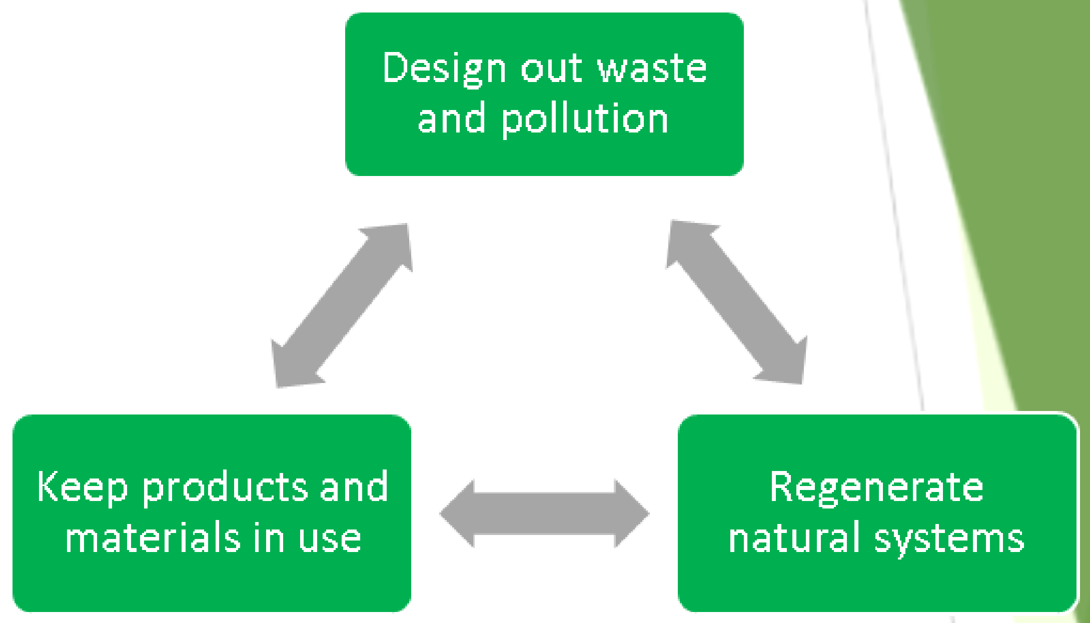


Figure 7. Key principles of Circular Economy defined by the Ellen Macarthur Foundation (Ellen MacArthur Foundation, 2015)

These principles were further developed to include the following:

1. Build Resilience through diversity: This is in the form of modularity, versatility and adaptivity that should be prioritised in building Circularity in design.
2. Rely on energy from renewable sources: Systems must aim to run on renewable energy.
3. Think in system: This is the process of understanding how component parts of a system are interrelated.

Figure 8 outlines the Circular Economy framework which shows that the system is broken down into two parts: technical and biological cycles. For the purposes of this report, only the technical cycle is applicable to construction and infrastructure. The Technical loop in Figure 8 represents recovery and restoration of products, components, and materials through strategies like reuse, repair, remanufacture or recycling.

The framework illustrated in Figure 8 is driven by four key concepts:

1. Power of inner circle: this aims to minimise comparative material usage. The tighter the circle (ie faster the return to re-use) the higher the savings on shares of materials, labour, energy, and capital.
2. Power of circling longer: This promotes the maximisation of the number of consecutive circles.
3. Power of cascaded use: This involves diversifying the purpose and use of the material or element.
4. Power of pure circle: The less likelihood of being exposed to contamination, the greater the redistribution efficiency while maintaining quality, which in turn, extends product longevity.

Each of the key concepts that drive the framework aims to promote the values of 'eco-efficiency' and 'eco-effectiveness' which is defined as the 'approach of minimisation and dematerialisation, that is based on minimising the volume, velocity, and toxicity of the material flow system' and 'transformation of products and their associated material flows such that they form a supportive relationship with ecological system and future economic growth' (Kalmykova, 2018).

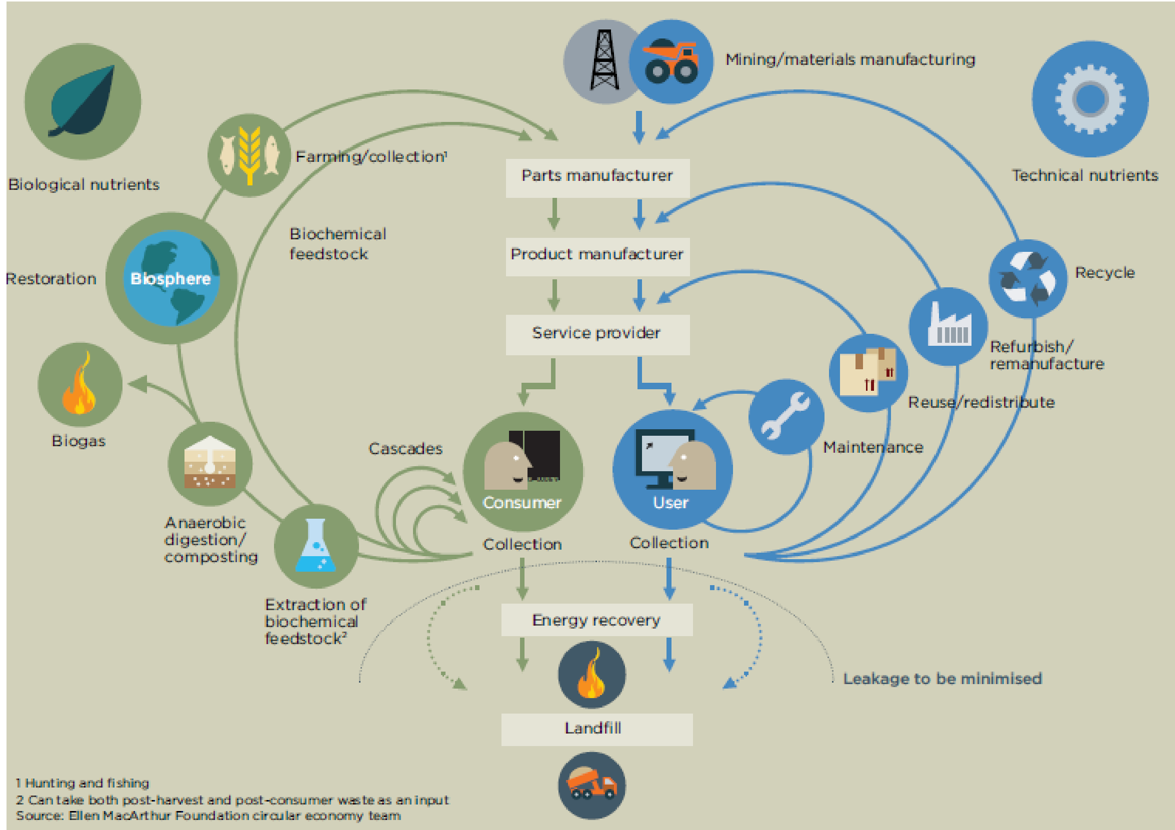


Figure 8. Circular Economy Framework proposed by the Ellen Macarthur Foundation (Ellen MacArthur Foundation, 2015)

Linking Circular Economy to infrastructure, the UK Green Building Council (UK-GBC) proposed the following goals:

- Designing out waste.
- Designing for resource efficiency.
- Design for deconstruction and disassembly.
- Using more renewable energy.
- Reducing embodied carbon over a whole building lifecycle.

The points outlined above clearly show similarities between the aims of Circular Economy practice and the objectives of the UK-GBC to integrate Circular Economy thinking and initiatives to infrastructure in the UK.

5.2. History of Circular Economy

Circular Economy is not a new concept. Historic examples include the re-use of building materials following the dissolution of monasteries in the 1500's, it is generally accepted that's its practical application in the built environment began to gain momentum in the 1970's. The movement was spurred by the rising concerns over the 'take-make-waste' approach of resource management. Realising the drawbacks affiliated with this approach, the idea of Circularity began to formalise.

The presently used term 'Circular economy' was first conceptualised in 1966. The term 'spaceman' economy was toyed, which suggested replacing the conventional open economic system with a cyclical system capable of continuous reproduction of materials, even though it cannot exist without inputs of energy (Boulding, 1996) (Kalmykova, 2018). In 1992, concept of a 'steady-state' economy became popularised which outlined further an economy that can operated under. The lowest feasible flows of matter and energy from the first stage of production to the last stage of consumption (Daly, Herman E. 1992). The idea of an 'industrial ecology' that the current Circular Economy definition incorporates was first introduced in 1989 by Frosch and Galopoulos. They envisioned an integration of industrial ecosystems in analogy to biological ecosystems with implementation of such biological imitation as an eco-industrial park where materials are recycled internally and where energy is the only external input (Ayres, 1996). This incited the now commonly used terminology of the 'cradle-to-cradle' concept that depicts a closed system of resource flows approached from a product life cycle perspective (Stahel and Reday-Mulvey, 1981).

Circular Economy is a concoction of different economic and ecological concepts that have emerged since the 1970's due to the sharp rise in the problems surrounding the 'take-make-waste' model. The intellectual roots of Circular Economy include the '3R principle' (reduce, reuse, recycle), regenerative design, performance economy, cradle-to-cradle, blue economy, green growth, natural capitalism, and biomimicry as well as the scientist fields of industrial ecology, industrial symbiosis studies, and ecological and environmental economics (Pauliuk, 2018).

Many key concepts that are used in the industry today have shaped the meaning and principles of Circular Economy which are outlined in Appendix A.

5.3. Transition towards Circular Economy

There is growing evidence of the adoption of Circular Economy in construction at both national and local level. In 2016, the UK Government Chief Scientific Adviser issued a report called 'From waste to resource productivity' which set the tone for a renewed approach to waste and recommended a review of innovative Circular economy practice throughout the Economy. This was followed by the UK government's 2017 'Industrial Strategy' outlining the commitment to moving towards a Circular Economy. Out of this came the Construction Sector Deal which recognises that more efficient process will help minimise the 60% of UK waste from construction, demolition, and excavation (UK Green Building Council, 2019).

In 2018, the Environmental Audit Committee committed to doubling resource productivity over the 25-year Environmental Plan's lifetime and to making the UK a world leader in resource. A new national Resource & Waste Strategy setting out how these targets were going to be attained in 2019. Parallel to the UK's efforts, the EU's Circular Economy Package (CEP) was ratified into law in July 2018 and member states are now working towards putting it into nation legislation. Despite the events of Brexit, there is progress across the UK, both regional and local, to legislate Circular Economy practices with the following Circular Economy statements (UK Green Building Council, 2019):

- Wales Future Generations Act
- Circular Economy Strategy Scotland
- Circular Peterborough
- Circular Glasgow
- Circular London
- Draft London Plan

From a policy point of view, the following recommendations have been made by the UK Green Building Council in conjunction with Defra and BEIS in December 2018 (UK Green Building Council, 2019):

- Accelerate better resources and waste data.
- Implement taxes that prevent resources going to landfill or incineration and instead generate incentives to encourage reuse.
- Implement regulation to encourage greater reuse and opportunities for Circular principles such as assimilating EU Circular Economy Package.
- Government should provide leadership and drive Circular principles through their own public procurement process.

5.4. Benefits of Circular Economy

It has been estimated that eco-design, waste prevention and re-use can bring net savings for EU (pre-Brexit) businesses of up to EUR 600 billion, while at the same time reduce greenhouse gas emissions. Moreover, the incentive to drive an improvement in resource productivity by 30% by 2030 could boost GDP by nearly 1% and create an addition of 2 million jobs. In the UK, it has been estimated that it can help create 50,000 new jobs and £12 billion of investment (Kalmykova, 2018).

A recent assessment of Circular Economy strategies finds a positive but limited effect on raw material demand, and another study demonstrated that the global implementation of core Circular Economy strategies can lead to savings of 6-11% of energy used to support economic activity (Ellen MacArthur Foundation, 2015). Further investigation into the impact of material efficiency in the steel cycle on material flows and Greenhouse Gas emissions, which includes a more ambitious plausibility that in the event of a quick strategy roll-out, a 50% emissions cut could be possible. However, this figure is driven by the assumption that no new blast furnaces would be constructed over the next 60 years (Pauliuk, 2018).

From a global perspective, the benefits of Circular Economy foreseen by the Ellen MacArthur Foundation suggest substantial net material savings and reduced exposure of price volatility. These predictions come from detailed product-level modelling which estimated that, in the medium-lived complex products industries, the Circular Economy represents net material cost saving at an EU level (Ellen MacArthur Foundation, 2015). The Circular Economy can also encourage creative thinking and stimulating innovations that will stem into the creation of jobs. The effects of a more Circular industrial model on the structure and vitality of labour markets still need to be further explored, but initial evidence suggests that impact will be positive. In short, it is estimated that due to resource efficiency, a saving of approximately £23 billion is expected for UK businesses (CE100, 2019)

5.5. Challenges to Circular Economy

To drive change, linking Circular Economy with business practice requires specific business models support by a framework capturing the Circular Economy principles which are as follows:

- Sustainability business model innovations
- Close-looped systems
- Product service system
- Sustainable product design

However, the Ellen MacArthur Foundation found that no business model is compatible with or contains Circular Economy goals and conclude that a new framework development is needed (Pauliuk, 2018).

At present, the application of Circular Economy in construction is within its infancy and has been limited to construction waste minimisation and recycling. Many studies have been undertaken to determine the humanistic aspects that hindered the progression of Circular Economy. These have shown that despite the awareness of Circular Economy among key stakeholders in the construction industry, the absence of incentives to design products and buildings for disassembly and reuse at their end of life is a significant challenge. Furthermore, the lack of market mechanism to aid in greater recovery and a financial case fuelled by the fragmented nature of the construction industry has also contributed to the hindrance of Circular Economy (Katherine Tebbatt Adams, 2017).

Existing technical specifications which are highly prescriptive and lead to tenders on familiar approaches can often be a barrier to Circular Economy. On the other extreme, expecting all projects to take on the risk of incorporating innovative Circular thinking is unrealistic. An element of traceability is required to verify the benefits of best practice. (Spencer, 2016).

One of the challenges to Circular Economy is that the actual value may only be realised many years into the future. However, this hinderance is already being rectified by the fact that monitoring both outcomes and enablers is gaining traction. (MI-ROG, 2018).

Another issue that prevents engineers from practicing Circular Economy principles is the lack of an existing interface between chemical waste and product legislation which is further fuelled by the fact that the current waste disposal law is designed for a linear economy.

A major social factor that has hindered Circular Economy practice are public perceptions of second-hand materials. The current thinking among engineers, both within the consultancy and contractor fields, is that any product or material that has been recycled, reused, or refurbished is inferior to something new (Sharman, 2017).

Furthermore, the financial and liability issues surrounding Circular Economy includes the complexity of identifying who is responsible for an asset once it has reached the end of its design life (Sharman, 2017). When the intended design life of a material comes to an end, it is likely that the value of the asset is diminished to the owner (i.e client), which therefore leads to a high chance of it being disposed (Lewandowski, 2015).

The UK Contractor Group conducted an electronic survey that was sent to professionals working in the construction sector to gain insight into their views on the concept of Circular Economy in the construction industry. Approximately 300 respondents undertook the survey over 6 weeks. This comprised 54% Contractors, 22% Suppliers, and 8% Developers (UKCG, 2017). One of the key findings of the research relating to the barriers of Circular Economy was obtaining the required technical infrastructure to instil the practice was a minor issue. However, 42% of respondents considered the current policy climate to be an important barrier. The conclusion made from the survey was that the most important barrier is that there needs to be a rethink in to the existing policy and contracts that have Circular Economy in mind (UKCG, 2017).

5.6. Enablers of Circular economy

Extensive research from academics and professionals has been conducted to understand what a Circular Economy driven world looks like. In general, the building blocks of Circular Economy, as defined by the Ellen MacArthur Foundation are:

1. Circular business models
2. Circular Design
3. Reverse logistics
4. Enablers and favourable conditions

From a policy point of view, Circular Economy implementation at a company level can be found in two Ellen MacArthur Foundation reports. The first 'Growth within: a Circular Economy vision for competitive Europe', developed by McKinsey, which puts forward the RESOLVE framework based on six business actions for businesses: Regenerate, Share, Optimise, Loop, Virtualise, and Exchange. The actions were built from the principles that govern Circular Economy and more importantly, outline examples of best practice to achieve the 6 business actions, as shown in by Figure 9.

Figure 9. The RESOLVE Framework developed by a joint effort from the Ellen Macarthur Foundation, McKinsey Center for Business and Environment and Stiftungsfonds für Umweltökonomie und Nachhaltigkeit (SUN) (Mckinsey Center for Business and Environment, 2018)

A survey conducted by the University of Loughborough in 2017, which was based off the research project 'Embedding Circular Economy in the Built Environment' (funded by the BRE Trust) outlined that a clear business case and commercial viability was ranked as the most important enabler by all stakeholders. This, it is hoped, will instigate the development of supportive metrics, tools and guidance (Katherine Tebbatt Adams, 2017). A top-to-bottom approach is needed to encourage the practice of Circular Economy in construction projects. From a technical perspective, further research into methods of greater recovery of materials through viable take-back schemes and assurance schemes for reused material are best practice examples that will encourage design consultants and contractors to engage with Circular Economy. Respondents were asked further about the most important steps to enable Circular Economy, and 42% of people believed that strong leadership from the industry scored a 5 (highest). Key statements that arose from the survey were: 'designer and architects need to start designing and specifying with Circular Economy in mind' and 'detailed study of various elements within construction and their suitability for re-use'. (UKCG, 2017).

One of the key stages in which change is needed is during the procurement processes of infrastructure projects. The White Paper written by the Major Infrastructure – Resources Optimisation Group(MI-ROG) forum outlines the latest initiatives to integrate Circular Economy thinking into common approaches to procurement in UK Infrastructure (Spencer, 2016) which include:

- Keeping resources in use for as long as possible.
- Extracting maximum value from resource while in use.
- Recovering and regenerating products and materials at the end of life.
- Keeping products, components and materials at their highest utility and value always.

Furthermore, it should be required that any company involved in the procurement stage of a project must demonstrate how design will encompass Circular Economy principles in the project, giving examples of choice of construction materials and process and quantifying total benefits, compared to standard approach. This should include (Spencer, 2016):

- Maximise retention/re-use of existing assets;
- Minimising use of non-renewable primary materials;
- Reduce waste;
- Ensure longevity; and
- Maximise value of materials once original purpose accomplished.

To aid this transition in thinking during the procurement process, a more risk-sharing approach through mechanisms such as collaborative performance frameworks or Design Build Finance Operate (DBFO) procurement models is encouraged. Procurement activities should be chosen based on cross functionality and an understanding of cross material flows, such as modularisation of different infrastructure components and their tracking and re-purposing over product life (Spencer, 2016). This will bring down the obstacles that prevent the easy flow of materials in the built domain minimise the volume of material entering landfills.

As well as changes in how projects are procured in infrastructure, Lauberscher and Marinelli identified six key areas of integration of the Circular Economy principles (Lewandowski, 2015):

1. Sales model – shift from selling volumes of products towards selling services and retrieving products after first life from customers.
2. Product design/material composition – change concerns the way products are designed and engineered to maximise high quality reuse of products, its components, and materials.

3. IT/data management – to enable resource optimisation a key competence is required, which is the ability to keep track of products, components, and material data. In the field of construction, the concept of material passport and the integration of BIM has been identified as the leading practice for improved data management in infrastructure.
4. Supply loops – turning towards maximisation of recovery of own assets where profitable and use of recycled/used component to maximise value of product, component and material flow.
5. Strategic sourcing for own operations – building trusted partnership and long-term relationships with suppliers and customers.
6. HR/incentives – adequate culture adaption and development of capabilities, enhanced by training programs and rewards.

Of all the outlined changes in the current business model, it is strongly argued that IT and data management is a key ingredient for Circular Economy. This is because they allow to keep track of products, components and material data which supports effective reverse logistic systems, material loops across cross industries and re-use of components (Lewandowski, 2015).

To ensure that at the end of the design life of a product, maximisation of re-use and return into the loop is achieved, end of life management is required. Research was conducted by Parlihad et al (Lewandowski, 2015) that identified the information required to achieve end-of-life decision making and established sets of characteristics of a lifecycle information system to support key stakeholders, while reviewing the existing methods that are currently practiced. The key characteristics of 'Design for Disassembly' designing includes (Lewandowski, 2015):

1. Inverse Manufacturing Product Recycling Information System (IMPRIS),
2. Recycling/Material Passport,
3. Products Lifecycle Management System (PLMS),
4. Integrated Recycling Data Management System (ReDaMa).
5. Lifecycle information monitoring systems comprises of: Information System for Product Recovery (ISPR), Life Cycle Data Acquisition System (LCDA).

Another important practice of implementing Circular Economy principles is the endorsement of Life-Cycle Assessment (LCA) defined as 'a tool for the analysis of the environmental burden of products at all stages in their life cycle – from the extraction of resources, through the production of materials, product parts and the product itself, and the use of the product to the management after it is discarded'. Thereby, a life cycle assessment involves looking at the 'cradle-to-cradle history of a product (Lewandowski, 2015).

With all the incentives for enabling Circular Economy outlined above, the Ellen Macarthur Foundation provides a summary of the key enabling factors that will lead to expected outlines, known as the 'value proposition' approach. This research paper particularly focuses on the role of design engineers in fulfilling the design' aspect of the flow chart proposed in Figure 10.

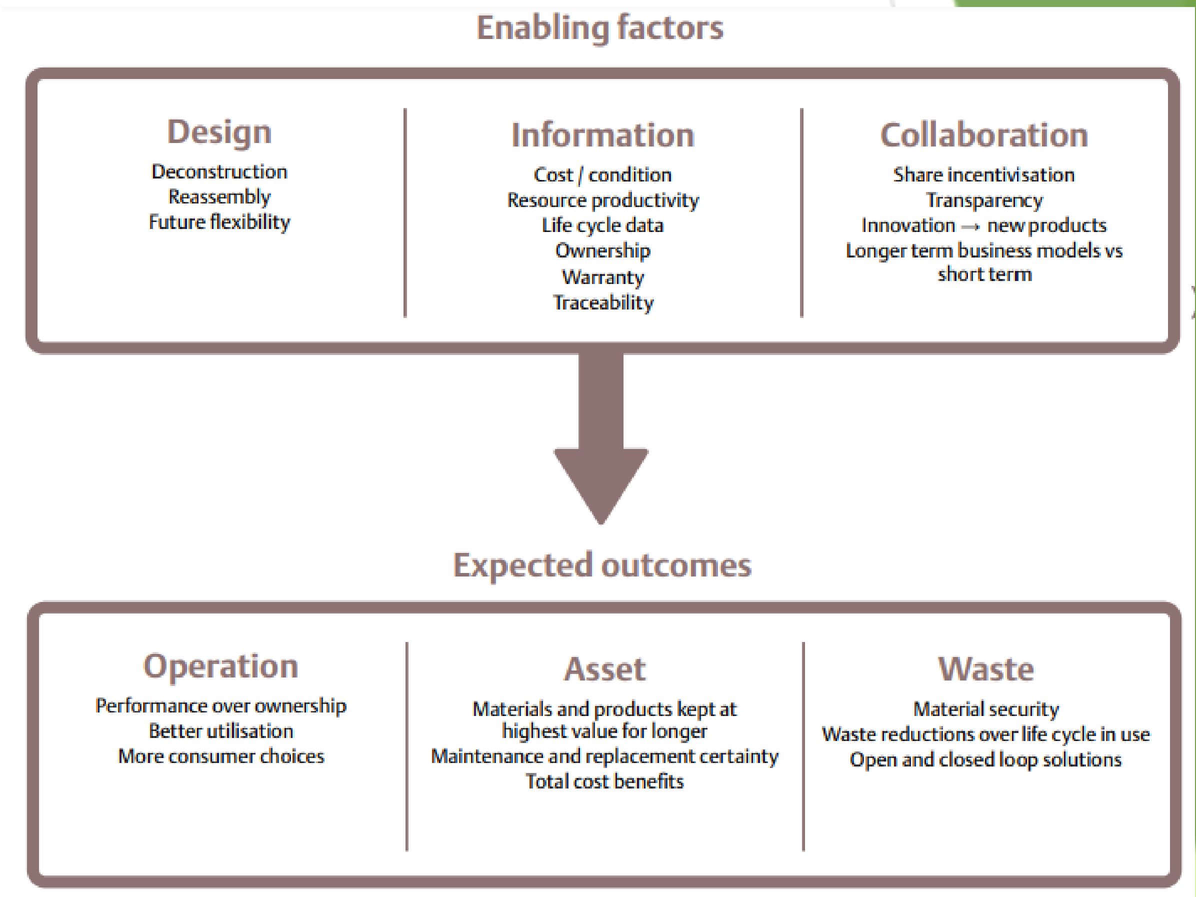


Figure 10. Summary of enabling factors of Circular Economy and the expected outcomes (CE100, 2019).

5.7. Measuring Circular Economy

As the efforts for resource efficiency and maximising value retention in construction materials and waste begin to take form in infrastructure, efforts to measure the Circularity are also emerging. To achieve this, organisations must first understand what success would look like if they were to measure the Circularity of the project. (MI-ROG, 2018). The following outlines four metrics that can be used to measure the Circular economy principles being instilled to the project.

1. Impact Based metrics
2. Productive-based metrics
3. Attribute-based metrics
4. Enabler-based metrics

A description and discussion of the limitations of each metric is found in Appendix B.

5.8. Current Efforts for Circular Economy in Infrastructure

As the benefits of Circular Economy in construction begin to be acknowledged, a range of market incentives and guidance are beginning to take form to achieve the principles of Circular Economy. Research on supply chain integration, reforming existing business models and methods of how to measure Circular Economy in a project are beginning to come to fruition which will aid both engineering organisations and policy makers. The following section outlines a variety of tools and guidance's that can be used to integrate Circular Economy into infrastructure.

5.8.1. BS 8001:2017

For design engineers to implement Circularity into their projects, a practicable business model is needed. To achieve this, the BS 8001:2017 was created by a drafting panel that included representatives from Ellen MacArthur Foundation, Institute of Environmental Management and Assessment and many more. The intention was to develop a best-practice guidance that could be adopted by Europe, and perhaps internationally, that would outline a coherent Circular Economy framework and could be adopted by all practicing engineering companies (Sharman, 2017).

The BS 8001:2017 states that there a six business model options that can support delivering a Circular Economy, which include:

1. On-demand
2. Dematerialization
3. Product life cycle extension/reuse
4. Recovery of secondary raw materials/by-products
5. Product as a service/product–service system (PSS)
6. Sharing economy and collaborative consumption

Circular Economy is seen as a wider movement towards sustainable development business practice. 'Quoted from the BS 8001:2017 document, 'Circular Economy is not a new concept. It blends the principles of multiple schools of thought, some of which date back to the 1960s' (Pauliuk, 2018). Our current socioeconomic metabolism is far away from a closed cycle.

However, one of the limitations of the document is that it is vague, particularly regarding the aspects of monitoring CE strategies. Moreover, the document fails to make a link between Circular Economy strategy monitoring and standardised quantitative tools life cycle assessment and material flow cost accounting (MFCA).

5.8.2. Take back scheme

Material loops are a core feature of Circular Economy (Lewandowski, 2015). It is proposed that products, their components and/or materials can be cascaded and reused/redistributed, remanufactured/refurbished, or recycled. This requires prior collecting back from the consumer and reverse logistics.

The Take-back scheme, defined by the Circular Economy Practitioner Guide, is 'an initiative organised by a manufacturer or retailer, to collect used products or materials from consumers and reintroduce them to the original processing and manufacturing cycle' (Guide, 2020). There are a range of recognised benefits that include the lower cost of goods due to secondary material supply, introducing alternative supply of critical raw materials, and reduced environmental impacts resulting from less production of virgin materials. The success of the scheme is typically measured by the mass of materials sold against those collected in a year. For construction, the long-term benefit of such is that it is difficult to track due to the long-term design life of permanent building and infrastructure projects. A case study of the use of the take-back scheme is provided in Appendix C which highlights a Highways England project detailing the intention to reuse as much of construction waste produced as possible. Though not common practice in permanent works, take back schemes are heavily utilised in temporary works since it is inherently short term and is highly driven by resource efficiency and optimising the value of construction materials by contractors and clients.

The success of a take-scheme will dependent heavily on building synergy between key stakeholders in the supply chain of construction materials, particularly focusing on who takes ownership of the product during operation and decommissioning. A limitation, however, is that to put the obligation of ensuring take-back scheme is successful on the manufacturers and may cause concern for those companies. This will potentially cause potential rift and legality issues.

5.8.3. BRE - CEEQUAL

A well-recognised body in the world of infrastructure that provides engineers the guidance to implement sustainable development goals in infrastructure projects is the British Research Establishment (BRE). Stemming out of BRE is CEEQUAL, an evidence-based sustainability assessment rating and certification scheme for civil engineering and infrastructure (BRE, 2019). The objectives of CEEQUAL are to:

- Create climate of sustainability awareness;
- Promote the importance of setting and delivering a sustainability driven strategy;
- Promote improved sustainability performance in projects, design and construction; and
- Recognise and promote the attainment of high economic, environmental, and social performance.

In relation to Circular Economy, the current guidance provided in the CEEQUAL manual outlines a series of assessment criteria's as shown in Figure 11. The purpose of the assessment criteria's is to optimise the maximisation of resource management and extend the longevity of resources which is key branch of Circular Economy.

Assessment criteria	Scoping guidance
7.4.1, 7.4.2 Business models for a circular economy	There is no one-size-fits-all approach for an organization to deliver its defined circular economy objectives. The decision by the Assessor and Verifier on applicability will depend on the nature, scale, location and context of the project.
7.4.3 Durability and low maintenance	Scope out only if there are no structures or major components in the project.
7.4.5 Future disassembly / de-construction	The decision to scope out will depend on the nature, scale, location and context of the project.
7.4.7 Retention of existing structures and materials	Scope out if no existing structures on site.
7.4.8 On-site use of demolition arisings	Scope out only if there was no demolition or deconstruction as part of the assessed works or if the nature of the works meant there was genuinely no opportunity for re-use of the materials within the project.
7.4.9 Cut and fill optimisation	Scope out only on projects where there is no excavation or in situations where, for example, a structure such as a tank is completely underground and there are no options on size (for example storm tanks).
7.4.10 Soil management	The decision to scope out will depend on the nature, scale, location and context of the project.
7.4.11 Beneficial re-use of topsoil	The decision to scope out will depend on the nature, scale, location and context of the project.
7.4.13 Reclaimed or recycled bulk fill and sub-base	Scope out if the project used no bulk fill or sub-base.

Figure 11. Outline of assessment criteria and scoping guidance for encouraging Circular Economy practice in a project from the CEEQUAL Version 6 Technical Manual (BRE, 2019) .

5.8.4. Construction Material Exchange

Zero Waste Scotland's Construction Material Exchange Tool enables contractors or those involved in the project to list reusable materials and advertise these to other businesses that may have a need for them. These materials can be posted online and exchanged with another project for re-use, getting better value than if they were sent for recycling or to landfill and improving resource efficiency (Resource Efficient Scotland, 2020)

5.8.5. Material Passport

A key component of instilling Circular Economy into construction is the process of documentation and traceability. From this desire, the concept of material passports has arisen in recent years. Leading the way to ensuring the practice of material passport is the EU funded 'Materials Passport Platform BAMB'. The purpose of this is to support the transition of the building sector toward Circularity by enabling users to find value potential throughout the building cycle. Cross party collaboration is key to ensure information is transitioned successfully through each key stage of the materials life, and so the platform allows the user to describe the materials health. Figure 12 outlines the level of information detailed in the material passport as proposed by EPEA (Better World Solution, 2019).

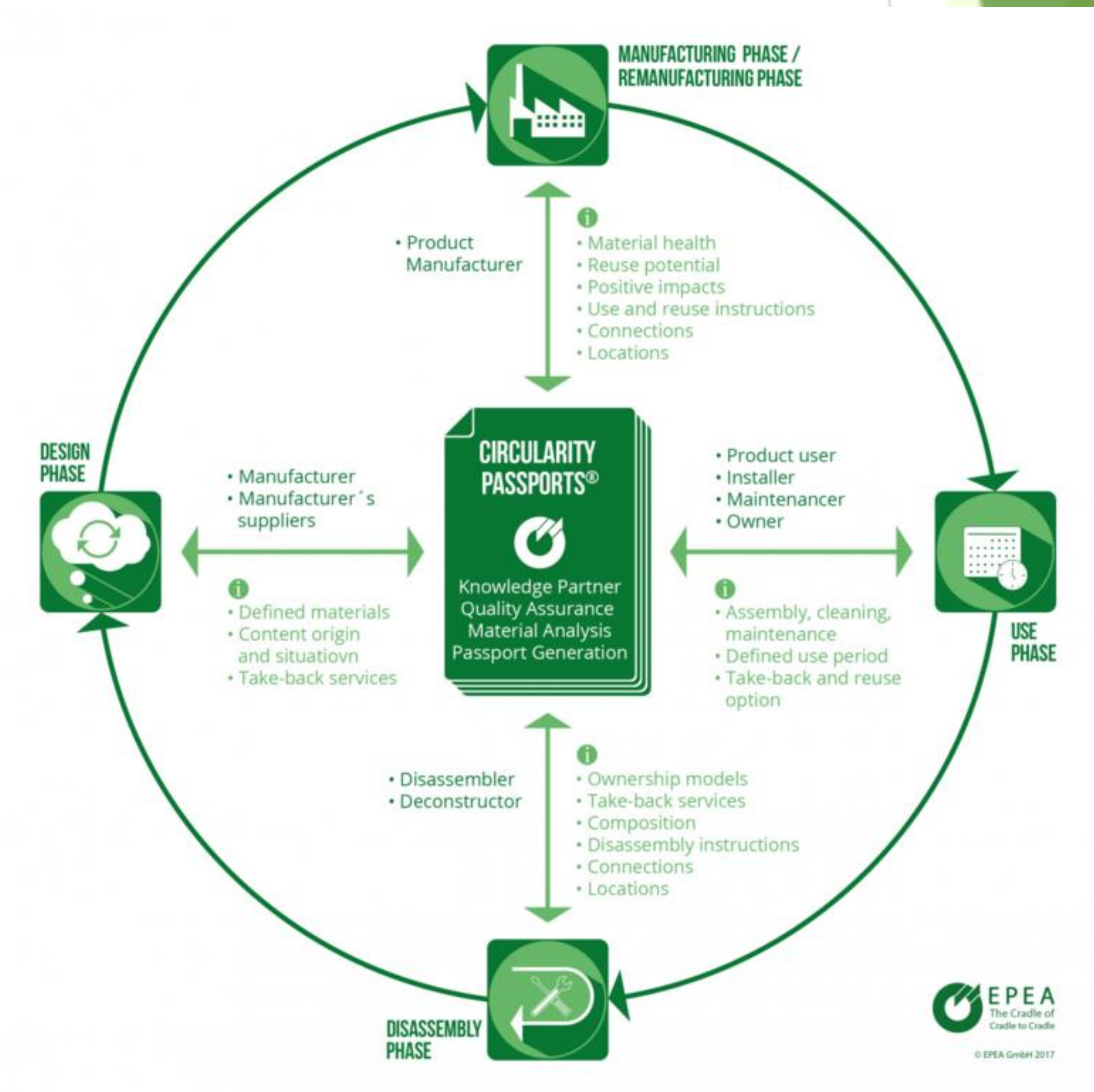


Figure 12. Outline of the information required in the Circularity passport created by EPEA (Better World Solution, 2019)

The material passport is to be integrated into the wider initiative to expand the use of Building Information Modelling (BIM) in construction projects. The use of material passports will enable the storage of data outlining what products are in the building, what they are made of and how they can be safely re-integrated into a supply chain for reuse. The storage of this information is fundamental for future asset owners to know how to correctly dissemble and send back into the built environment.

5.9. Circular Economy Case Studies

Across the world, efforts to instil Circular Economy into the everyday practice of designing and managing infrastructure has already begun to take form. The following outlines the nations and cities that have already adopted strategies and policies that incorporate the principles of Circular Economy into future construction projects are listed below:

- China, National Development Strategy
- Venlo, Netherlands
- Toronto, Canada
- Queen Elizabeth Park, London, UK

Each case study, discussed in more detail in Appendix D, outlines the small steps that are being taken across the world to implement Circular Economy into construction. All cases show the power of enforcing Circular Economy through passing laws in a top-to-bottom process.

6. Design Engineers role in Circular Economy

The purpose of this section is to outline where design engineers can maximise the value of Circular Economy in infrastructure projects using the concepts of 'designing for disassembly and reuse'.

6.1. Design for Disassembly (DfD)

An important enabler of Circularity is of 'Design for Disassembly' (DfD) that has been recently adopted in design. It is defined as the process of 'designing products so that they can be easily, cost-effectively and rapidly taken apart at the end of the products life so that components can be re-used and or recycled' (Mule, 2012). There are three important factors in DfD:

1. Selection and use of materials;
2. Design of the components and product; and
3. Selection and use of fasteners.

It is considered an essential action to reduce the use of energy and resources and production of waste in building construction (Thromark, 2017). The concept is built on the ideals of material recovery, value retention and meaningfulness in the next use. The benefits of DfD, particularly the environmental and social motives, make it a clear indicator of circularity. Designers are encouraged to consider how the design can be disassembled for future use. One governing principle is that the proportion of material waste is inversely proportional to the mass of a component.

To ensure that the built environment is designed for disassembly, as-built drawings should be provided with a 'deconstruction plan' in the specifications. To encourage disassembly, bolted, screwed, and nailed connections are recommended. Furthermore, the encouragement of 'interchangeability' will ensure the use of materials and systems that exhibit principles of modularity, independence, and standardisations that will facilitate re-use. Strategies of DfD include (Guy & Ciarimboli, 2005):

- Minimise different types of materials which reduces the complexity and number of separation processes.
- Avoid toxic and hazardous materials that increase potential human and environmental health impact, and potential future handling costs, liability risk and technical difficulties.
- Avoid composite materials and make inseparable products from the same materials that are then easier to recycle.
- Avoid secondary finishes to materials which may cover connections and materials, making it more difficult to find connection points.
- Use prefabricated subassemblies which may be disassembled for reuse as modular units, or for efficient further separation off-site.
- Use lightweight materials and components that are more readily handled by human labour.
- Identify point of disassembly to permanently reduce the time in planning the disassembly process.
- Build disassembly instructions into the product that will help users understand how to take it apart.
- Design foundations to allow for potential vertical expansions of a bridge, wall building etc.

One example of a recent practice of designing for disassembly is 'The Bay Bridge Steel Programme' which emerged out of a desire to salvage and repurpose the metal that once made the eastern span of San Francisco's Bay Bridge, originally constructed in 1933 (replaced in 2013). The steel in question, according to the application of material, would be available for civic and public area projects within the state of California. The program represents a unique opportunity to adaptively reuse infrastructure, not necessarily for the same purpose, but between different factions of society.

The limitation of DfD is that it is difficult to measure or quantify the DfD of a material or design element as it currently does not have a reliable measure indicator. Another key challenge at this present time is financial cost. Currently, demolition is far cheaper than taking a building apart by hand even considering the money generated by the sale of the recovered materials. Furthermore, there is a lack of labour training in the industry, specifically, inspiring a generation that knows how to take apart buildings as well as assembling them. Another problem is the long life of a built physical asset and the difficulty of maintaining information about material properties. Hence, innovations such as material passports must materialise before designing for disassembly becomes feasible in the industry. Finally, the intended purposes of a material used to construct a design may change by the time the design has reached disassembly stage. For example, steel and concrete form most of the construction material in infrastructure but may not be the case in 50 years or so, and so its value to society is dropped, and therefore the desire to re-enter the material back into the built environmental may be less warranted. This makes the idea of designing for a second life more difficult to implement or consider.

Like all innovative thinking, the introduction of designing for disassembly should be encouraged and considered in the optioneering stage. This is to maximise the time of opportunity for designers to successfully integrate the key design features to the asset.

The option stage of a project is fundamental to setting the tone and direction that will draw in Circular Economy principles. Developed by the UK Green Building Council for buildings, a hierarchal design process can be followed similarly for infrastructure as outlined in the table below.

Table 1.Hierarchy of actions applied when considering designing for disassembly components.

Action	Description
Design out	• Designing out the need for component or material
Reused, remanufactured or recycled products	• Use recycled materials over new • Use remanufactured components over new
Product selection	• Use products with labels such as Cradle to Cradle • Select products that can remanufactured or reused at the end of first life • Use materials with recycled content • Select materials that be reused at the end of fist life • Select materials that can be recycled after first life • Consider leasing short lived components.

7. The Design for Disassembly Toolkit

Having discussed the methods of measuring Circular Economy in infrastructure, this section outlines the Circular Economy Toolkit developed for design engineers to use, ideally during the options stage of a project to enable the implementation of DfD principles to achieve the goals of Circular Economy, and more widely, sustainable development. The toolkit is broken down into two parts:

1. Qualitative Assessment of each material, in the form of a 'Design for Disassembly Log'. The log will summarise the method of installation, source of material and what stage within the built domain the material is to re-enter of each material and element entering the built domain.
2. Quantitative Assessment in the form of a design for disassembly checklist, aimed at scoring a material or element based on the percentage of actions achieved for achieving 'design for disassembly' and giving an overall score for the proposed design option.

The purpose of the tool kit is to enable a design team to adopt Circular Economy thinking for their project, specifically instilling disassembly, and re-use features to the design. For the tool to be used effectively, a range of design solutions must be compared using the assessment tool outlined below. It is anticipated that the assessment tool is to be completed in a resource efficiency workshop (or equivalent meeting between the main stakeholders of the project) and used to aid in the decision-making process.

7.1. Assessment Methodology

7.1.1. Qualitative Assessment

The method of determining the Circularity of a given design solution qualitatively offers the design team the opportunity to discuss and interpret the means of incorporating design features into the project that improves the ease and likelihood of reintroducing it back into the built environment. The approach will enable the user to understand how the principles of designing for disassembly will be achieved.

It is envisaged that the tool is used as early as possible in the design to determine methods of installation, source of material and end of design life options to maximise the chance of innovative thinking. The key aspects of the assessment that the design team are to discuss and summarise in the document are as follows:

- Outline each material considered for a given design option;
- Quantify the mass (kg) of each material of each design option. This will then be used in the quantifying the DfD Index which is to be discussed in detail in Section 6.1.3;
- Identify the purpose of the design option and the corresponding affiliated materials;

- For each material or design element considered, the method of installation and means of connection is to be discussed. This will ensure that the methods of dissembling the system is considered early in the project and ensure that the client is on board with the process;
- Determine the source of the material. The tool requires the user to identify how the element or material is sourced. The assessment provides a list of 4 possible avenues in which the material is sourced from which includes: Virgin, Recycled, Reprocessed, and Reused. This section of the assessment will ensure that the decision makers of the project have ensured that not only shall the design be considered for future reuse, but also that the design incorporates as much recycled or reusable materials to continue the Circularity of a previous project; and
- Outline the most likely end of design life options. Each material considered for a given design option will have its own trajectory after the end of its design life. This is a key aspect of the assessment and its main purpose is to get the design team to think about the various avenues that the material is sent down in its design life. It is critical that the client plays are forefront role in this engagement between stakeholders as maintenance of the assets is critical to improve the chance of reusability. The section of the assessment must be used to think about whom is responsible for disassembling and reintroducing the material of design element into the construction ecosystem.

An example of this part of the assessment is outlined in Appendix E.

Once the assessment has been conducted, the results can be used to guide the design team towards an improved Circular project which incorporates the principles of designing for disassembly and future reuse. The results of the assessment will be provided to the client to maintain and use whilst undertaking maintenance or future changes.

A limitation of the tool is that it relies heavily on cross-party collaboration and knowledge sharing which inadvertently invites the possibility of self-selection bias. Certain key information regarding the designing for disassembly aspect of the design may be purposefully withheld or hidden from other members of the design team to push for a certain design solution due to, but not exclusive to, cost-driven motives. Another concern surrounding the assessment is that it is difficult to compare each design solution without a quantitative element.

7.1.2. Quantitative Assessment

To overcome the limitations of the first part of the assessment, a second part is introduced; the 'Design for Disassembly Checklist'. This entails the process of scoring a design solution, between 0 to 1, 0 representing a completely non-Circular design and 1 representing a completely Circular design, to measure its Circularity. The concept is inspired by the premise that there are 4 critical stages that the material goes through, and subsequently can be reintroduced into as shown in Figure 13. The figure outlines the current take-make-waste model but re-links the disassembly stage back to the stages before the material is assembled. The four key stages within the domain of the built environment are:

1. Recycled.
2. Reprocessed.
3. Assembled into Element.
4. Element in operation.

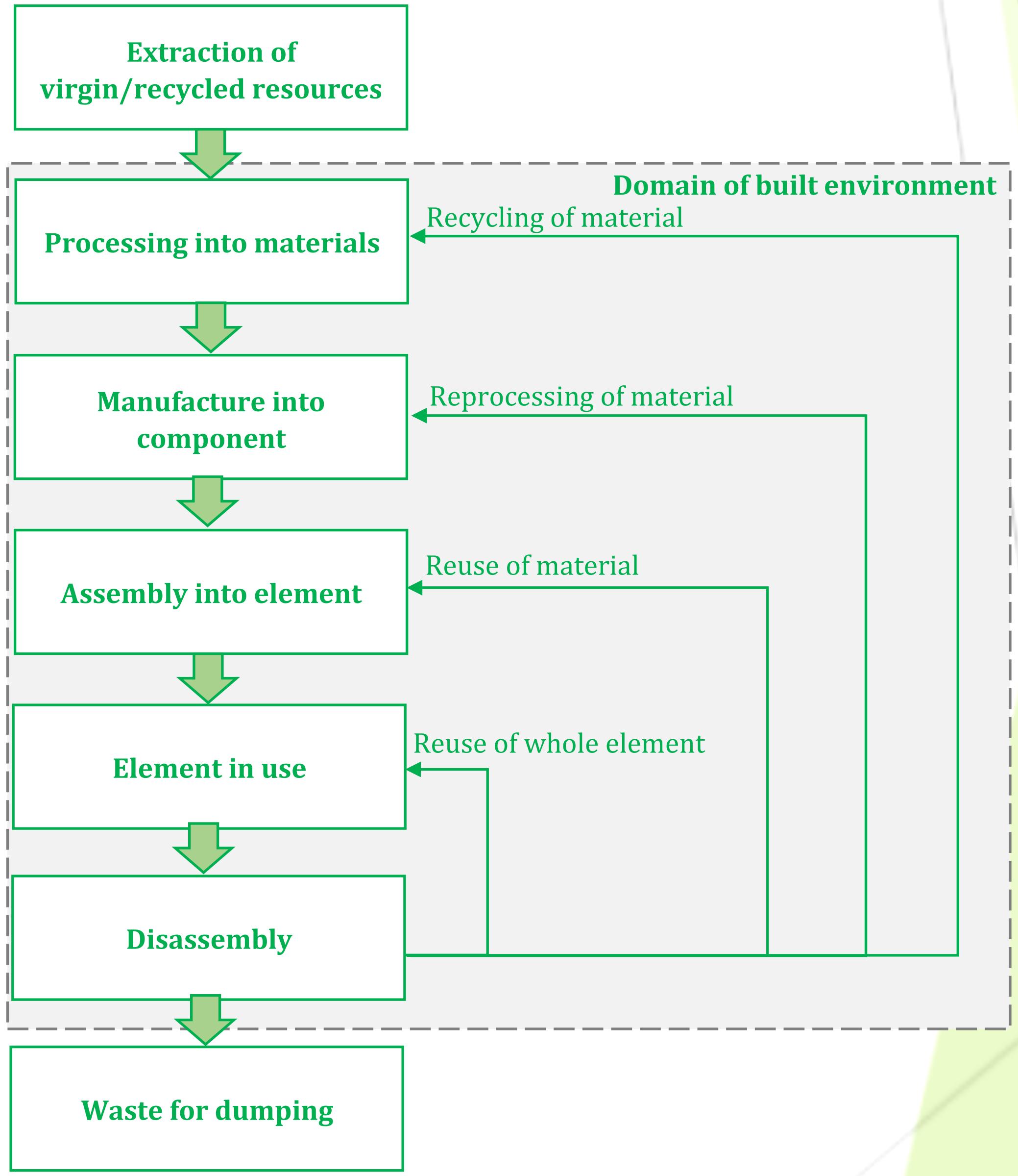


Figure 13. Idealised design life and critical stages of a material and corresponding paths for material to re-enter back into the built environment.

The assessment introduces 4 key guidelines, developed by Philip Crowther at the University of Technology, Australia, where each guideline represents a certain path that a material can take to renter the built domain. Each guideline outlines various deliverables that the design team must incorporate to the design to maximise the possibility of taking the corresponding path. The following summarises what each guidance is intended for (Crowther, 2000):

Guidance A: A total of six deliverables are defined that will guarantee that the material considered in a design option can be recycled.

Guidance B: A total of four deliverables are defined that will ensure that the material considered in a design option can be reprocessed.

Guidance C: A total of eleven deliverables are defined that will ensure that the material considered in a design option can be reused.

Guidance D: A total of seven deliverables are defined that will ensure that the entire element considered in a design option can be reused.

Appendix F outlines the guidelines and corresponding deliverables that are required to be assessed for a given design solution. The assessment provides the user with an explanation of each deliverables to limit the room for subjective interpretation and maximise reliability. The tool is to be used as a checklist, going through each deliverable and simply stating 'YES' or 'NO' if the material considered can achieve a certain deliverable. Once this has been processed, the percentage of 'Yes' and 'No' is measured and will be used to score the DfD Index (I_{DfD}) as will be discussed in the next section.

The checklist will also ask the user to outline what document will be used to communicate, which include:

- Drawings
- Hazard Log
- CDM Review
- Final Submission reports

In addition, the checklist will also require the user to outline who the design team must consult with to ensure that the deliverable is achieved, which includes either/or:

- Contractor
- Client
- Suppler and/or manufacturer

7.1.3. Design for Disassembly Index (I_{DfD})

The purpose of this section is to introduce the process of scoring the DfD Index for each design option considered in a project. A material or element after the end of its use can be reintroduce it back in the domain of the built environment in many ways. However, a key aspect of this assessment tool is to recognise the greater value of designing material and elements to be reusable over recycling. The benefits of reuse over recycling are as follows:

- Energy consumption: Recycling is energy intensive. A large amount of energy is needed to transport, process and reassemble recycled materials.
- Pollution: Along the same lines, because so much energy is attributed to recycling, a greater of share of pollution is caused by recycling over reuse.
- Cost Consumption: Recycling, particularly in the UK, is an expensive procedure. Re-using products for the same or alternative purpose introduces an opportunity for profitability.
- Encouraging higher quality: When designing for reusability over recycling, the material selection will be inclined for opt for quality over quantity.

The method of calculating the DfD Index is outlined in Appendix G.

Once the checklist is completed for all materials considered for each option and a final DfD Index is calculated, the user can then rank them from highest to lowest to aid the design team and decision-makers in choosing the most Circular design in the project.

8. Assessment Results

8.1. Research Material

A total of two past projects undertaken by Tony Gee and Partners LLP (TGP) were used to trial the toolkit and quantifying the DfD Index for design solutions considered in the project.

8.1.1. Cumberland Road

TGP were appointed as the lead temporary works designers. The project involved the construction of a new contiguous pile wall and piles to reinstate the 'Chocolate Path' which had failed due to a major landslide. The scheme consisted of designing the temporary works to support the construction sequence and designing the crane platform and piles to support the cranes used to install the permanent works.

8.1.2. Midlands Metro Alliance (MMA)

TGP were appointed as the permanent works designers for the new 11km tramline being introduced to connect Wednesbury and Brierly Hill. The project involved several earthworks, retaining wall and new embankment designs at various locations. The research focused on a retaining wall to be introduced at the toe of a slope cutting to allow the widening of an existing railway.

The two projects were selected to attempt to draw out a varied response on how the assessment can be used in delivering Circularity to both temporary and permanent works and how the distinct nature of the two can vary the outcomes of the assessment. Moreover, the two projects were both geotechnical projects to maintain a common theme and ensure comparability between the information gathered.

8.2. Material Selection Process

The following section outlines the various design options that were considered for the Cumberland Road and Midland Metro Alliance project. All options considered in the material selection process have all been assumed as feasible design solutions from a technical, constructability, and cost perspective.

For Cumberland Road, three design options were considered in the options stage of the project and are outlined below:

- Option 1: 450 mm diameter concrete Contiguous Pile Auger (CFA) piles installed into the ground. Ekki mat installed to support rig and transfer loads to piles to avoid damage to road. Engineering Granular Fil installed between voids to provide extra confidence of load transfer to piles.
- Option 2: Same as Option 1 but with the use of steel Universal Column (UC) ground bearing piles (254x254x73) instead of CFA pile.
- Option 3: Same as Option 1 but with the use of 219 x 10 Circular Hollow Section (CHS) ground bearing piles instead of CFA pile.

Appendix H outlines a description of each option and key assumptions made for quantifying the mass of material for each design solution to ensure a 'like-for-like 'comparison is achieved.

For MMA, five design options were considered in the options stage of the project and is outlined below:

- Option 1: Steel sheet pile wall driven into the ground. Local excavation from the proposed base of the retained height of the wall is assumed to be negligible as this is not required to construct the wall since the sheet piles are driven.
- Option 2**:** Kingpost wall with pre-cast concrete panels spanning between the Universal Column (UC) steel sections. The wall is also comprised of in-situ concrete which forms the embedded length of the wall. Excavation of the material behind proposed location of wall is required to facilitate installation of the wall and therefore the quantity of excavated material is considered. Subsequently, granular backfill will be installed.
- Option 3: same as option 2 but with structural timber spanning between the UC Section as oppose to pre-cast concrete panel. The same process of excavated material behind the proposed location of the wall is considered as per Option 2.
- Option 4: In-situ reinforced concrete contiguous pile wall. The wall is to be comprised of 600mm diameter piles at 750mm spacing. As per Option 2, excavation of material behind the proposed location of the wall is required and considered in the assessment.
- Option 5**:** L-shape reinforced concrete gravity wall. As per Option 2, excavation of material behind the proposed location of the wall is required and considered in the assessment.

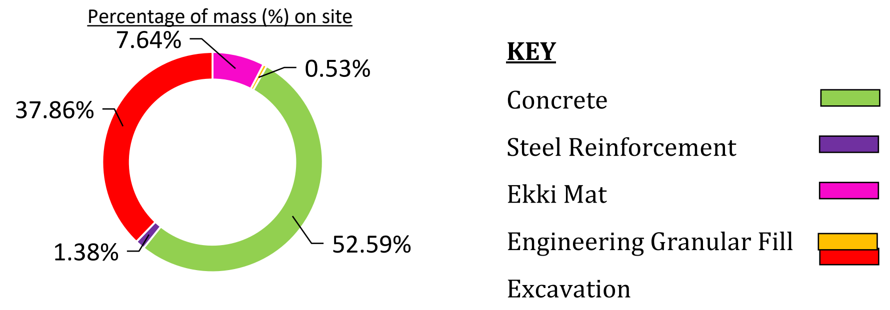
Appendix I outlines the key assumptions made for quantifying the mass of material for each design solution to ensure a 'like-for-like 'comparison is achieved.

Appendix J provides a table summarising the of mass (kg) of each material for a given design solution per project. The table below outlines the percentage of mass of each material considered for each solution which is will then be used to determine the final DfD Index of the option.

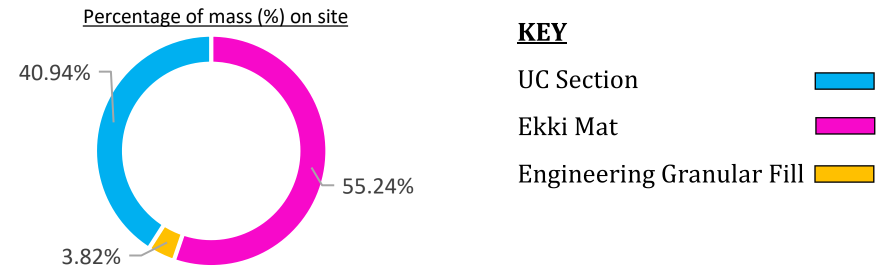
Table 2. Summary of quantify on site for Cumberland Road and Midlands Metro Alliance.

Cumberland Road

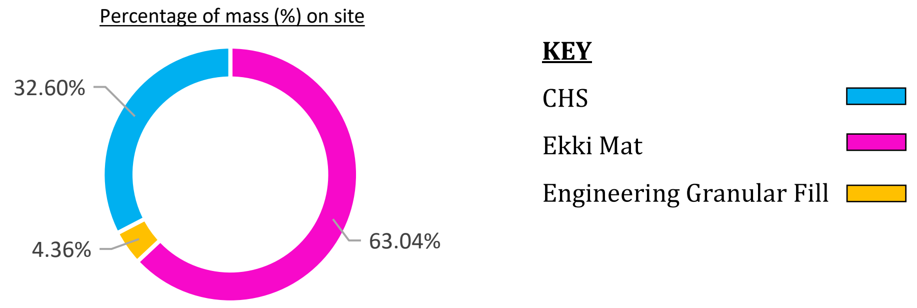
Option 1 – Concrete CFA Pile



Option 2 – Steel UC Section

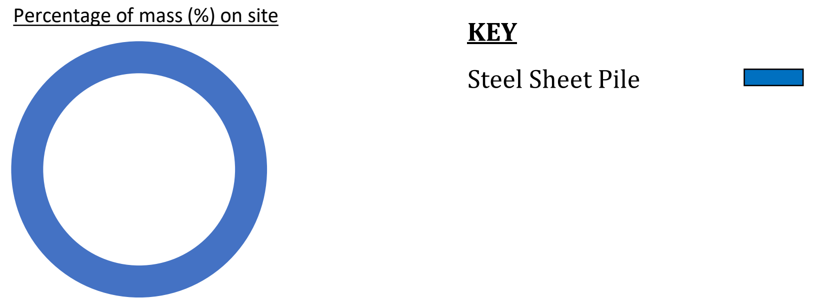


Option 3 – Steel CHS

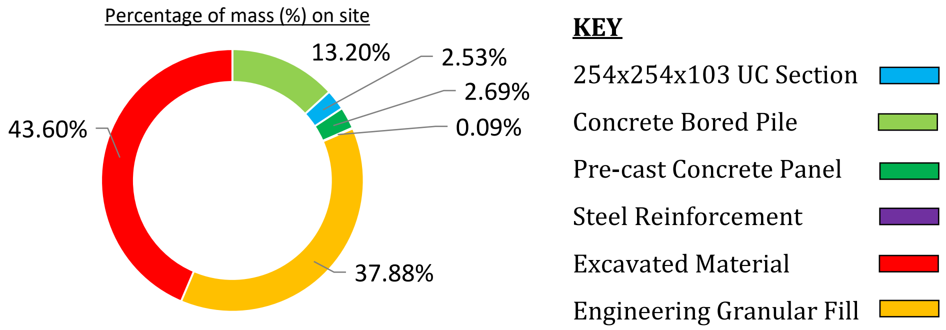


MMA

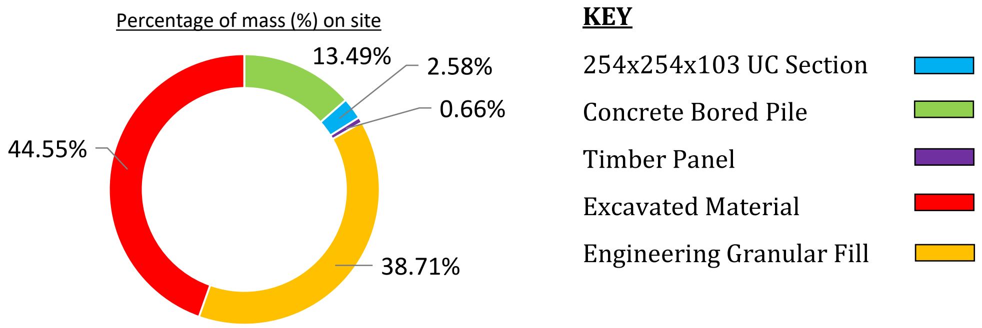
Option 1 – Sheet Pile wall



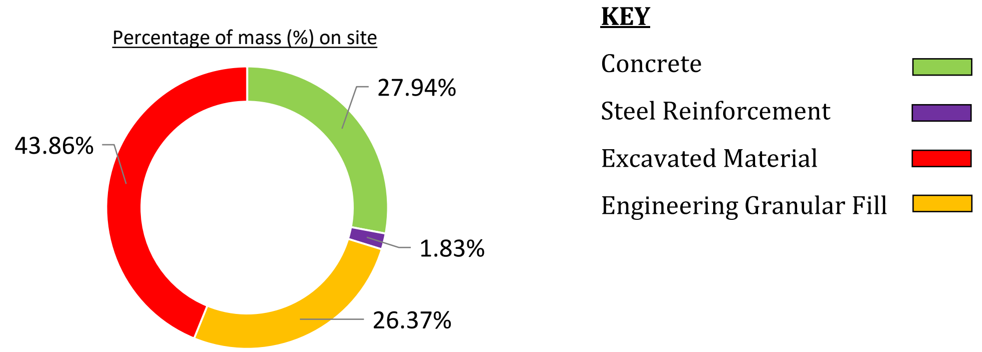
Option 2 – Kingpost Wall with pre-cast concrete panel



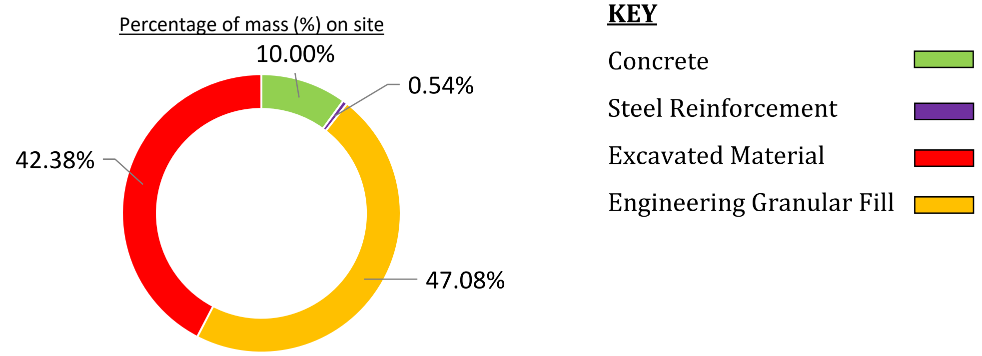
Option 3 – Kingpost Wall with timber panel



Option 4 – Contiguous Pile Wall



Option 5 – L-Shape reinforced concrete gravity wall



The results above outline the following key observations from this exercise for each respective project.

7.2.1.1 Cumberland Road

The CFA pile are found to be signifcantly more heavy (3461Mg) with the UC and CHS end bearing pile being up to 86% and 88% lighter respectively. It is important to recognise at this stage of the project that the lightest option is preferred due to reduced construction activity in assembling, and subsequently, dissasmbling. For option 1, the concrete contributed 53% to the total mass of the option, the largest of all materials considered. However, for options 2 and 3, the ekki mats have 55% and 63% of the total mass on site respectively, representing the largest of all matrerials assumed in the analysis. For all three options, the engineering granular fill is found to contribute approximately 2% to the total mass, the lowest of all materials per options. A key obersavation made is comapring the percentage of excavation material produced for each option. For option 1, 38% of the total material on site is due to excavation. This is in stark contrast to options 2 and 3, where no excavation is produced as a result of pile and piling platform installation. This is important to register as the the design team must make sure to take into account the waste that will produced as a result. By quantifying the mass of material on site, as well determining the DfD Index, the process can enable the design team to consider constructability as a function of mass of material and the knock-on effect of waste production which contributes to the final DfD Index.

7.2.1.2 MMA

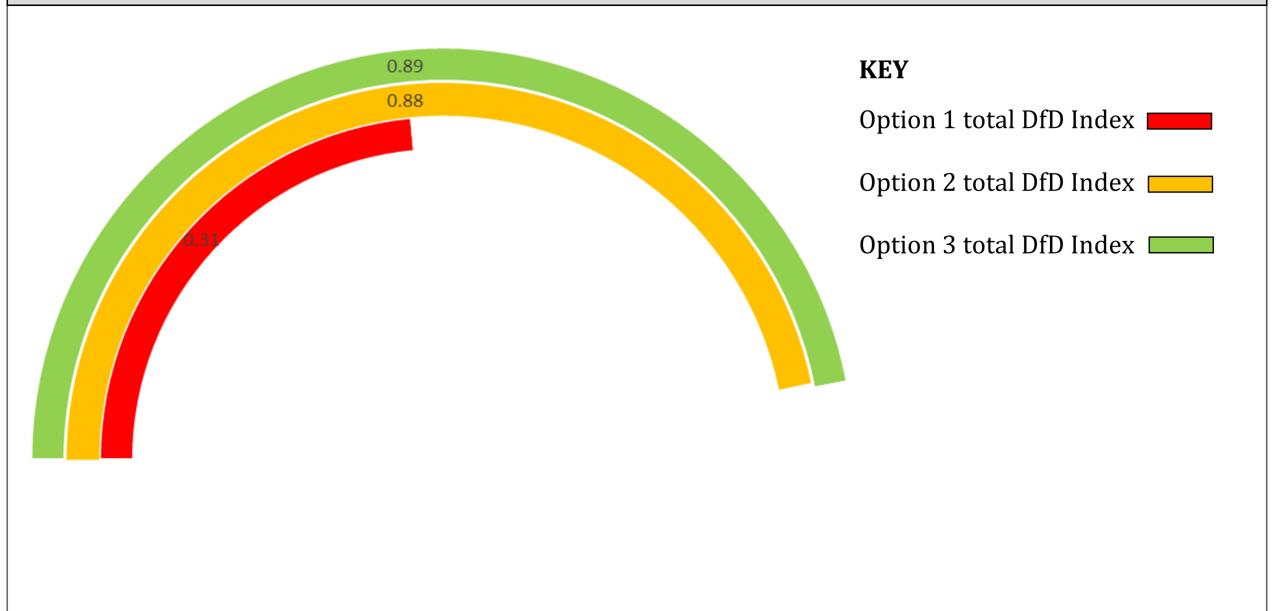
Option 4, the contiguous pile wall solution, was was found to be heaviest of all options (3072 Mg), with the sheet pile wall solution being the lightest (140 Mg). For option 4, the excavated material has the highest percentage of the total mass, of 44%. As outlined previously, a key aspect of delivering Circular Economy is to appreciate both the design elements that engineers introduce to the eco-system as well as the waste that leaves the site to find oppurtunity for resuse. The sheet pile wall solution was unique, only needing one element to form the design solution. As outlined above, the appeal of using lighter, fewer materials for a design solution is that heavyweight plants on site and construction activity can be reduced. Where excavation was required to facilicate the installation of the design elements per option, the material produced as a result of this process formed an average 43% of the total mass of each opton.

8.2.2. Quantifying DfD Index

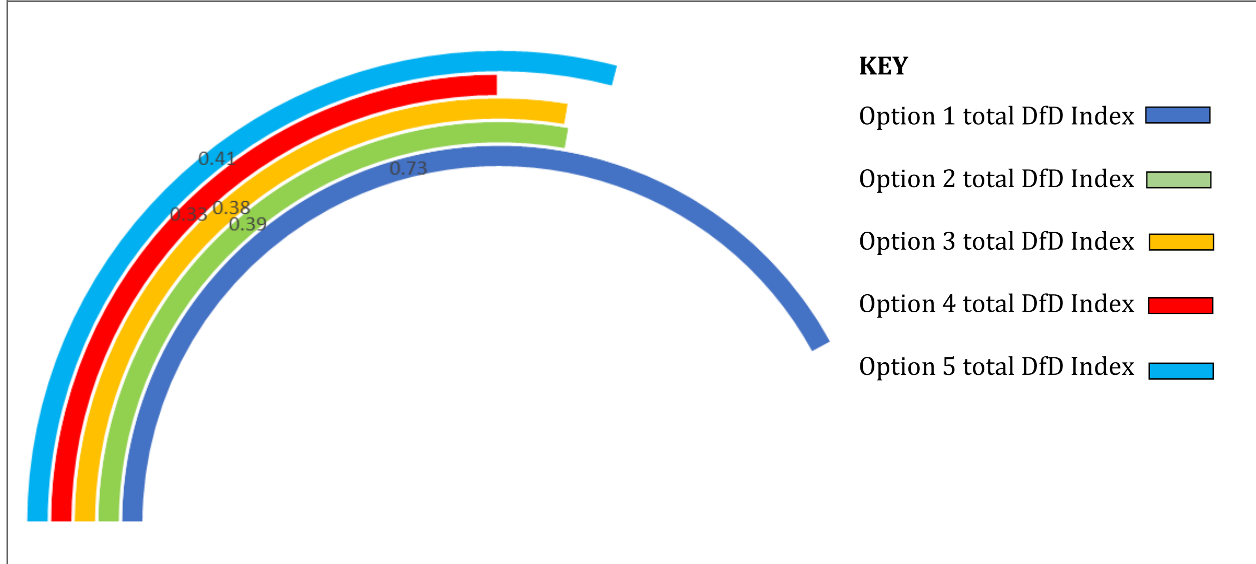
Once the mass of material and subsequent percentage of total mass is calculated, the design team must go through the DfD checklist to determine the percentage of actions achieved for a given guidelines. For each option, the DfD Index per material is calculated to determine the final DfD Index for each design option. Appendix K and L outline the assumptions made when using the DfD checklist for Cumberland Road and MMA respectively. Appendix M outlines the DfD Index for each material of a given design option. The final DfD Index of the proposed design solutions is summarised in the following table.

Table 3.Summary of DfD Index for Cumberland Road and MMA.

Cumberland Road



MMA



A packed Circular map is used to illustrate the relationship between the mass fraction and DfD Index for each material considered in Cumberland Road and MMA as illustrated in Table 4 and Table 5 respectively. The size of the bubble is proportional to the mass fraction of each material. A colour map is used to represent the scale of the DfD Index (red = 0, green = 1).

Table 4. Packed Circular Map illustrating the mass fraction and DfD Index for Options 1 to 3 for Cumberland Road.

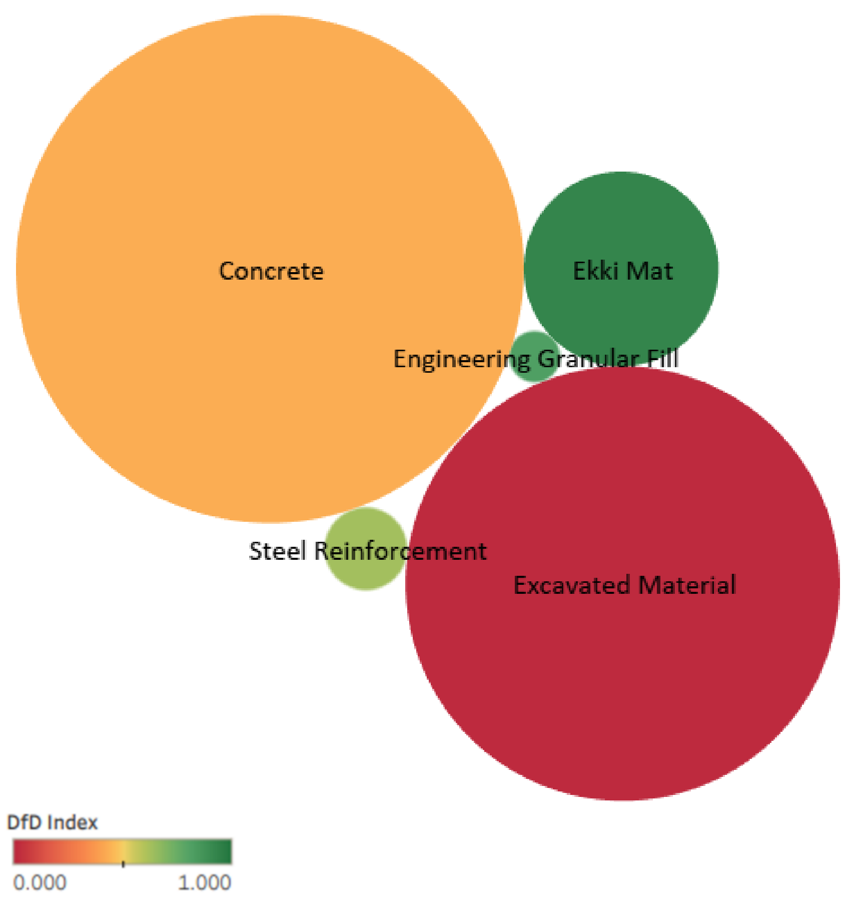
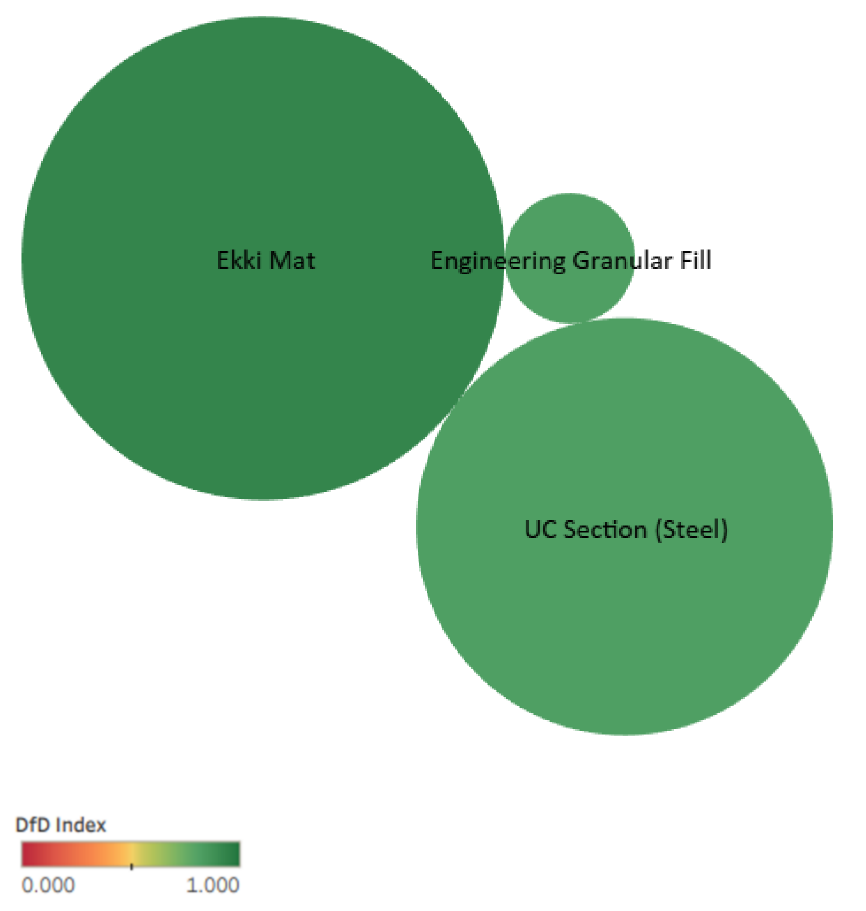
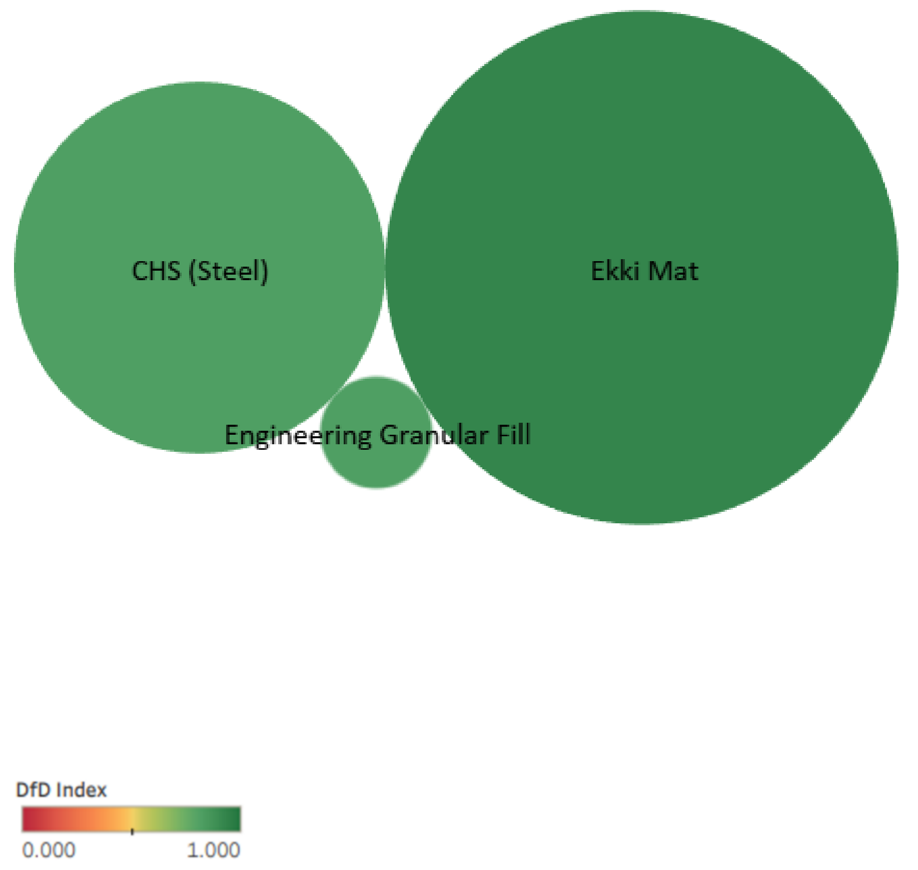
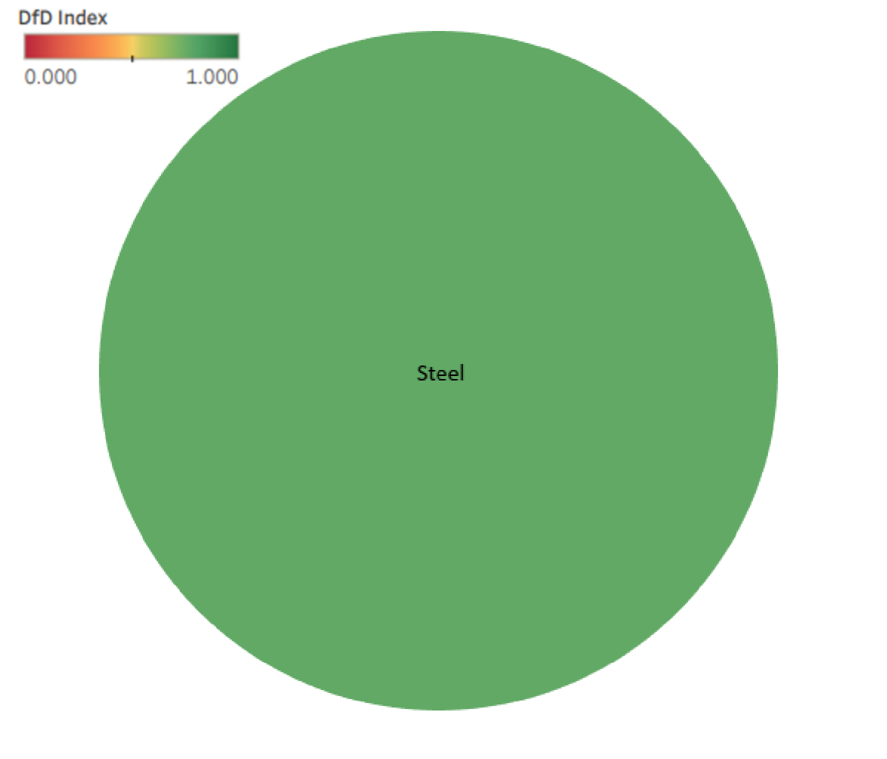
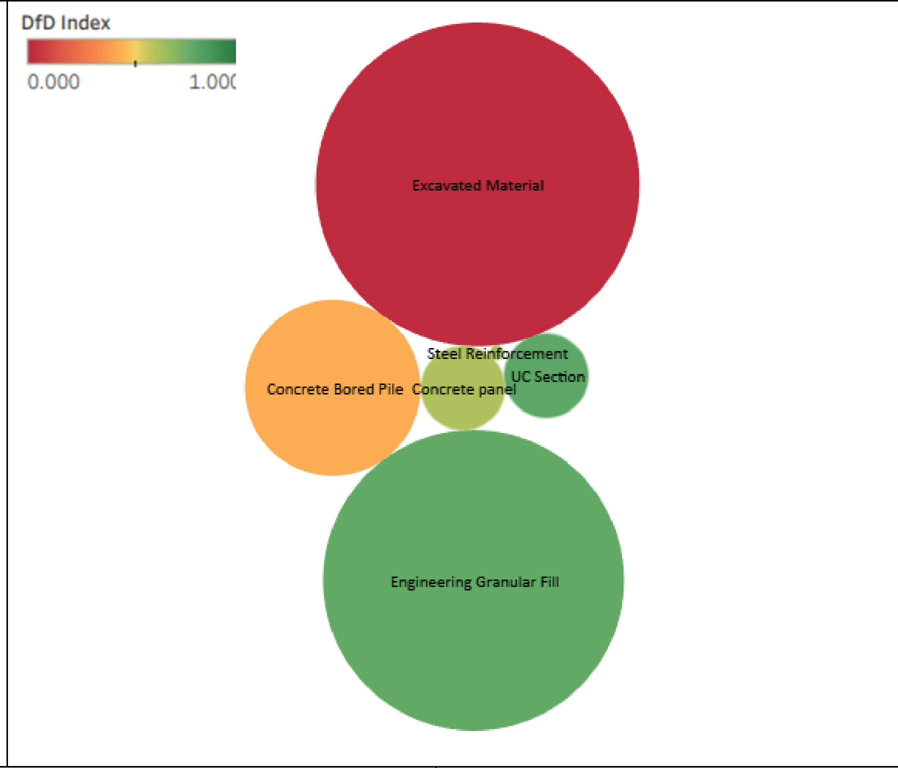
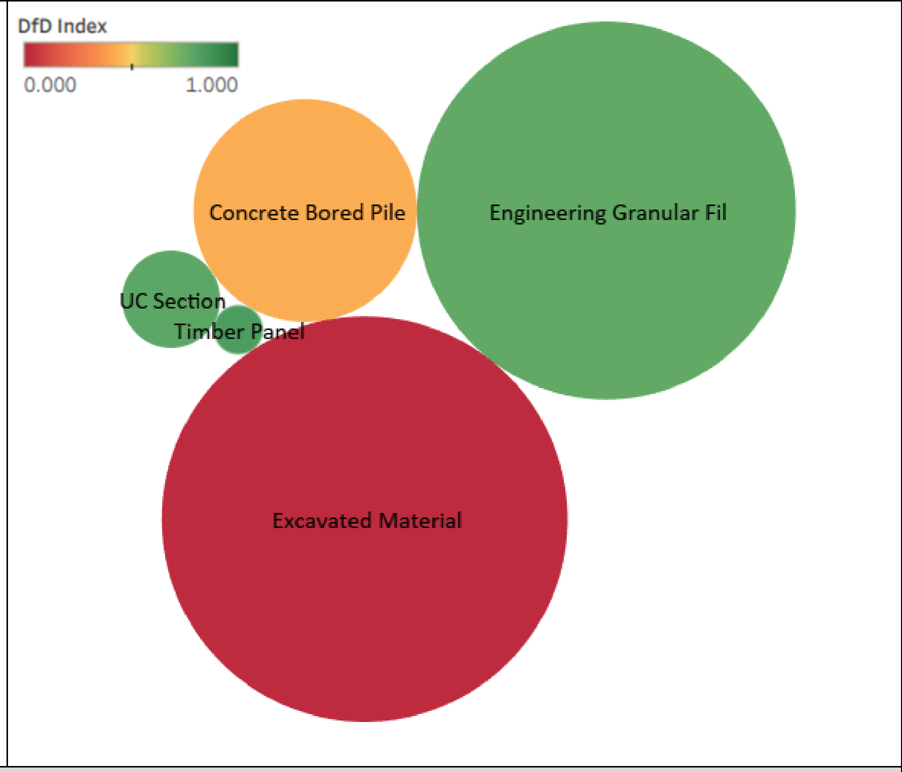
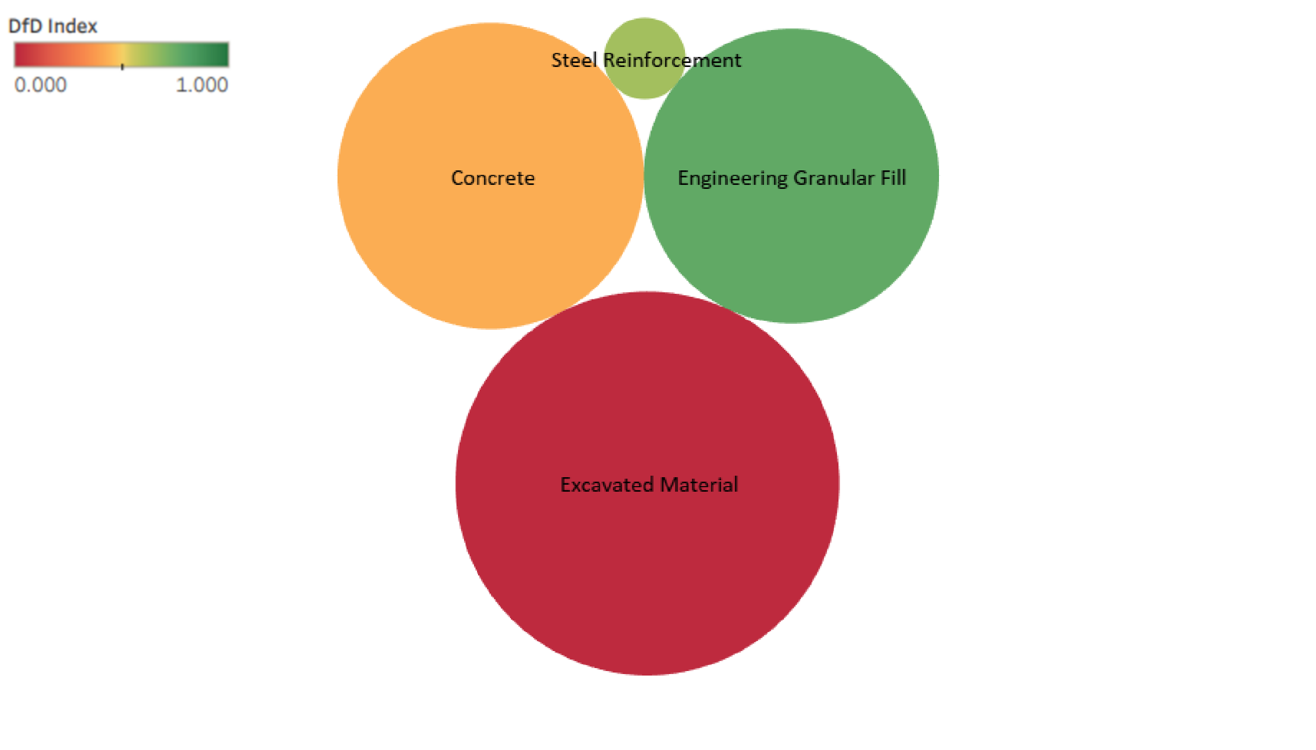
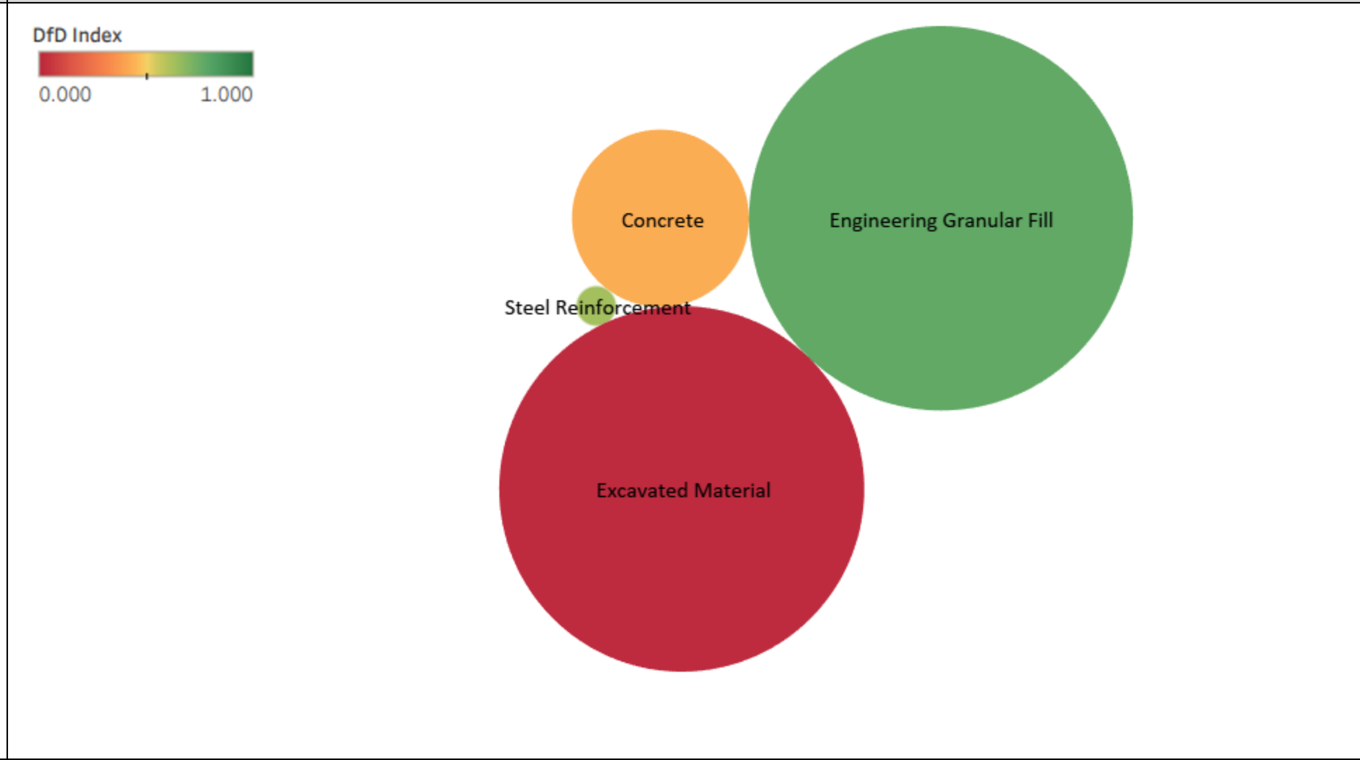
Option 1	Option 2	Option 3
		

Table 5. Packed Circular Map illustrating the mass fraction and DfD Index for Options 1 to 5 for MMA.

Option 1	Option 2	Option 3
		

Option 4	Option 5
	

7.2.3.1 Cumberland Road

The results above show that Options 2 and 3 have a DfD Index of 0.88 and 0.89 respectively, which are larger than Option 1 with a DfD Index of 0.31. This shows that, the steel sections provide a significantly greater 'design-for-disassembly' friendly solution. The CHS steel bearing piles solution (Option 3) is found to a have marginally higher DfD Index since the percentage of total mass of the Ekki mat is considerably higher than that compared to the UC section steel bearing solution (Option 2). With a DfD Index of 0.94, the ekki mat is found to be the most favored material for all 3 options.

The analysis shows that one of the main reasons for this large discrepancy between Option 1 and the other two options is the difference in percentage of Guidance C and D affiliated actions that are achieved. This is highlighted by the fact that the steel piles achieve approximately 64% and 86% of actions affiliated with Guidance's C and D respectively. However, assuming the materials are fully retrievable from the ground, only 27% and 57% of actions concerning Guidance C and D, respectively are achieved for concrete. For the steel reinforcement, despite being the same material as the steel piles, only achieves 45% and 71% of actions concerning Guidance C and D respectively. This is mainly since the steel reinforcement is embedded within the concrete pile and therefore difficult to extract for reuse.

A key assumption made for the CFA Pile (Option 1) was that the DfD Index was calculated by considering the DfD of the steel reinforcement and concrete separately. If, however the pile was treated as single material, then it would subsequently mean that the pile would be automatically assigned with a DfD Index of zero since there is no method of recycling or reusing reinforced-concrete piles. In this case, the total DfD Index of Option 1 would be reduced to 0.08, which is a 75% drop from the original DfD Index of 0.31. Since it is likely that the CFA piles are to remain on site due to client and contractor preference, it is more likely that the DfD Index for this option is 0.08. This is common practice since the time and cost associated to dissembling the piles would be highly costly with negligible financial gain as the value of the piles is diminished.

Cases where reinforced concrete piles are used, more research is needed into the re-use of reinforced concrete piles that can substantially reduce the DfD Index of other materials to improve the Circularity of the project. For Cumberland Road, a considerable quantity of material is excavated. Conservatively, it was assumed that all the excavated material would be sent directly to landfill, giving it a DfD Index of 0. However, currently approximately 95% of excavated material is recycled and therefore a DfD Index of 0.1 can be assumed. This represents a material that is fully recyclable. Hence, an alternative assumption that may have been adopted was to assume a DfD Index of 0 for the concrete and steel, but a DfD Index of 0.1 for the excavated material, taking the total DfD Index of Option 1 is 0.11. This is still comparatively lower than 0.31 but offers are more conservative assessment of Option 1.

Continuing with the discussion of the impact of excavated material but reverting to the assumption that it has a DfD Index of zero, the results emphasised importance of construction techniques. For example, CFA piles are typically bored (excavated and fill) rather than driven (pushing through into the soil), with the latter being the preferred choice of installation for the steel piles. For option 1, the excavated material makes up 39% of the total mass of material on site. By instead opting for driven piles over bored, the amount of excavated material is dropped to zero, taking the total DfD Index of option 1 solution to from 0.31 to 0.50, representing a 39% increase.

Furthermore, if the concrete and steel reinforcement both have a DfD Index (for reasons discussed previously) of zero but assuming the piles are installed by being driven into the ground, the DfD Index rises from 0.08 to 0.12. This suggests that the project's DfD Index can be improved by approximately 33%, simply by re-thinking the method of installation. This shows that in cases such as buried reinforced concrete foundations, the Circularity of a project can be significantly improved by the construction methodology, without changing the material selection. Moreover, a positive knock-on effect is also observed by reducing the waste produced on site, so does the cost of removing waste from site come down. This represents a positive correlation between cost and Circularity.

For all three design solutions, the ekki mats were found to have the highest DfD Index standing at 0.94. This is certainly reflective of the current practice in the temporary works industry where an individual ekki mat is reused on multiple projects, provided the structural integrity is maintained. During the assessment, the ekki mat proved to be a highly circular product, for the following reasons:

- It is modular in nature as the planks are prefabricated and transported directly to site.
- They are typically ordered 'off the shelf' meaning the sizes of the ekki mat planks are standardised.
- No mechanical or adhesive connection is required. A key attribute of ekki mats are that they can be removed from site.
- Leading on from the fact that each plank is not connected by any means, they are subsequently freely interchangeable.
- They are normally fully exposed and are in direct contact with the rig. This means that they abide by the principles of 'hierarchy of disassembly where the most Circular materials of a design are readily accessible.

The quantity and purpose of the ekki mats, serving as the piling platform, was assumed the same for all options. Despite having the same DfD Index for each option, the ekki mat only makes up 8% of the total mass on site for option 1. However, for Option 2 and 3, the ekki mat makes up 55% and 62% respectively. This suggests that reducing the weight of materials with a lower DfD Index can then increase the weight of influence that materials with a high DfD Index have on the final DfD Index. However, this should not warrant the user of the assessment to simply increase the mass of ekki mats on site for the purposes of increasing the total DfD Index of option unless there is reasoning to do so.

The granular fill is also found to be highly 'Circular' due to a high DfD Index. Similarly, to the ekki mat case, the extent of influence on the total DfD Index is lower for option 1 than it is for options 2 and 3. Moreover, the granular fill is naturally highly Circular, and it was expected to have a similar DfD Index to that of the ekki mat. However, the following actions could not be achieved due to the specific requirements of the project:

- Could not achieve the principles of 'hierarchy of disassembly' as the granular fill was buried.
- For the same reason of not achieving 'hierarchy of disassembly', access to all parts of the design could not be achieved.
- The fill could not be removed from the overall system without lifting the ekki mats from position.
- No standardised structural not geotechnical grids could be assigned as the voids on site were sporadic and could only be determined while on site.

7.2.3.2 MMA

Option 1, the sheet pile wall, achieved the highest DfD Index of 0.73. However, the design option that achieved the lowest DFD Index was the contiguous pile wall with a DfD Index of 0.33. By comparing the two extremes, the following deductions can be made:

- The sheet pile wall can be installed by being driven into the ground and does not require any excavation. This significantly reduces the percentage of mass of waste material sent to landfill, which is in stark contrast with the contiguous pile wall solution, and indeed all the other options considered for MMA. This reinforces that minimising construction waste sent to landfill is critical to achieving a high DfD Index.
- Each sheet pile section is mechanically fastened to one another. However, the contiguous pile wall is comprised of reinforced concrete, making separation of each material difficult.
- Leading from this, the sheet pile wall can subsequently be reused for the same purpose and the analysis shows that this design option achieved 64% and 72% of actions affiliated with Guidance's C and D, respectively. This reaffirms the concerns surrounding buried reinforced concrete piles as expressed in the Cumberland Road case study.

When comparing Options 2 and 3, it was originally thought before the analysis was conducted that option 3 would achieve a higher DfD Index, since timber panels are considered more desirable for recycling and reuse than pre-cast concrete panels. Option 2 has a marginally higher DfD Index than option 3, despite the timber panels having a significantly higher DfD Index (0.83) than the combined concrete and steel reinforcement (0.42 and 0.63 respectively). Despite the timber panels being considerably more Circular, the weight of the material, which is approximately 1% of the total mass of material, is considerably lower than the pre-cast concrete panels, which makes up nearly 3% of the total mass of material on site. Therefore, the influence of the timber panels on the final DfD Index is lower. This inadvertently increases the influence of the other materials, including the less Circular materials such as the excavated material and consequently reduces the final DfD Index. The reliability of the results is therefore brought into question, since the results suggest that by replacing the pre-cast concrete panels with a more Circular and sustainably sourced solution such as timber panels, the final DfD Index is reduced, undermining the principles of sustainable development and Circular Economy. However, this phenomenon is largely attributed to the fact that the percentage of total mass attributed to the excavated material is increased. Since the DfD Index is assumed zero, the final DfD Index is driven down.

Continuing from the results observed from Cumberland Road, a sensitivity check was undertaken where all buried material was assigned with a DfD Index of 0. The following result were found:

- For option 1, only 20% of the sheet pile wall is exposed, and the remaining 70% is buried. If extraction from the ground is unachievable, then the DfD is reduced from 0.73 to 0.16.
- For options 2 and 3, the concrete bored pile is buried, and therefore the total DfD is reduced from 0.39 and 0.38 respectively to 0.33. However, by assuming a DfD Index of 0.1 for the excavated material, the total DfD Index is improved to 0.37, which is considerably low (approximately 25) reduction compared to the original DfD Index of options 2 and 3.
- For option 4, approximately 70% of the entire length of pile wall is buried. This therefore results in a drop from 0.33 DfD Index to 0.23. Sticking to this assumption but assigning a DfD Index value of 0.1 to the total excavated material, an improvement to the total DfD Index is experienced, moving up from 0.23 to 0.27.
- For option 5, only the base of the reinforced concrete L-shape wall is buried, accounting for 50% of the total mass of the wall. Hence, the DfD Index is reduced from 0.41 to 0.39. However, by assuming that the DfD Index of the excavated material is 0.1, the DfD Index of option 5 is increased from 0.39 to 0.43. The DfD Index is ultimately greater compared to the original assumptions made about the excavated material DfD Index and buried concrete. This exemplifies the importance of recycling excavated material. This suggests that the lack of circularity of materials being considered in a product can be compensated by actively ensuring that all excavated material (material leaving the current eco-system) is sent to be recycled.

8.2.3. Stakeholder Engagement

In order to ensure that each deliverable action in the DfD checklist is achieved, the design team is required to outline whom is to be informed or consulted with. This section discusses the patterns that had emerged amongst each key stakeholder and will discuss the main role in which they played in fulfilling the achievable actions. An example of this is outlined in Appendix N.

Client

In reference to Appendix F, action D7 of the DfD checklist, it was consistently shown that the design team is to inform the clients of their role in maintaining all the information that details the methods of disassembly of their asset(s) after its design life or purpose has been fulfilled. The client's role in ensuring the traceability of the different components and materials that form their assets is essential to maximising the volume of material re-entering the built domain. This is also an opportunity for the design team to recommend the use of 'material passports. From a value retention perspective, it is key to the client that materials that are considered for disassembly and reuse are well maintained to retain their integrity and quality. The client's role in fulfilling circularity in the project is through asset management after the end of construction.

Supplier and Manufacturer

The role of the supplier and manufacturer in the two projects assessed in this research was found to be the provider of key pieces of information to the design team. It was found that for actions A1 to A3 (see Appendix F), the design team were to consult with the supplier and manufacturer and determine the key pieces of information regarding the recycled content, types of material, and possible toxic and hazardous elements in the material being considered. Another key observation made was the involvement required from the supplier and manufacturer on action C8 of the DfD checklist, which outlines 'use minimum number of different types of connectors. This is an action where avoiding connectors altogether for the ekki mats improves the possibility of disassembling them and avoiding permanent damage to the structure which improves the possibility of establishing a take-back scheme between the contractor, supplier and manufacturer. Moreover, action C2 of the checklist, outlined as 'modular design' is a key area in which the design team can request from the supplier and manufacturer the chance to reuse any ekki mats that have been used in previous sites to minimise the production of new ekki mats.

Contractor

The contractor has an instrumental role in determining the constructability factor of each achievable action. Actions such as 'providing standard and permanent identification of material types', 'permanently identify point of disassembly' and 'using materials intended for handling' can be better determined through discussions between the contractor and design team to ensure that a practical solution is achieved and communicated on the drawings. The contractor typically has a preference for methods of connections, and so it is the responsibility of the design team to persuade the contractors of the preference for mechanical over adhesive connections. In this case, the contractor plays the decision-making role. It was evident that Guidance's A and B had minimal involvement or engagement from the contractor, but Guidance's C and D had more so. This suggests that the method of construction is critical to ensuring that the material can then be dissembled. Figure 14 illustrates the need for all three key stakeholders to fulfill their responsibilities to ensure that the deliverables of Circular Economy are fulfilled in a project.

Figure 14. Illustration of the key stakeholder that the designer must engage with. If all the stakeholders fulfill their responsibilities, the possibility of fulfilling the achievable deliverables in the Design for Disassembly Checklist.

8.3. Summary of results

The purpose of this section is to discuss the results from the assessment and to outline the key observations made for each material and specific design element. The following highlights key deductions made during the assessment:

- Identifying the point of disassembly is easily achievable for temporary works where the site is to be restored to its original status. One material/element that exemplifies this are Ekki mats which are ideal for contractors when disassembly is a key performance indicator of the project. In the case for the steel piles, should the client have been opened to the idea of removing the piles for future re-use, the toolkit provided various deliverables that would maximise the possibility of removing them. For example, cut-off points could be implemented above the road level to easily identify the location of the pile to ease the process of extraction. The current practice of 'setting out points' on drawings, which allocate global co-ordinates (easting, northing) and elevation of elements could be utilised to relocate the buried piles. This is a prime example of storing construction information to ensure recoverability, especially for buried elements.
- For permanent works, identifying the points of disassembly is more difficult to achieve at the end of the 60 to 120 years design life.
- The reusability of materials and elements is greater for temporary works over permanent. This is because the value of the product after use is more predictable and more likely for the client and contractor to appreciate its financial value. In contrast, it is difficult to predict if the materials considered in this assessment will be used in 60 to 120 years.
- The client's involvement in the delivery of designing for disassembly and reuse comes in the form of maintenance and keeping record of the information related to the construction and deconstruction of the asset they are responsible for.
- The supplier and manufacturer have a far greater involvement in achieving circularity when the element is prefabricated and modular in nature as exemplified when comparing reinforced concrete to the ekki mats. The supplier and manufacturer involvement are also magnified when the information on the structural strength is not as well studied and available. Hence, the supplier and manufacturer are responsible for providing the necessary information to the designer to proceed with the design.
- Information on each product is easily attainable given the limited number of supplier and manufactures involved in the scheme. Hence, achieving this guideline can be easily attained.
- For this project, all elements considered are standardised. For most temporary works, simplicity is critical, and therefore a key component of achieving this is to use standardised products from suppliers to ensure the project program is optimised.
- Given the nature of Ekki mats, mechanical fastening between interacting Ekki mats and other structural components is not required. This makes the assembly and disassembly process considerably easier and therefore more Circular. This is a prime example of avoiding adhesive connections and opt for materials that are mechanically fastened.
- Design engineers, if it already has not been considered, should advocate for improved synergy between the contractor and supplier to discuss the possibility of a 'take back scheme'.
- For concrete piles to be considered economically feasible to extract from the ground, the cost of selling for recycling must increase for it to be financially feasible. For this to be so, government enforced initiatives in the market should be implemented in the future.
- Steel reinforcement, despite being a highly recyclable and perhaps even a reusable material, is difficult to retrieve as it is buried and embedded into concrete. This shows that designers should make sure that materials that are inherently Circular, must be easily accessible when the structure is being disassembled.
- Recent development in the construction industry has seen the rise in the use of reused steel-oil barrels. The costs associated with this product are unknown, but they are assumed to be considerably lower than British Standard steel. In the case for Cumberland Road, the cost of the steel piles was a driving factor for the client deciding to opt for CFA piles over steel, the recycled oil barrels could satisfy the clients agenda for keeping the project cost minimal while also fulfilling the benefits of Circular Economy.

9. Future Consideration

To improve the reliability of the results, it could also be argued that a separate weighting system could be developed for each deliverable of a given guidance. The current analysis assumed that each deliverable has an equal weight. However, it could be argued that, for a given project, the client has an incentive to use more recycled materials in the project but has less interest in using more mechanical connections over adhesive. For future consideration, the assessment tool will be developed to allow the user of the spreadsheet to alter the weighting class of each action.

It is also envisaged that the toolkit will also be trialed on various structures projects, such as bridges, and other geotechnical projects such as earthworks. It is intended that the more projects that the toolkit is tested on, the greater trust towards the results the toolkit will provide to the user. It will also provide the opportunity for standardization of the results given the nature of infrastructure projects which will massively improve the efficiency of using the toolkit.

This research was focused on developing a Circular Economy assessment tool, specifically targeting ways of designing elements, structures, and services to be dissembled for future use. From a sustainable development perspective, this helps stimulate more economic opportunities such as reducing material costs for future projects, significantly reducing the strain on landfill sites, and envisaged more innovation in the production of construction materials to be more Circular. It is encouraged that this assessment tool is used in conjunction with the environmental checklist which are used to ensure compliancy with CEQUAL standards to mitigate the environmental impact of infrastructure projects. It is also envisioned that the toolkit is used in a resource efficiency workshop in order to appreciate the extent of improvement on Circular Economy can have on improvement on value retention and resourcefulness.

10.Conclusion

This report has outlined the benefits of Circular Economy in delivering the goals of sustainable development in UK infrastructure. This was achieved by first understanding the prevailing socio-economic and environment issues concerning the UK and the affiliated impact that infrastructure is having on propelling these problems. It was then proposed that Circular Economy provides the remedy to tackling these problems by encouraging a more 'cradle – to – cradle' approach to delivering and managing infrastructure projects as oppose to the current 'take-make-waste' model that has dominated.

The report also focused on the ways in which Circular Economy can be encouraged into the UK Infrastructure domain, which include, but not exclusive to, creating market mechanisms to encourage reuse of second-hand construction material, improved IT and technology to enhance traceability of assets and greater encouragement from the government to introduced guidelines on business models tailored towards Circular Economy. Although the advantages of Circular Economy are well understood and gaining increasing recognition in the industry, this report also covers the hindering factors that have prevented it from coming to fruition. The report also introduces the effort being made to normalise Circular Economy-thinking in the process of designing and managing infrastructure as well as case studies that exemplify the actual practice of Circular Economy in construction.

The involvement of design engineers and how the principles of Circular Economy can be adopted into the physical design of infrastructure were discussed, which introduced the concept DfD. A toolkit was proposed to enable better decision-making for design engineers to incorporate features that improve disassembly and recoverability of a material. The toolkit consisted of a DfD log and a DfD checklist which is used to assess the extent of Circularity of each material considered for a given design option.

The toolkit was trialled on two projects to understand its effectiveness in measuring the Circularity of a project and delivering the most resource-efficient, value-driven design to the client. One of the takeaway observations of the toolkit was the success in creating a metric system that improved comparability between different design solutions.

The UK Infrastructure has a major role to play in the fulling the sustainable development goals and challenges. Although still in its infancy, the integration of Circular Economy thinking, despite the numerous challenges facing it, offers an exciting and optimistic alternative to the current wasteful and short termism way in which companies in the industry operate and ensure that in the future, sustainable development takes centre stage in UK Infrastructure projects.

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Appendix A – key concepts that have shaped Circular economy principles

Key Concepts	Definitions
Cradle-to-Cradle' approach	first defined by German chemist Michael Braungart and American architect Bill McDonough, the concepts introduce that idea that all materials involved in an industrial and commercial domain should be considered as 'technical' or 'biological' nutrients. The framework focuses on designing products for continuous recovery and reutilisation as nutrients within the economy.
Performance Economy	Walter Stahel, architect and industrial analyst, outlined the 'Potential for Substituting Manpower for Energy' in his 1976 research report to the European Commission outlining his vision for an economy in loops and the subsequent impact on job creation, economic competitiveness, resource saving and waste prevention;
Biomimicry	This concept introduces the idea that nature can be studied to inspire new innovations and technologies, such as the leaf inspiring the fruition of solar cells.
Industrial Ecology	sometimes referred to as the 'science of sustainability', this is the study of resource and corresponding energy flows through the life span of a product. The concepts specially aim to focus on creating a closed loop process where waste is treated as an asset and thus entered back into the industrial ecosystem. This subsequently eliminates the notion of 'undesirable by products. The concept goes one step further and points out the value of a systems thinking approach for the model to capture the wider impacts it has on the global ecological constraints.
Natural Capitalism	This aims to encourage the recognition of the interdisciplinary and overlapping nature of the shared interests between the environmental and business. The idea is to build a business case for taking care of nature to preserve our natural resources and subsequently protect the economy.
Blue and Green Economy	This is an open-source movement that encourages better stewardship of our natural resource while ensuring economic growth, improved livelihoods, and jobs.
Regenerative Design	A process-orientated whole systems approach that aims to incorporates the process of restoring, renewing, and revitalising the energy and material used to create the design.

Appendix B – metrics to measure Circular Economy

Option 1: Impact Based metrics:

There are a range of metrics that are being used at both infrastructure projects/asset and organisational levels which be considered as proxy indicators to Circular economy outcomes (Mckinsey Center for Business and Environment, 2018):

- Energy use and/or energy related carbon emissions
- Water use
- Water generation
- Landfill diversion
- Materials use and/or material-related carbon emissions
- Proportion of recycled content
- Natural capital account

A limitation of this metric is that are always retrospective. They will have mist impact when tracked. Another limitation is that they do not provide any context to impact generated (Mckinsey Center for Business and Environment, 2018).

Option 2: Productive-based metric:

This enables the designer to consider the impacts relative to the value created. For example, as outlined in the Ellen Macarthur Foundation Growth Within report, GDP generated per unit of net virgin finite material input. Whilst GDP is not applicable to infrastructure organisations, the concept of units of virgin finite material input relative to output of an organisation could be a useful metric. A high level organisation level metric could be considered is total value created over resource inputs, taking into account the service and utility aspect of value created (Mckinsey Center for Business and Environment, 2018).

It is proposed that this method of measure is goof for measure of actual performance of Circular economy.

Option 3: Attribute metrics:

Ellen Macarthur Foundation Growth Within Report also suggests secondary metric (Mckinsey Center for Business and Environment, 2018):

- Product utilisation (average utilisation across all products)
- Product depreciation/lifetime
- Material value retention ratio (value of recovered materials/value of net virgin materials). An indicator of material value retention ratio could be utilised at both an asset and organisational level and is linked to the concept of residual value.

Option 4: Enabler-based metrics

Examples of enablers that could be monitored include proportion of procurement activities which incorporate Circular economy requirements, number of Circular economy innovation initiatives implemented, number of proportion of procurement/projects that incorporate whole life costing, number of proportion of assets and/or asset components that have end-of-life adaptability plan (MI-ROG, 2018).

Appendix B – Take Back Scheme case study

M42 Junction 6 Improvement Scheme

The benefits of the take back scheme are only recognised from a short-term perspective. For example, Highways England published an Environmental Statement for the £282 million M42 Junction 6 Improvement scheme. To minimise the environmental impact of the project, an assessment on the estimated quantities of waste arising during construction of scheme was undertaken. A total of two out of a possible 12 waste types, plastic and cardboard/paper were eligible for the 'take-back 'scheme as a form of potential management route. The predicted recovery rate expected from plastic and paper/cupboard during construction was approximately 80% and 85% respectively, however no information on the actual rate was published. This example shows that the extent of immaturity of the take-back scheme in construction, particularly in infrastructure. Take back only done for environmental goals, and ability to measure economic value has not been appreciated.

Appendix D – Circular Economy Case Study

China

China, a nation developing into a future superpower, has been experiencing a significant rise in population and subsequently heavy investment in developing infrastructure and urban development. As a result, there are many theoretical studies due to early adoption (year 2002) of Circular economy as the nationwide development strategy in China. The intention was that Circular economy would promote sustainable urban development in China to ensure equilibrium between urban and rural areas. Waste elimination and reallocation of resources were regarded as good strategies for encouraging rural populations to remain in rural area. This then led to 2003 Cleaner Production Promotion Law, which was then amended to Law on Pollution Prevention and Control of Solid Waste in 2005. Viewed as revolutionary at its time, the CE Promotion Law was implemented in 2009 (Kalmykova, 2018).

What makes China distinguished to UK is that China is a developing country. The informal collection and recycling sector are substantial. The policies in these countries are aimed at streamlining the waste and secondary materials flow through official channels only, including bans on informal recycling. In developed countries however, such as Germany and Sweden, promotion of the reuse and repair centres as well as tax breaks for the repair shops have been suggested (Kalmykova, 2018)

Netherlands, Venlo

In 2006, the city of Venlo, along with the Chamber of Commerce, inspired by the principles of cradle to cradle, decided to evolve the image and economy of the city to incorporate the principles of Cradle to Cradle (C2C) (Foundation, 2019).

In 2009, the idea transpired into action, and the design of the new Venlo City Hall, along with other new structures, implemented careful decision making of use of materials and energy saving technologies. The construction commenced in 2012 and was finished in 2016. The use of C2C economics has now enabled the continuous material recovery and reutilisation in a technical and biological system. This was achieved by designing in the ability to dissemble the components of the structure and enable to recoup ability of the original investment to the structures. This is a prime example of the effective use of the 'buy and buy-back scheme' business model and elaborates the economic benefits of Circular economy (Foundation, 2019).

The building itself, a renovated old neighbourhood factory, was built on the edge of the River Meuse, an area that would gain from the regeneration and economic development. The building is connected to the natural system by harnessing rainwater harvesting, converting carbon dioxide to oxygen and filters particulates, and creates habitats for birds and insects. A major aspect of Circularity is the documentation of the products using digital material passports. This facilitates the tracking of product ensuring that there is evidence of the asset's material constituents, along with how to dissemble, then recycle or return them to manufacturer. By creating a log of residential material value, the buildings value can be quantified in terms of material banks. To maximise the desirability of being able to dissemble and reuse the building, certain materials were avoided (Foundation, 2019).

While the primary aim was to improve the built environment, the secondary driving factor was to capture long-term economic saving, protecting human health, and promoting the ambition and image of the city. The tender stage also shined light on Circular economy's ability to inspire new ideas and initiatives, with over 50 proposals submitted in response to the specification od the tender. The city's image, once associated with agriculture and logistics, is now increasingly welcoming to new businesses inviting more 18-24-year-old to the city. Such examples of the long-term impacts of the project was that it inspired the inspired the first Cradle to Cradle Product Certification Training centre in Europe that opened in Venlo (Foundation, 2019).

Toronto, Canada

Toronto's Circular Economy Procurement Implementation Plan and Framework is aimed to become a significant tool in enhancing economic growth, creating social prosperity and steering towards zero waste production in the city. The Framework is consistent with the direction set out in the city's Long-Term Waste Management Strategy, by encouraging existing suppliers to adopt Circular economy business models. The purpose is to fulfil the SWMS objective to change how resources are regarded, such as, by designing systems and products to enable greater recovery of materials.

It is intended that a three-trial period is undertaken, with the construction and engineering industry being included in the targeted sectors. A total of CAD 1.8 million has been allocated over three years to cover the costs of various initiatives that involve Circular economy principles.

In these early stages, the core indicators of success are as follows:

- Economic – cost savings od the city, waste reduction savings
- Environment – percentage of waste diverted from landfill, CO2 savings, percentage of recycled content, raw materials avoided
- Social – number of associated jobs created, number of people that have received Circular economy training, asset sharing activities.

Queen Elizabeth Olympic Park, London

The Queen Elizabeth Olympic Park, London is a sporting complex built for the 2012 Olympic and Paralympic Games, situated to the east of the city adjacent to the Stratford City development. One example of this was the Podium café.

The designers of the cafe followed the waste hierarchy during the design process and identified 4 specific ways that enables waste to be designed out:

1. Timber frames changed to cross laminated timber as this can be manufactured offsite in controlled conditions which reduce re-working and onsite waste
2. Deep foundations changed to shallow raft foundation, reducing excavation level by 275 mm
3. Studded steel drilled piles changed to precast concrete piles reducing the amount of waste
4. BIM modelling and coordination of services was undertaken to minimise logistical clashes and enable the preformation of holes

Another example was the Olympic Station. The minimalist structure was designed to be extremely light and resource efficient, using 90 % less steel than the Bejing 2008 Birds Nest Stadium. This was achieved by the re-use of surplus gas pipelines for compression truss structures which saved 2,500 tonnes of new structural steel, saving approximately £500,000. Further optimisation was achieved by using new blockwork techniques which reduced the amount of steel support required, further saving £40,000. Most notably, 104,000 tonnes of recycled crush concrete were re-used after being used onsite for a temporary platform, eliminating the need to import the quantity of virgin materials, saving £1 million and more than 20,000 lorry movements. Furthermore, the London Aquatics Centre was designed to ensure waste reduction was achieved through several methods:

- Offsite/modular construction to minimise onsite waste
- Just-in-time ordering
- Pre-fabrication
- Pre-deconstruction auditing and material assignment
- Ordering to precise specification (to avoid over-ordering)
- Design for deconstruction and reuse with similar functionality
- Regular review of programme to understand what materials were available and when
- Correct storage of materials to avoid degradation.

Appendix E – DfD Log

Example of assessment being undertaken on the steel reinforcement used on pre-cast concrete panel.

Purpose	Total mass (kg)	Fixings		Sourced	Explanation of most desirable source	DfD Index	End of design life options (highlighted most desirable option)	Impact to Sustainable Development	Explanation of most desirable end of design life and guideline compliances
		Method of installation	Connected to						
Reinforcement in pre- cast panels spanning between kingpost wall	12000	Reinforcement to be cast into the concrete beams offsite and delivered to site.	Chemically bonded to concrete.	Virgin material Recycled material Reprocessed Re-used for alternative purpose Re use for same purpose	Recycled: Steel manufactured from recycled material. Approximately 90% of produced reinforced steel in UK sourced from recycled metal.	0.36	Dispose – landfill Recycle Reprocess Re-use for same purpose Re-use for different purpose	Production of steel associated with high CO2 footprint. Becoming more expensive to produce and price influenced by international relation meaning availability volatile.	Given the modular nature of the pre-cast concrete panels and that it is not chemically bonded to UC sections, it is advised that the panels be considered for reprocessing or reuse. Should no use be found, panel to be demolished into steel and concrete constituent. Prior to extracting steel, concrete would first need to be demolished and therefore use for concrete needed to be outlined prior to retrieving steel in concrete. Steel to be extracted and considered for reprocessing, pending on condition. Should integrity be comprised, steel to be recycled. Steel inherently with residence time of 250-290 years which exceeds deign life of king post. Steel assessed for future reuse.

Appendix F – Quantitative Assessment, Design for Disassembly Checklist

Table below outlines the DfD Checklist with Guidelines and corresponding deliverables for designing elements for disassembly (Crowther, 2000).

Guideline A: Recycling							
No.	Deliverable	Description	Achieved?	Communicated on	Stakeholder Involvement		
					Client	Contractor	Supplier and Manufacturer
A1	Use recycled material	Increased use of recycled materials will encourage industry and government to develop new technologies for recycling, and to create a larger support network for future recycling and reuse					
A2	Minimise the number of different types of material	This will simplify the process of sorting on site and reduce transport to separate reprocessing plants.					
A3	Avoid toxic and hazardous materials	Reduce potential of contaminating materials that are being sorted for recycling and will reduce the potential for human health and risk.					
A4	Make inseparable subassemblies from the same material	Large amounts of one material will not be contaminated by small amounts of foreign materials that can be separated.					
A5	Avoid secondary finishes to materials	Coatings may contaminate the base material and make recycling more difficult where possible use material that provide their own suitable finish or use separable mechanically connected finishes.					
A6	Provide standard and permanent identification of material types	Many materials such as plastics are not easily identifiable and should have some form of non-removable and non - contaminating identification mark to allow future sorting.					
Guidance B: Reprocessing							
B1	Minimise number of different types of components	This will simplify the process of sorting on site and make the potential for re-processes more attractive due to the larger quantities of same or similar items.					

B2	Use a minimum number of wearing parts	This will reduce the number of parts that need to be removed in the remanufacturing process and thereby make reprocessing more efficient.
B3	Use mechanical connections rather than chemical	This will allow the easy separation of components and materials without force and reduce contamination to materials and damage to component.
B4	Where appropriate, make chemical bonds weaker than the parts being connected	If chemical bonds are used, they should be weather than the components so that the bonds will break during disassembly rather than the components, for example mortar should be significantly weaker than the bricks.
Guidance C: Material reused		
C1	System where parts are more freely interchangeable and less unique to one application	This will allow alteration through the relocation of components without significant construction work.
C2	Modular design	Use components that are compatible with other systems both dimensionally and functionally
C3	Separate structure from services	Allow parallel disassembly where some parts of the structure ay be removed without affecting other parts.
C4	Provide access to all parts of the structure	Ease of access allow ease of disassembly. If possible, allow for components to be recovered from within without use of specialist plant equipment.
C5	Use components that are sized to suit intended means of handling	Allow for various possible handling options at all stages of assembly, disassembly, transporting, reprocessing and reassembly.
C6	Provide means of handling components during disassembly	Handling during disassembly, may require points of connection for lifting equipment or temporary supporting device.
C7	Provide realistic tolerance to allow for movement during disassembly	Process may require greater tolerance than the manufacture process or the initial assembly process.

C8	Use minimum number of different types of connectors	Standardisation of connections will make disassembly quicker and require fewer types of tools, even if this result in the oversizing of some connections. This will save time of assembly and disassembly time.
C9	Design joints and connectors to withstand repeated use	Minimise damage and wear and tear from the assembly/disassembly procedure.
C10	Use hierarchy of disassembly related to expected life span of the component	Make components with short life expectancy readily accessible and easy to disassemble, components with longer life expectancy may be less accessible.
C11	Reusable parts more easily accessible	Allow maximum advantage from reuse program.
Guidance D: Element reuse		
D1	Standardise the parts while allowing for infinite variety	This will allow minor alterations to the structure without major works.
D2	Use standard structural and geotechnical grids	Grid size to be related to the materials used such as structural spans are designed to make most efficient use of product
D3	Lightweight materials and components	This will make handling easier, quicker and less costly, thereby making reuse a more attractive option.
D4	Use a minimum number of different components	Fewer types of component mean fewer different disassembly operations that need to be known, learned and remembered. Encourage construction sequence drawings for future use. This will also ensure more standardisation in the reassembly process which will make the option of relocation more attractive.
D5	Permanently identify point of disassembly	Points of disassembly should be clearly and identifiable and not be confused with other design features.
D6	Provide spare parts on site storage	Both intended to replace damaged components and to facilitate minor alterations to buildings.

D7	Sustain all information on the manufacture and assembly process	Measures should be taken to ensure the preservation of information such as 'as built drawings' information about disassembly process, material and component life expectancy, and maintenance requirement	
DfD Factor, I_{DfD}			

Appendix G – Calculation of the DfD Index

The first process of calculating the percentage of actions achieved for each Guideline. Once this is done, the final DfD Index is calculated by allocating a different weight to each guideline. It assumes and therefore places greater weight on guidance's supporting reusability over recycling. This is achieved by assuming the following weight for each guideline which will then be used the factor the percentage of actions achieved for the guideline:

- Guideline A: accounts for 10% of the final DfD Index;
- Guideline B: accounts for 20% of the final DfD Index;
- Guideline C: accounts for 30% of the final DfD Index; and
- Guideline D: accounts for 40% of the final DfD Index.

Based on the assumptions made above, the following expression represents the correlation between the percentage of actions achieved for each guidance and the DfD Index for a given material(j):

$$I_{DfD,j} = 0.1x_{A,j} + 0.2x_{B,j} + 0.3x_{C,j} + 0.4x_{D,j}$$

Where:

$x_{A,j}$ Percentage of Guidance A actions achieved, expressed as a fraction.

$x_{B,j}$ Percentage of Guidance B actions achieved, expressed as a fraction.

$x_{C,j}$ Percentage of Guidance C actions achieved, expressed as a fraction.

x_D, j Percentage of Guidance D actions achieved, expressed as a fraction.

The DfD Index will vary between 0 and 1, where 0 represents a material that cannot be disassembled and reintroduced to the built environment, and 1 represents that all actions are achieved and that the material can be reintroduced into any stage of the built environment.

Once the DfD Index has been determined for each material considered in a design solution, the mass of each material(j) is determined. It is key that the percentage of total mass (%) of each material considered in the design is determined as this will then be equated to the percentage of weight of influence on the final DfD Index of the design solution. It is therefore assumed that the percentage of total mass (%) is proportional to the DfD Index of a given design option (t) as outlined in the following expression:

$$I_{DfD,t} = \sum_{j=1}^{j} M_{\%,j} I_{DfD,j}$$

Where:

$M_{\%}$ Percentage of total mass (%) of material or element j

Appendix H - Assumptions for quantifying the mass of material for Cumberland Road

Design Solution	Materials	Figure
Option 1- Concrete Pile	Concrete, reinforced steel, Ekki Mat, Engineering Granular Fill, Excavated Material	
Option 2- H-Section Pile	H-Section Steel, Ekki Mat, Engineering Granular Fill	
Option 3- Circular Hollow Section Pile	Circular Hollow Section Steel, Ekki Mat, Engineering Granular Fill	

Assumptions

- Site area of approximately 120m by 6m (720 m^2). Pile spacing of 1.5m by 1.75m assumed for all options, approximating 240 piles. Length of 11m assumed due to detailed design;
- CFA piles consists of C40/50 strength concrete and reinforced steel all cast in-situ. Reinforced in CFA piles comprised of six 12mm diameter steel reinforcement. Shear links comprised of 8mm diameter steel reinforcement spaced at 250mm. 20% extra reinforcement to account for anchorage;
- Total mass of excavation produced from each option assumed to be due to piling. Hence, Options 2 and 3 assumed to produce no excavation due to the assumption that the piles are driven;
- Ekki Mat comprised of 2-layer D60 hardwood timber. Total of thickness of 400 mm assumed across entire area of site; and
- Engineering Granular Fill assumed to account for 10% of site due to voids due to Ekki Matt arrangement;
- All buried material is assumed to be retrievable from the ground;
- All excavated material from site is assumed to be sent to landfill; and
- All materials are assumed to be sourced locally to minimize cradle-to-cradle carbon footprint.

Appendix I - assumptions for quantifying the mass of material for MMA

Design Solution	Materials	Figure
Option 1 - Sheet Pile Wall	Steel	
Option 2 - Kingpost Wall with precast Concrete Panel	Concrete (bored pile and panel), steel reinforcement, H-section steel, granular fill, excavated material	
Option 3 - Kingpost Wall with Timber Panel	Concrete, steel reinforcement, H-section steel, timber panel, granular fill, excavated material	

Option 4 – Contiguous Pile Wall	Concrete, Steel Reinforcement, and Engineering Granular Fill, Excavated Material	
Option 5 – L-shape pre-cast reinforced concrete Gravity Wall	Concrete, Steel Reinforcement, and Engineering Granular Fill, Excavated Material	

Assumptions:

- Site area of approximately 120m long. Maximum retained height assumed 1.6m as suggested from the required level of cutting into the existing slope cutting to facilitate the track widening. The maximum retained height is assumed uniform across site. For Option 1, 2, 3 and 4, the embedded length is assumed 6m, totaling to a length of 7.6m from the top to the bottom of the wall;
- For Option 2 and 3, the UC section was assumed as 254x254x73. The spacing between the sections was taken as 1.35m. The concrete bored pile diameter was assumed as 450mm. The total number of piles therefore assumed was approximately 67. The total length of an individual UC section was assumed as 7.6m and the concrete bored pile length was assumed as 6m;
- For Option 2, the pre-cast concrete panel size was taken as 120mm deep 250mm wide. Therefore, for each span, approximately 7 panels was required, totaling to approximately 469 pre-cast concrete panels required for the permanent works. The longitudinal reinforcement in the pre-cast concrete was assumed as five 12mm diameter reinforced steel bars. The concrete strength class was assumed as C40/50.
- For Option 3, the strength class of the panels was assumed as C24. The section sizes were assumed the same as the pre-cast concrete panels outlined above.
- For Option 4, the concrete strength class of the bored pile wall was C40/50. The longitudinal reinforcement in the pile was assumed as thirteen 20mm diameter reinforced steel. The shear link reinforcement in the pile was assumed as 10 mm diameter shear links at 150mm spacing.
- For Options 2 to 4, the excavation required behind the base of the proposed retained height of the wall was determined by assuming a 45° slope regrade into the existing slope. Hence, the total area of excavation per meter run along the wall length was 3.4m^2/ per meter run. For a 120 m long site, the total volume of excavation and backfill was assumed as approximately 410 m^3.
- Total mass of excavation produced from each option assumed to be due to piling. Hence, Options 2 and 3 assumed to produce no excavation due to the assumption that the piles are driven;
- For Option 5, the required excavation required to install the wall was assumed as 5.1m^2/ per meter run along the wall with a total volume of excavation and backfill of 615m^3. The steel reinforcement in the wall was assumed as 20 mm diameter bars spaced at 200mm for the longitudinal reinforcement. The shear links was assumed as 10 mm diameters spaced at 150mm. In addition, an extra 20% extra of reinforcement was assumed to account for lapping and anchorage length. The width of the base of the wall was assumed the same as the retained height, and the thickness was assumed as 300 mm across the wall length. The concrete strength was assumed as C40/50;
- During discussions with the client and contractor, it was opted for the engineering backfill where required to be sourced from the abandoned ballast on the track to minimise cost of sourcing material to site;
- Gabion-Basket and Redi-rock wall was omitted from the analysis as the client required a minimum design life of 120 years; and
- All materials are assumed to be sourced locally to minimize cradle-to-cradle carbon footprint.

Appendix J – table of mass of material assumed in analysis

Cumberland Road		
Option 1 – Concrete CFA Pile		
Material	**Mass (Mg)**	**Percentage (%)**
Concrete	17925	52.59
Reinforcement Steel	47	1.38
Ekki Mat	261	7.64
Engineering Granular Fill	18	0.53
Excavated Material	1344	37.86
Total	3461	100
Option 2 – Steel UC Section		
Material	**Mass (Mg)**	**Percentage (%)**
254x254x73 UC S355	193	40.94
Ekki Mat	261	55.24
Engineering Granular Fill	18	3.82
Total	472	100
Option 3 – Steel CHS		
Material	**Mass (Mg)**	**Percentage (%)**
219x10 CHS S355	135	32.60
Ekki Mat	261	63.04
Engineering Granular Fill	18	4.26
Total	414	100
MMA		
Option 1 – PU18 Sheet Pile wall		

Material	Mass (Mg)	Percentage (%)
Pu 18 Sheet pile	140	100
Total	140	100
Option 2 – Kingpost Wall with pre-cast concrete panel		
Material	**Mass (Mg)**	**Percentage (%)**
254x254x107 UC S355	55	2.53
Concrete Bored Pile	283	13.20
Pre-cast Concrete Panel	58	2.69
Steel Reinforcement	2	0.09
Excavated Material	934	43.60
Engineering Granular Fill	811	37.88
Total	2141	100
Option 3 – Kingpost Wall with timber panel		
Material	**Mass (Mg)**	**Percentage (%)**
254x254x107 UC S355	55	2.58
Concrete Bored Pile	283	13.49
Timber panel	14	0.66
Excavated Material	934	44.55
Engineering Granular Fill	811	38.71
Total	2097	100
Option 4 – Contiguous Pile Wall		
Material	**Mass (Mg)**	**Percentage (%)**
Concrete	856	27.94
Steel Reinforcement	56	1.83
Excavated Material	1349	43.86

Engineering Granular Fill	811	26.37
Total	3072	100
Option 5 – L-Shape reinforced concrete gravity wall		
Material	**Mass (Mg)**	**Percentage (%)**
Concrete	261	10.00
Steel Reinforcement	14	0.54
Excavated Material	1106	42.35
Engineering Granular Fill	1229	47.08
Total	2610	100

Appendix K – Cumberland Road assumptions for determining the DfD for materials.

- The buried CFA piles have been assumed to be retrievable out of the ground. Typically, buried reinforced-concrete piles remain buried and is considered highly uneconomical to retract nor feasible to reuse.
- Given the modular nature of the CHS and UC end bearing piles, extraction from the ground after the end of the temporary works is considered feasible, provided an end of use plan is considered by the contractor or client.
- The de-construction of the temporary works is assumed to be in the reverse order of the construction sequence.
- Ekki mats are not mechanically nor chemically fastened to one another.
- The current practice in engineering and construction is that the chemical bond between steel and concrete is assumed sufficient to achieve the required structural integrity. Hence, weakening the chemical bond between the steel and concrete is considered unfeasible. However, designer and contractor to consider using weaker concrete strength class if suffices and safety to life is not undermined.
- All excavated materials from the site is sent straight to landfill and subsequently assigned with a DfD factor of zero;

Appendix L – MMA assumptions for determining the DfD for materials

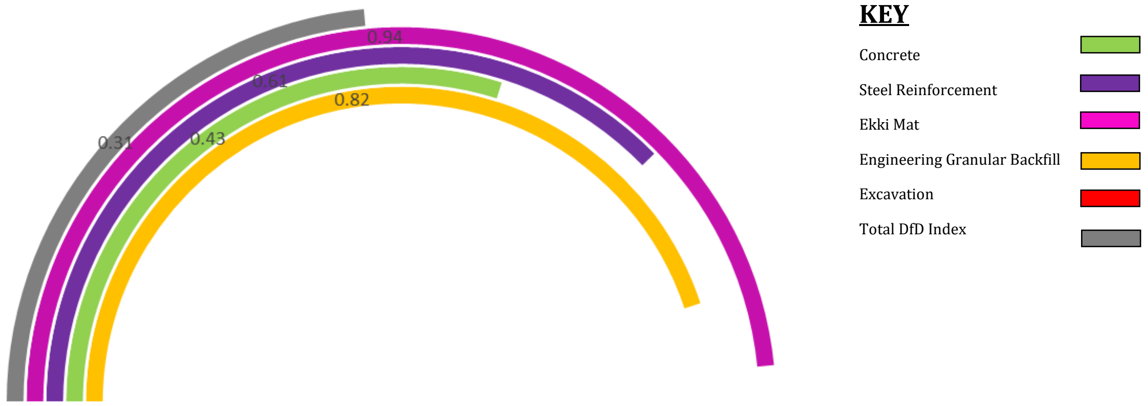
- Similarly, for the Cumberland Road case study, all buried materials, including the contiguous pile wall, bored piles for the king post wall, and the sheet driven pile wall, have been assumed to be retrievable out of the ground.
- Exposed elements are assumed to be economically and technically retrievable after the end of their design life.
- The materials required for the temporary works to construct each option was ignored.
- For the Kingpost wall solutions (Options 2 and 3) the connection between the panels and steel UC posts was assumed to be mechanically connected.
- Like Cumberland Road, and indeed most projects in the UK, the current practice in in the construction industry is that the chemical bond between steel and concrete is assumed is critical for achieving structural integrity. Hence, for all options where reinforced concrete was considered, the possibility of weakening the chemical bond between the concrete and reinforced concrete was not considered.
- All excavated materials from the site is sent straight to landfill and subsequently assigned with a DfD factor of zero;
- The Options 2, 3 and 4, the installation of concrete piles was assumed to be bored. This therefore meant that the amount of exaction material produced by boring had a contributive affect to the total excavated material.
- For option 1, the sheet pile wall was assumed to be driven into position. Each sheet pile section was assumed to be mechanically fastened.

Appendix M – Summary of DfD values for each material for given design solution.

Cumberland Road

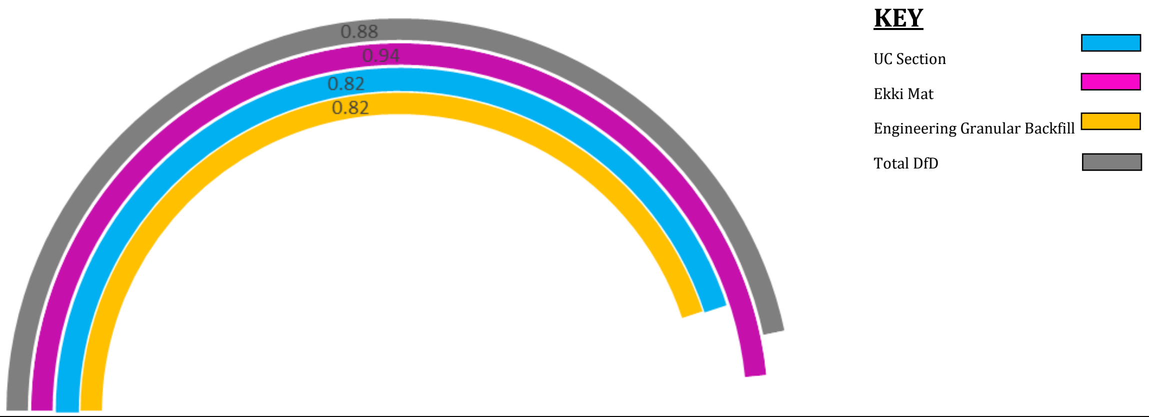
Option 1 – Concrete CFA Pile

Material	DfD Factor	Weight of DfD (%)
Concrete	0.35[1]	52.59
Reinforcement Steel	0.61[1]	1.38
Ekki Mat	0.93	7.64
Engineering Granular Fill	0.82	0.53
Excavated Material	0	37.86
Total	0.31	100



Option 2 –Steel UC Section

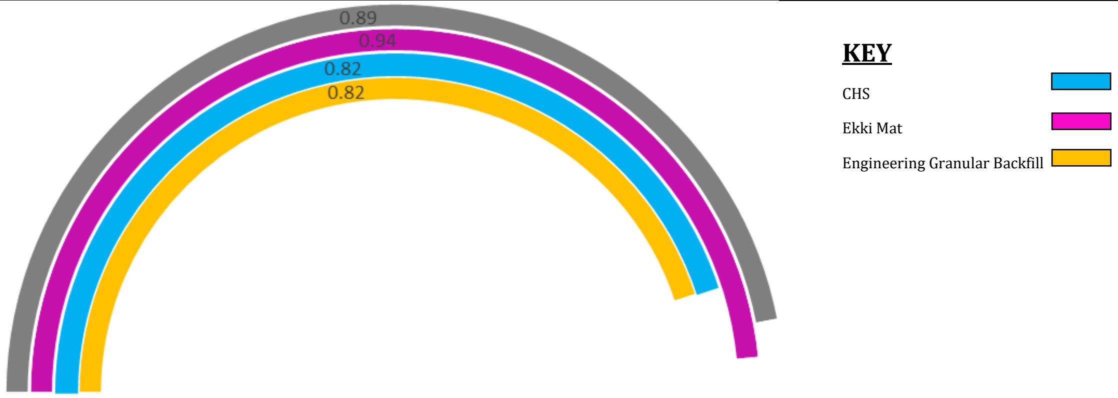
Material	DfD Factor	Weight of DfD (%)
254x254x73 UC S355	0.82	40.94
Ekki Mat	0.94	55.24
Engineering Granular Fill	0.82	3.82
Total	0.88	100



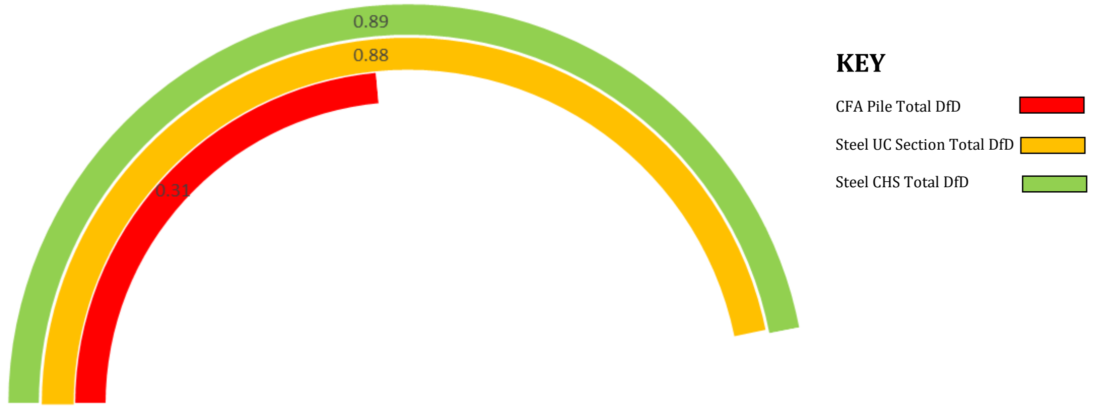
Option 3 – CHS

Material	DfD Factor	Weight of DfD (%)
219x10 CHS S355	0.82	32.60
Ekki Mat	0.94	63.04

Engineering Granular Fill	0.82	4.26
Total	0.89	100



All Options



MMA – IS15-03

Option 1 – PU Sheet Pile

Material	DfD Factor	Weight of DfD (%)
PU 18 Sheet pile	0.73	100
Total	0.73	100

Option 2 – Kingpost Wall with pre-cast concrete panel

Material	DfD Index (I_{DfD})	Weight of DfD (%)
254x254x107 UC S355	0.78	3
Concrete Bored Pile	0.35	13
Pre-cast Concrete Panel	0.61	3
Steel Reinforcement	0.63	0.09

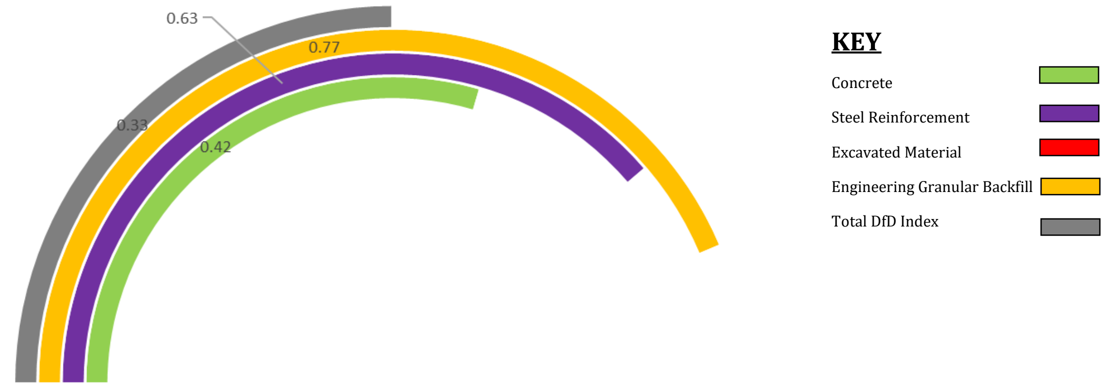
Excavated Material	0.00	44
Engineering Granular Fill	0.77	38
Total	0.39	100

Option 3 – Kingpost Wall with timber panel

Material	DfD Index (I_{DfD})	Weight of DfD (%)
254x254x107 UC S355	0.78	3
Concrete Bored Pile	0.35	13
Timber panel	0.83	1
Excavated Material	0.00	45
Engineering Granular Fill	0.77	39
Total	0.38	100

Option 4 – Contiguous Pile Wall

Material	DfD Index (I_{DfD})	Weight of DfD (%)
Concrete	0.35	28
Steel Reinforcement	0.63	2
Excavated Material	0.00	44
Engineering Granular Fill	0.77	26
Total	0.33	100



Option 5 – L-Shape reinforced concrete gravity wall		
Material	**DfD Index (I_{DfD})**	**Weight of DfD (%)**
Concrete	0.35	10
Steel Reinforcement	0.63	0.5
Excavated Material	0.00	42.5
Engineering Granular Fill	0.77	47
Total	0.41	100

All Options

Note:
[1] Buried cast in-situ reinforced concrete (concrete and reinforced steel) assumed to be retrievable from the ground and therefore is able to be sent back into the 'cradle-to-cradle' cycle.

Appendix N – Stakeholder Involvement section of DfD Checklist – Worked Example

Table 6.Example of DfD checklist being used for ekki mat for Cumberland Road.

Guideline A: Recycling							
No.	**Deliverable**	**Description**	**Achieved?**	**Communicated on**	**Stakeholder Involvement**		
					Client	**Contractor**	**Supplier and Manufacturer**
A1	Use recycled material	Increased use of recycled materials will encourage industry and government to develop new technologies for recycling, and to create a larger support network for future recycling and reuse	Yes	Final Submission Report			✓
A2	Minimise the number of different types of material	This will simplify the process of sorting on site and reduce transport to separate reprocessing plants.	Yes	Final Submission Report		✓	
A3	Avoid toxic and hazardous materials	Reduce potential of contaminating materials that are being sorted for recycling and will reduce the potential for human health and risk.	Yes	Hazard Log and CDM Review		✓	
A4	Make inseparable subassemblies from the same material	Large amounts of one material will not be contaminated by small amounts of foreign materials that can be separated.	Yes	Final Submission Report		✓	
A5	Avoid secondary finishes to materials	Coatings may contaminate the base material and make recycling more difficult where possible use material that provide their own suitable finish or use separable mechanically connected finishes.	Yes	Drawings	✓	✓	
A6	Provide standard and permanent identification of material types	Many materials such as plastics are not easily identifiable and should have some form of non-removable and non -contaminating identification mark to allow future sorting.	Yes	Drawings and Final Submission Report	✓		
Guidance B: Reprocessing							
B1	Minimise number of different types of components	This will simplify the process of sorting on site and make the potential for re-processes more attractive due to the larger quantities of same or similar items.	Yes	Drawings and Final Submission Report		✓	

B2	Use a minimum number of wearing parts	This will reduce the number of parts that need to be removed in the remanufacturing process and thereby make reprocessing more efficient.	Yes	Final Submission Report	✓
B3	Use mechanical connections rather than chemical	This will allow the easy separation of components and materials without force and reduce contamination to materials and damage to component.	Yes	Drawings and Final Submission Report	✓
B4	Where appropriate, make chemical bonds weaker than the parts being connected	If chemical bonds are used, they should be weather than the components so that the bonds will break during disassembly rather than the components, for example mortar should be significantly weaker than the bricks.	Yes	Drawings	✓
Guidance C: Element Assembled					
C1	System where parts are more freely interchangeable and less unique to one application	This will allow alteration through the relocation of components without significant construction work.	Yes	Drawings	✓
C2	Modular design	Use components that are compatible with other systems both dimensionally and functionally	Yes	Drawings and Final	✓
C3	Separate structure from services	Allow parallel disassembly where some parts of the structure ay be removed without affecting other parts.	Yes	Drawings and Final Submission Report	✓
C4	Provide access to all parts of the structure	Ease of access allow ease of disassembly. If possible, allow for components to be recovered from within without use of specialist plant equipment.	Yes	Drawings and Final Submission Report	✓
C5	Use components that are sized to suit intended means of handling	Allow for various possible handling options at all stages of assembly, disassembly, transporting, reprocessing and reassembly.	Yes	Drawings	✓
C6	Provide means of handling components during disassembly	Handling during disassembly, may require points of connection for lifting equipment or temporary supporting device.	Yes	Drawings and CDM Review	✓
C7	Provide realistic tolerance to allow for movement during disassembly	Process may require greater tolerance than the manufacture process or the initial assembly process.	Yes	Drawings and Final Submission Reports	✓

C8	Use minimum number of different types of connectors	Standardisation of connections will make disassembly quicker and require fewer types of tools, even if this result in the oversizing of some connections. This will save time of assembly and disassembly time.	Yes	Drawings and Final Submission Reports	✓	
C9	Design joints and connectors to withstand repeated use	Minimise damage and wear and tear from the assembly/disassembly procedure.	Yes	Final Submission Reports		✓
C10	Use hierarchy of disassembly related to expected life span of the component	Make components with short life expectancy readily accessible and easy to disassemble, components with longer life expectancy may be less accessible.	Yes	Drawings and Final Submission Reports	✓	
C11	Reusable parts more easily accessible	Allow maximum advantage from reuse program.	Yes	Drawings and Final Submission Reports	✓	
Guidance D: Element in use						
D1	Standardise the parts while allowing for infinite variety	This will allow minor alterations to the structure without major works.	Yes	Final Submission Reports		✓
D2	Use standard structural and geotechnical grids	Grid size to be related to the materials used such as structural spans are designed to make most efficient use of product	Yes	Drawings	✓	
D3	Lightweight materials and components	This will make handling easier, quicker and less costly, thereby making reuse a more attractive option.	No	n/a		
D4	Use a minimum number of different components	Fewer types of component mean fewer different disassembly operations that need to be known, learned and remembered. Encourage construction sequence drawings for future use. This will also ensure more standardisation in the reassembly process which will make the option of relocation more attractive.	Yes	Drawings and Final Submission Reports	✓	
D5	Permanently identify point of disassembly	Points of disassembly should be clearly and identifiable and not be confused with other design features.	Yes	Drawings	✓	

D6	Provide spare parts on site storage	Both intended to replace damaged components and to facilitate minor alterations to buildings.	Yes	Final Submission Reports	✓	✓	
D7	Sustain all information on the manufacture and assembly process	Measures should be taken to ensure the preservation of information such as 'as built drawings' information about disassembly process, material and component life expectancy, and maintenance requirement	Yes	Drawings and Final Submission Reports	✓		
DfD Index, I_{DfD}		0.94					

Table 7. Example of DfD checklist being used on sheet pile wall for Midlands Metro Alliance.

Guideline A: Recycling							
No.	**Deliverable**	**Description**	**Achieved?**	**Communicated on**	**Stakeholder Involvement**		
					Client	**Contractor**	**Supplier and Manufacturer**
A1	Use recycled material	Increased use of recycled materials will encourage industry and government to develop new technologies for recycling, and to create a larger support network for future recycling and reuse	Yes	Final Submission Report			✓
A2	Minimise the number of different types of material	This will simplify the process of sorting on site and reduce transport to separate reprocessing plants.	Yes	Final Submission Report		✓	
A3	Avoid toxic and hazardous materials	Reduce potential of contaminating materials that are being sorted for recycling and will reduce the potential for human health and risk.	Yes	Hazard Log and CDM Review		✓	
A4	Make inseparable subassemblies from the same material	Large amounts of one material will not be contaminated by small amounts of foreign materials that can be separated.	Yes	Final Submission Report		✓	
A5	Avoid secondary finishes to materials	Coatings may contaminate the base material and make recycling more difficult where possible use material that provide their own suitable finish or use separable mechanically connected finishes.	Yes	Drawings	✓	✓	

A6	Provide standard and permanent identification of material types	Many materials such as plastics are not easily identifiable and should have some form of non-removable and non - contaminating identification mark to allow future sorting.	Yes	Drawings and Final Submission Report	✓
Guidance B: Reprocessing					
B1	Minimise number of different types of components	This will simplify the process of sorting on site and make the potential for re-processes more attractive due to the larger quantities of same or similar items.	Yes	Drawings and Final Submission Report	✓
B2	Use a minimum number of wearing parts	This will reduce the number of parts that need to be removed in the remanufacturing process and thereby make reprocessing more efficient.	No	n/a	✓
B3	Use mechanical connections rather than chemical	This will allow the easy separation of components and materials without force and reduce contamination to materials and damage to component.	Yes	Drawings and Final Submission Report	✓
B4	Where appropriate, make chemical bonds weaker than the parts being connected	If chemical bonds are used, they should be weather than the components so that the bonds will break during disassembly rather than the components, for example mortar should be significantly weaker than the bricks.	Yes	Drawings	✓
Guidance C: Element Assembled					
C1	System where parts are more freely interchangeable and less unique to one application	This will allow alteration through the relocation of components without significant construction work.	No	n/a	
C2	Modular design	Use components that are compatible with other systems both dimensionally and functionally	Yes	Drawings and Final	✓
C3	Separate structure from services	Allow parallel disassembly where some parts of the structure ay be removed without affecting other parts.	Yes	Drawings and Final Submission Report	✓
C4	Provide access to all parts of the structure	Ease of access allow ease of disassembly. If possible, allow for components to be recovered from within without use of specialist plant equipment.	Yes	Drawings and Final Submission Report	✓

C5	Use components that are sized to suit intended means of handling	Allow for various possible handling options at all stages of assembly, disassembly, transporting, reprocessing and reassembly.	No	n/a		
C6	Provide means of handling components during disassembly	Handling during disassembly, may require points of connection for lifting equipment or temporary supporting device.	Yes	Drawings and CDM Review	✓	
C7	Provide realistic tolerance to allow for movement during disassembly	Process may require greater tolerance than the manufacture process or the initial assembly process.	Yes	Drawings and Final Submission Reports		✓
C8	Use minimum number of different types of connectors	Standardisation of connections will make disassembly quicker and require fewer types of tools, even if this result in the oversizing of some connections. This will save time of assembly and disassembly time.	Yes	Drawings and Final Submission Reports	✓	
C9	Design joints and connectors to withstand repeated use	Minimise damage and wear and tear from the assembly/disassembly procedure.	Yes	Final Submission Reports		✓
C10	Use hierarchy of disassembly related to expected life span of the component	Make components with short life expectancy readily accessible and easy to disassemble, components with longer life expectancy may be less accessible.	Yes	Drawings and Final Submission Reports	✓	
C11	Reusable parts more easily accessible	Allow maximum advantage from reuse program.	Yes	Drawings and Final Submission Reports	✓	
Guidance D: Element in use						
D1	Standardise the parts while allowing for infinite variety	This will allow minor alterations to the structure without major works.	Yes	Final Submission Reports		✓
D2	Use standard structural and geotechnical grids	Grid size to be related to the materials used such as structural spans are designed to make most efficient use of product	Yes	Drawings	✓	
D3	Lightweight materials and components	This will make handling easier, quicker and less costly, thereby making reuse a more attractive option.	No	n/a		
D4	Use a minimum number of different components	Fewer types of component mean fewer different disassembly operations that need to be known, learned and remembered.	Yes	Drawings and Final Submission Reports	✓	

		Encourage construction sequence drawings for future use. This will also ensure more standardisation in the reassembly process which will make the option of relocation more attractive.				
D5	Permanently identify point of disassembly	Points of disassembly should be clearly and identifiable and not be confused with other design features.	Yes	Drawings		✓
D6	Provide spare parts on site storage	Both intended to replace damaged components and to facilitate minor alterations to buildings.	No	n/a		
D7	Sustain all information on the manufacture and assembly process	Measures should be taken to ensure the preservation of information such as 'as built drawings' information about disassembly process, material and component life expectancy, and maintenance requirement	Yes	Drawings and Final Submission Reports	✓	
DfD Index, I_{DfD}		0.73				