Citation for published version:
Dams, B, Maskell, D, Shea, A, Allen, S, Driesser, M, Kretschmann, T, Walker, P & Emmitt, S 2021, 'A circular construction evaluation framework to promote designing for disassembly and adaptability', *Journal of Cleaner Production*, vol. 316, 128122. https://doi.org/10.1016/j.jclepro.2021.128122

DOI:
10.1016/j.jclepro.2021.128122

Publication date:
2021

Document Version
Peer reviewed version

Link to publication

A circular construction evaluation framework to promote designing for disassembly and adaptability

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July 14, 2021

Abstract

This paper formulates a concise, free-to-use Circular Construction Evaluation Framework (CCEF) based upon international design code guidelines to assess and quantify the circularity credentials of an existing or proposed construction project. Central to the principles of circular construction is designing for disassembly and adaptability - the ability of a building's elements and connecting components to be disassembled and reused, or rearranged, after the initial design life. Analysis of modern methods of construction and the compatibility of systems with the concepts of designing for disassembly and material reuse inform the development of the CCEF. Circular construction is facilitated by simplicity, standardisation and modularity in design, sustainably-sourced materials, transparent and accessible mechanical connections and the adoption of a manufacturing-style approach towards durable and reusable standardised components and materials. The CCEF allows users such as clients, consultants, contractors, local and national planning and infrastructure policy professionals to evaluate both whole building and elemental levels at the early design and planning stages in a new-build, refurbishment or renovation project. Implementation of a scoring system is demonstrated by the evaluation of example buildings with varying usage of conventional and bio-based materials. It is shown by use of the framework that a simple standardised construction using reversible connections and previously used material elements rates highly, demonstrating a greater extent of circularity in the construction.

Keywords— Circular economy, modern construction systems, disassembly, adaptability, material reuse, evaluation framework

Word count - 8493 (excluding references and tables)

Abbreviations	
BIM	Building Information Modelling
BREEAM	Building Research Establishment Environmental Assessment Method
CBA	Circular Building Assessment
CCEF	Circular Construction Evaluation Framework
CEIP	Circular Economy Indicator Prototype
CET	Circular Economy Toolkit
DRM	Design Research Methodology
EPD	Environmental Product Declaration
GTB	Green Transformable Building
LCA	Life Cycle Assessment
MMC	Modern Methods of Construction
OSB	Oriented Strand Board

1 Introduction

The construction industry has traditionally been conservative (Salama, 2017) and risk-averse (Agustí-Juan et al., 2017), governed by short-term economic considerations based around the client-driven parameters of time, cost and quality, with emphasis typically placed upon time and cost (Bowen et al., 2012). Buildings are typically designed for a primary and singular purpose, ultimately possessing one design life of relatively modest duration. Design life length is not necessarily governed by the expiration or failure of the structural materials used, but may be due to changing societal and market factors (Durmisevic, 2006). This results in the functional use of the building being no longer suitable, or the external appearance undesirable, despite the building being capable of a longer design life structurally. Buildings are treated as a single entity during the design stage, which is not the case considering that different elements, or layers, of buildings have significantly differing design lives (Crowther, 2015).

Circularity can be defined as a regenerative approach to resources, and all derived materials and products, based on high quality cycles and ideally without the addition of virgin resources (Geldermans and Jacobson, 2015). Circular economy can further be described as a living economic system, with value creation based on use (and re-use) instead of value destruction based on consumption (Het Groene Brein, 2015). The aim of a circular economy approach to construction is to eliminate waste of valuable natural materials and re-use materials once the initial design life of a construction project has come to an end (graphically demonstrated in Figure 1). The final disposal element, associated with the established linear economy principle embedded in traditional construction, is removed. The concept of circular construction requires that a building should not be merely a static, physically whole entity, but instead should be a changing, evolving combination of functions and processes and be able to adapt to changing societal or functional requirements over long periods of time. Designing a building for future disassembly and re-use requires long-term vision and planning from a very early design stage as traditional construction materials typically cannot be readily re-used (Geldermans and Jacobson, 2015).

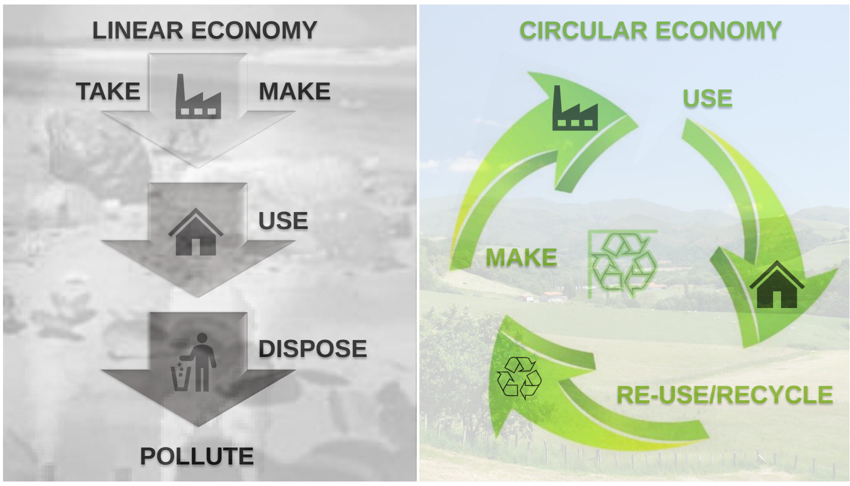


Figure 1: Linear versus circular economy

In 2019, the United Kingdom government published a document identifying seven modern methods of construction (MMC) categories (MMC working Group and Government, 2019): prefabricated 3D primary structural systems (volumetric units), prefabricated 2D primary structural systems (panels), prefabricated linear structural components (beams, columns), prefabricated non-structural assemblies (kitchen/bathroom units), off-site Additive Manufacturing (automated 3D printing), on-site productivity improvements (for example, walling systems to accommodate bricks) and increased on-site automation. Concrete/cement, steel and timber are identified as materials suitable for modern framing (MMC working Group and Government, 2019) and essentially classified as being mainstream modern construction materials, of which only timber (and engineered timber) is a bio-based material. This emphasises how bio-based materials are widely considered as emerging technologies and not yet established as mainstream construction materials. Bio-based materials can form not only a sustainable alternative to high environmental-impacting conventional construction materials such as concrete and steel, but offer other beneficial properties (Maskell et al., 2018). Sustainably managed bio-based materials can offer a renewable supply chain and reduce carbon emissions through the natural processes of bio-material sequestering carbon (Lawrence et al., 2012), thus locking carbon into constructed buildings.

Designing for disassembly and adaptability, although established and understood in manufacturing, is not traditional within the construction industry and cannot be considered established or common practice within the sector (Crowther, 2015). Designing for disassembly can be defined as design which facilitates construction to be reversible, and dismantled connections and elements to be reusable following the conclusion of the design life for potential use in another building. Designing for adaptability relates to the future-proofing of a building and can be defined as design which allows for reconfiguration or conversion to reflect changes in the purpose or use of a building during the design life of the structure, minimising the risk of demolition as a result of economic, societal or functional obsolescence (Ross et al., 2016; BSI, 2020). A change in a buildings' use may be enforced by economic considerations, user needs, capabilities and changing lifestyles (Durmisevic, 2019). An adaptable building can be expanded horizontally (if suitable adjacent land is available) or vertically (if planning regulations or foundation designs permit) (BSI, 2020) and enhanced by the replacement of current materials by future, contemporary higher performing materials as technologies emerge (Morgan and Stevenson, 2005).

Labels, calculation methods and subscription software have been developed over the course of the past decade to analyse circularity in product systems. Circular labels can be awarded to completed projects by professional bodies such as the Building Research Establishment, whose Environmental Assessment Method (BREAAM, UK), uses a star rating system (Building Research Establishment, 2020) and the Flemish Initiative Systematic Maintenance of Buildings (VLISOG) / Flemish Construction Confederation (VCB) (Belgium) circular building label (Circular Economy Toolkit, 2020*a*). Lieder and Rashid (2016) formulated a circular economy principals framework incorporating resource demands and waste scenarios aimed at the manufacturing sector. In 2020, The Institute of Structural Engineers, United Kingdom published an LCA-based guide to calculating embodied carbon in a building (Orr et al., 2020). Data can be extracted from a BIM model to evaluate the circularity of a product flow using Life Cycle Assessment (LCA) software tools based upon BS EN ISO 16739:2016 (Barnard, 2019) and the software 'One click LCA' has developed a commercially available add-on tool which extracts data from models such as Revit (Castro and Pasanen, 2019). The Ellen MacArthur Foundations' Circulytics tool uses a spreadsheet format to evaluate the operations, business models and product flows of a company to aid transition to circular economy principles and practice (Dewick et al., 2020). Free-to-use online tools designed to measure circularity in a product include Circular Economy Toolkit (CET) and Circular Economy Indicator Prototype (CEIP) Saidani et al. (2017). These consist of LCA-informed questions covering design, manufacture, commercialisation, use, maintenance and end-of-life. Questions require a 'yes', 'no' or 'partly' answer (CET) (Circular Economy Toolkit, 2020*b*) and points are awarded for positive answers adhering to circular principles (CEIP) (Cayzer et al., 2017).

Quantitative assessment of adaptability in buildings is a developing area of research still in its infancy; there is a scarcity of adaptation and demolition data from case studies, which makes the empirical validation of models challenging, with validation of existing frameworks relying on intra-model comparisons (Rockow et al., 2019). Developed adaptability models are designed particularly to apply to existing buildings, although frameworks can also be aimed at early design stages. Langston and Shen (2007) devised the Adaptive Reuse Potential (ARP) model which defines a descending curve graph depicting a useful life period as a fraction of the full design life a building is structurally capable of providing. Conejos et al. (2013) published the Adaptstar method which awards a star-rating to a particular project; although data sets were limited, in conjunction with the ARP model, Adaptstar showed that buildings which possessed higher adaptability possessed lengthier useful lives and took longer to become obsolete. The Learning Buildings framework (Ross, 2017) and Adaptable Buildings Design framework(Allahaim et al., 2010), which focus on physical elements and consider a building as possessing different physical layers, are methods which utilise probability and uncertainty and are aimed at early project design stages, looking to predict potential changes in a buildings design life. Andrade and Bragança (2019) present a framework aimed at early design stage which incorporates interface design and gives interfaces and materials equal weighting as the two principal criteria categories, with various weighting factors added to sub-categories. Interface design sub-categories incorporate both type and accessibility of connections, and assembly methods and sequences. Becker et al. (2020) also uses a weighted sum approach for an adaptability framework which surveyed construction industry professionals, including intuition-based responses to four categories of simplicity in design, building layer separation, design life and floor plan. Nijs et al. (2011) outlines a framework which focuses on classifying connection methods to act as interfaces between the different elements, or layers of a building.

Building upon existing literature and frameworks specialising in particular aspects of construction, this paper presents a formulated comprehensive Circular Construction Evaluation Framework (CCEF), specifically to assess the circular credentials of proposed and extant construction projects, with a broad range of criteria encompassing material properties (with particular consideration for element reuse), suitability for disassembly and adaptability, material information and health and safety. The framework aims to provide architects, engineers, consultants, contractors and particularly client organisations who wish to practice and execute sustainable values, with a comprehensive, transparent and free-to-use method to assess the circularity of a project in early design and planning stages, with a view to guiding and informing design decisions and increasing circularity. The CCEF is designed to complement existing LCA-informed circularity assessments, circularity labels for products, probability-based adaptability frameworks and methods which award a star rating, by being a readily accessible, free-to-use, scoring framework specifically targeted at construction industry projects and the practice of designing for disassembly and adaptability, with deconstruction and reuse of elements accommodated within a broad range of criteria. Early stage use of the CCEF is also intended to complement labels awarded by an external professional body at project conclusion. Methods and materials suitable for circular construction are identified through demonstrative implementation of the CCEF using four example buildings.

2 Methodology

The international standard BS ISO 20887:2020 relating to sustainability in buildings and civil engineering works contains guidance for assessing and measuring the degree of disassembly and adaptability for a system and shows a summary chart for a mechanical and electrical engineering scenario, in which circularity parameters are marked if present in the mechanical and electrical services design. (BSI, 2020). The CCEF utilises the guidance in BS ISO 20887:2020 as a basis for adaptation, expansion and application to construction elements and whole building design. For consistency, throughout the CCEF, assessment criteria will ultimately be assigned a rating from zero (non-circular) to five (circular). Alternative criteria, such as a percentage or a 'yes' or 'no' answer, can be related to a zero to five rating for consistency and allow the development of a consistent numerical value to denote circularity - with the higher the value, the greater the circularity of the building in question. When a percentage is indicated, this can be approximated from zero percent scoring zero, twenty percent scoring 1, with an incremental 20% scoring an additional point. The use of percentages allows for quantitative assessment as well as qualitative. When a criterion is answered by 'yes' or 'no', a 'no' answer will score zero and a 'yes' scores five. To create the CCEF, material, LCA and disassembly and adaptability considerations have been explored to decide how best to include and formulate the numerous criteria, and how materials and systems may be evaluated.

2.1 Material considerations

Reinforced concrete is typically based on Portland cement and has traditionally been cast in-situ, creating monolithic structures which are strong, stiff and fire-resistant, but also energy-intensive (Turner and Collins, 2013). Cast concrete elements cannot readily be disassembled for further, subsequent use within construction and demolition is the dominant end-of-life scenario (Salama, 2017). Material can be crushed to separate reinforcing steel bars and re-used in applications such as paving or roads, but this is an energy-intensive process (Salama, 2017) and can be regarded as down-grading. Stone and bricks can be salvaged and reused if mortar is lime-based; however, stronger Portland cement-based mortars, which have dominated masonry construction since world war two, cannot be readily removed. Therefore, unless lime mortar is used, masonry presents a challenge for circular construction (Webster and Costello, 2005).

Structural steel linear members can be disassembled, by removing connections or cutting members, yet reuse of members requires additional processes to verify continuing structural integrity (Zygomalas and Baniotopoulos, 2016) and member reuse is rare; <10% in the United Kingdom and in decline due to high costs, low client/market demand, time constraints (with demolition being quicker) (Tingley et al., 2017) and the presence of sprayed-on coatings and treatments. For disassembly, bolted or clamped connections are preferable to welded connections (Webster and Costello, 2005). Glass is used extensively in modern projects, particularly large office buildings. Double glazed units have a typical design life of fifteen years; reuse is typically unrealistic due to the variety of glass available and difficulties in re-sizing into required dimensions for a new building. Recycling and re-melting glass is challenging due to difficulty in identifying coatings used (thermal infrared, reflective, emissivity). Laminated glass with various Polyvinyl butyral

(PVB) foils is also difficult to reuse - current techniques to divide the glass from the foil are inefficient, although ongoing research is being conducted in this field (Arup and Reifer, 2019).

Timber is the most established structural and façade bio-based material. Structural timber can be reused in structural applications, flooring and partitions (Webster and Costello, 2005). Previously-used structural timber elements are dimensionally stable; however the condition of poorly-treated, low-durability members can be compromised by fungal decay, insect attack, knots or fixing-holes (Brol et al., 2015). Timber structures with larger and fewer members are easier to disassemble than frames with many members (Webster and Costello, 2005). Engineered timber solutions such as glulam in many aspects offer an improved product over natural timber; for example enhanced durability, strength and greater spans (Fiorelli and Dias, 2006), although engineered and composite products use binding additives which may be not be bio-based (Stark et al., 2010). An inherent risk to circularity with augmenting bio-based materials with synthetic matter is that it may result in hybrid composites which cannot readily be reused (Guy and Ciarimboli, 2005), and present challenges for LCA inventory data (La Rosa et al., 2014). Bio-based structural materials as an alternative to timber include natural and engineered bamboo products (Sharma et al., 2015) and straw bale within a composite panel with a timber frame and lime render (Maskell et al., 2015; Yin et al., 2018). Alternative bio-based façade materials include methods of treating timber, for example subjecting wood to acetylation treatment (Accsys, 2019) or using products based on other bio-based sources such as rice husks (Resysta Technology, 2019). However, these are emerging technologies yet to be established with international standards.

When considering materials for the CCEF, reinforced concrete, masonry and large quantities of glass which are challenging to reuse score lower. Steel members which can be disassembled and reused improve the materials rating of a project. Bio-based materials from sustainably managed sources which can be reused following first design life also score higher in the CCEF, with according reductions in line with increased additional synthetic materials, resulting in composites which cannot be readily reused or recycled.

2.1.1 Life cycle assessment considerations

Life cycle assessments (LCA) can assess environmental impact and performance of materials (Hill and Dibdiakova, 2016) and evaluate the sustainability of whole construction systems (Hossain and Ng, 2018). Environmental Product Declarations (EPD) contain quantified environmental information on a product attained from LCA (Del Borghi, 2013) in accordance with relevant standards, such as EN 15804 for construction materials. EPDs can then be used for building-level LCA and help facilitate comparability with other products of a similar function. Carbon is sequestered within bio-based material and can remain until disposal (Lawrence et al., 2013). EPDs can be challenging to produce for bio-based materials; the sequestration of carbon dioxide is difficult to analyse and quantify (Tellnes et al., 2017). Long-term carbon sequestration may have positive effects and the lack of temporal information is a significant limitation of conventional LCA according to EN 15804 and EN 15978 (Levasseur et al., 2010; Peñaloza et al., 2016; Cooper et al., 2020). Key aspects are the gradual release of sequestered biogenic carbon as bio-based materials degrade during use, or post-use in landfill (Fouquet et al., 2015), and the sudden release of carbon during end-of-life incineration. In the context of circular bio-based construction, it is intended for buildings to have multiple design-lives, thus long-term sequestration of carbon is an important consideration. LCA faces a further issue with end-of-life scenarios - if an element cannot be reused or recycled, it must be disposed of. Disposal scenarios can involve elements going to landfill, incineration (Fouquet et al., 2015), or composting in the case of certain biodegradable matter (Towprayoon et al., 2019). Additional considerations are where materials originated, and in the case of bio-based materials, land-use change (De Rosa et al., 2018).

For the CCEF, materials with EPDs attract a higher score. Being able to reuse or recycle material following the first design life scores higher than material which cannot be reused and requires demolition resulting in landfill disposal, incineration or material downgrading for alternative, non-construction applications.

2.2 Disassembly and adaptability considerations

In a circular building, disassembly and adaptability require planning during initial design stages. A disassembly plan consisting of drawings and specifications showing connection details (BSI, 2020) and encased services which do not interfere or entangle with structural, insulation or façade components (Guy and Ciarimboli, 2005), facilitate disassembly and reuse and therefore will score highly on the CCEF. On-site labour being able to readily access components and connections, and deconstruct in a safe manner with minimal risk, would further aid circularity (Morgan and Stevenson, 2005) and score well. Toxic coatings and materials such as lead and asbestos introduce health and safety complexity during disassembly (Guy and Ciarimboli, 2005) and will result in lower scores. In relation to adaptability, an aim of the CCEF scoring methodology is to reward a planned project that chooses materials, construction methods and connections which are physically capable of equating the useful design life with the physical first design life of a building. Consequently, the CCEF is differentiated from existing adaptability frameworks by focusing on whether a building physically can be adapted through simple, standardised design and reversible connections, rather than predicting the possibility that it may need to be during the first physical design life as a result of economic, social or environmental factors.

2.2.1 Design life expectancy

Different aspects of a building have differing design life expectancies. Analyses typically use a "6 'S'" layered system of site, structure, skin (façade), services (mechanical and electrical), space plan (internal layout) and stuff (occupant possessions) - each having a different expected time span of use (as shown in Figure 2) (Brand, 1994). Layers need to be dismountable for an adaptable, future-proof building where elements can be replaced as required (Geldermans and Jacobson, 2015) due to end-of-life (for example, façades - which would be expected to expire before structural elements) or simply with a new, improved product. Design for disassembly protocols aim to increase awareness of design approaches among stakeholders and provide incentives to retain, or increase, the value of a building with guaranteed multiple re-use options of the building systems, components and materials. Design needs to consider multiple future scenarios for a building (Durmisevic, 2019). It can be aimed to design for three future functions and reuse

70% of building materials (Durmisevic et al., 2019) and life-cycle cost analysis can typically be based on a 50-year first design life or use (Durmisevic, 2006). Adaptability in design, with a view to facilitating multiple future uses of a building, scores highly on the CCEF.

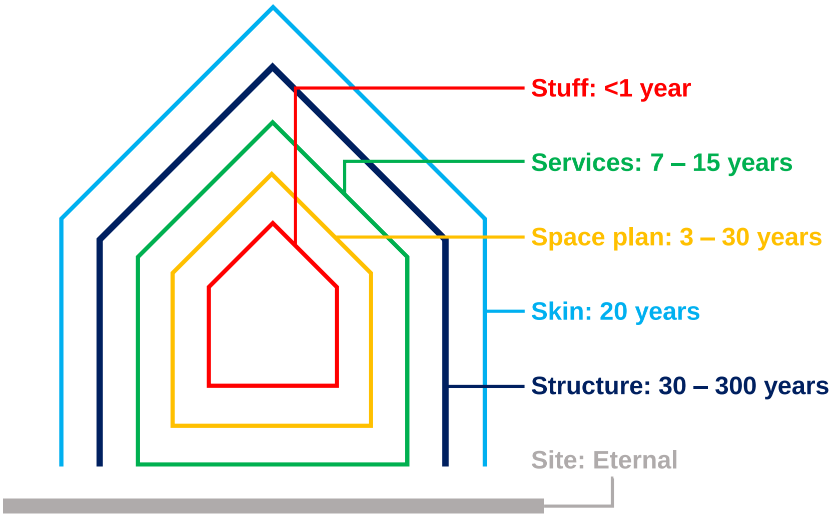


Figure 2: The “Six ’S’” diagram, with each ’S’ layer possessing different typical life spans. ’Stuff’ denotes furniture, equipment and possessions. Adapted from Brand (1994)

2.2.2 Prefabrication

Traditionally, the construction industry has been distinct from the manufacturing sector in that buildings are typically a prototype (Bryden Wood, 2018). Bespoke, complex or architecturally innovative design can be aesthetically attractive; but when considering circularity, simplicity, standardisation, modularity and transparency in design is to be encouraged. Repeated structural grids with regular dimensions, consistency of structural element or linear member dimensions throughout the building (Morgan and Stevenson, 2005), the enabling of large spans maximising use of mobile partitions and simple open-plan spaces (Guy and Ciarimboli, 2005) are all conducive to circular construction. Elements prefabricated off-site, standardised elements and components (Aapaoja and Haapasalo, 2014) and interchangeable three-dimensional modular units are desirable (Bekdik et al., 2018). Modularity has been described as an enabler of circular buildings (Nußholz et al., 2019) when combined with a design for disassembly approach (Minunno et al., 2020). The fabrication of full modular building systems, rather than individual elements and connections, would promote economic viability (Arup and Reifer, 2019). Prefabrication and modularity can further offer advantages such as reduction of project schedules, increases in quality control, efficiency and productivity, improved safety, shorter project schedules, reduction in waste material (and greater reuse) and cost reductions (Azhar et al., 2013; Generalova et al., 2016; Shahtaheri et al., 2017; Abdelmageed and Zayed, 2020), although costs can vary geographically according to the level of maturity in the regional local prefabricated construction industry (Hong et al., 2018).

Elements constructed off-site are subjected to loads during transportation to site and handling, for example vertical accelerations arising from uneven roads and tracks (Godbole et al., 2018), a particular issue in countries with less developed transport systems (Wuni and Shen, 2020). Increasing the mass of the material being transported (Godbole et al., 2018), adopting dimensional and geometric tolerance strategies and transport loading simulation models within the project (Shahtaheri et al., 2017), the use of Building Information Technology (Abdelmageed and Zayed, 2020) and upgrading infrastructure can minimise damage and dimensional variability resulting from transit and lifting loads. It can be submitted that reducing transportation-related risk may require the increase of material used per structural element (Quale et al., 2012) in addition to increasing the quantity of elements loaded on to a given vehicle. Design optimisation models can minimise quantities of materials used (Abdelmageed and Zayed, 2020). Generalova et al. (2016) reported an example of modular steel construction (using recycled steel) in which material savings were made and it can be reasoned that the reduction of material waste and over-ordering through off-site improvements in efficiency, quality control and design optimisation can compensate for extra structural material required for transportation. Extra structural material used may be less material than is wasted due to on-site practice, plus there is an additional LCA trade-off where extra material used in prefabrication (embodied carbon) leads to greater efficiencies and operational carbon reduction during the design life (Quale et al., 2012).

It is therefore the stance of this study that, despite the challenges transportation may provide, modular, prefabricated and standardised elements which can be disassembled and reused are conducive to constructing in line with circular economy principals. Therefore, the position of the CCEF is that prefabricated elements score highly and increase from linear, through 2D panels to modular standardised 3D units. Structures designed in a manner that allows for parallel assembly and disassembly would further save on-site time and costs. A move towards a more manufacturing-orientated mind-set in the construction industry would promote off-site prefabrication of elements and connections which can be disassembled and reused or reconfigured. Conversely, in-situ monolithic structures which are challenging, if not impossible to partially or wholly reuse, attract lower scores.

2.2.3 Connections

Connections can dictate whether connected elements can be disassembled and reused (Morgan and Stevenson, 2005). Cost and speed of construction have led to widespread use of chemical connections and pure mass being used to connect components, resulting in massive, monolithic constructions suitable for one initial design life (Durmisevic, 2006). Chemical connections typically result in strong and stiff bonds. However, regarding future disassembly, use of chemical connections, including welding (Webster and Costello, 2005), is typically to be avoided, as disassembly is either difficult or not possible (Durmisevic, 2019). Binding or sealing agents introduce complications with reuse and are typically not compatible with circular construction (Guy and Ciarimboli, 2005). The use of dry, mechanical connections (bolts, screws, dowels, clamps) is to be encouraged (Morgan and Stevenson, 2005; Durmisevic, 2006); nails and toothed plates are an exception and less suitable for disassembly (Morgan and Stevenson, 2005). It is advantageous for dry connections to be accessible and uniform, with minimal variation. Stainless steel is a suitable material for durable, reusable connections (Guy and Ciarimboli, 2005). Interlocking or gravity-connected members are also to be encouraged; it is suggested that gravity connections acting in shear (with no moment) are highly suitable for circular construction (Durmisevic, 2019). Being easy to assemble and disassemble, gravity connections can be concealed within a timber frame or used to attach new structural elements to existing structural frames (Rotho Blaas, 2020).

Informed by this, the CCEF allocates high scores to dry gravity-based, interlocking or screwed mechanical connections suitable for disassembly, and standardisation in the connections used, with minimal variation. Low ratings are applied to bonded, chemical connections which cannot be readily disassembled.

2.2.4 Element reuse

A building which has come to the end of a design life and is ready for disassembly can be described as a donor site, donating elements to new or reassembled/recycled buildings. Materials from donor sites can be registered and compiled into a database (Rose and Stegemann, 2018), thus creating an inventory of available construction elements suitable for re-use. For example, the Madaster foundation maintains a database (Madaster, 2020) in which property owners can register materials used in their building, creating an inventory of available materials which could be re-used after the design life of the building. Information such as material type, classification (load-bearing, insulation or façade), previous history (production, supplier warranty and donor building details), dimensions, shape, presence of additional material (coatings, renders, binders, synthetic or toxic material) and condition can be documented. A matchmaking process can be developed between materials required for new projects, and suitable previously used materials from donor buildings. Optimisation software, for example ’Fastcut’ (FastCAM, 2020), can identify appropriate catalogued elements from donor buildings. Use of elements from a donor building and extensive information recorded for used elements, thus promoting reuse following the first design life, scores highly on the CCEF.

2.2.5 Foundation design

Reinforced concrete is the predominant foundation material in modern construction. The basic types of foundation (strip, trench, pad, raft and pile), are all dominated by poured concrete. Timber (or concrete) posts or piers may be used though, which typically rest on concrete pads or natural rock. Circularity is promoted by foundations designed to allow for greater structural loads arising from future modification, rearrangement or expansion (especially vertical) following a change in use and commencement of a new design life. Suitable foundations with a view to designing for disassembly are pads, piles (if required by ground conditions) and ground beams (Morgan and Stevenson, 2005). Pouring large volumes of concrete using strip, trench or raft foundations is less suitable. It is reasoned that simple, regular, rectilinear grids of pads or piles into which columns can be assembled and disassembled (using dry mechanical connections) would provide a viable foundation solution for adaptable, circular construction and therefore score higher on the CCEF.

2.3 Implementation with four example buildings

To demonstrate implementation, the developed CCEF, informed by the considerations detailed above, is applied to four example buildings featuring differing materials and methods of construction, ranging from conventional to bio-based materials and bespoke to modular design, with a view to ascertaining how significantly different construction solutions would achieve a numerical rating, denoting the degree of circularity in the project. All four buildings are assumed to be multiple-storey, use non-reclaimed glass for windows and are built to a high standard with an expectation to last for a first design life of at least fifty years. For all four examples, superstructure materials and methods vary, and foundations are assumed to be reinforced concrete pads for all four buildings. In the descriptions below, the buildings are linked back to the MMC.

2.3.1 Building 1

Building 1 functions as an example of in-situ construction using a conventional material and a degree of on-site automation. The architecturally-designed prototype building utilises traditional formwork to realise an in-situ cast reinforced poured concrete frame consisting of beams, columns, shear walls and slabs. The building is designed in accordance with Eurocode EN 1992-1 (Eurocode, 1992) and concrete structures (Bond et al., 2006). In the example, recycled steel has been assumed for the reinforcing steel. Concrete elements vary in thickness and feature variable rebar designs. Insulation consists of sprayed low-density polyurethane foam and external façade and wall elements feature masonry in the form of brickwork bonded with Portland cement mortar.

2.3.2 Building 2

Building 2 forms an example of prefabricated linear structural system using a conventional material; a steel-framed building with a rectilinear design and open plan spaces. The building is designed in accordance with Eurocode EN 1993-1 (Eurocode, 2005) and the Steel Construction Institute / Tata Steel / British Constructional Steelwork Association Limited design manual P363 (Steel, 2016). Structural steel members consist of both closed hollow sections and open I-beam sections, which are assumed to be new material. The steel rebar required for the concrete composite floor slabs are assumed to be from recycled steel. Structural steel members are assembled using connection plates fastened with threaded bolts. The interior and exterior walls are made from prefabricated panels framed using new lightweight steel. Insulation is provided by mineral wool batts, which are dry and can be dismantled.

2.3.3 Building 3

Building 3 is an example of prefabricated linear structural system using bio-based materials and a simple rectilinear design. Glulam beams form the structural frame, using newly manufactured members from timber taken from sustainably managed forests. Glulam members are assembled using connection plates and fastened with threaded bolts. The building is designed in accordance with the Eurocode BS EN 1995-1 (BSI, 2004) and BS EN 14080 (Ong, 2015). New oriented strand boards (OSB) form the walls and floors and insulation is provided by spraying hempcrete (a bio-based composite material with hemp shivs mixed with lime render) on to the OSB boards.

2.3.4 Building 4

Building 4 is a modular construction system consisting of off-site prefabricated three-dimensional modular units, serving as an example of a 3D volumetric primary structural system. The modules can be replicated and extended and the components can facilitate the rearrangement and reconfiguration of floor space, walls and openings. The design features interlocking elements in addition to dry, mechanical connections which can be disassembled. The design also features members which are connected only by the force of gravity. The timber frames, studs and joists consist of natural timber material reclaimed from a previous design life in a donor building, the details of which are known and recorded in detail. Sheep's wool batts are used for insulation and the façade consists of timber, although the façade timber is new material. Future expansion has been accounted for in design, with the scope for modular units to be placed both adjacent to the building and an extra floor of vertical expansion.

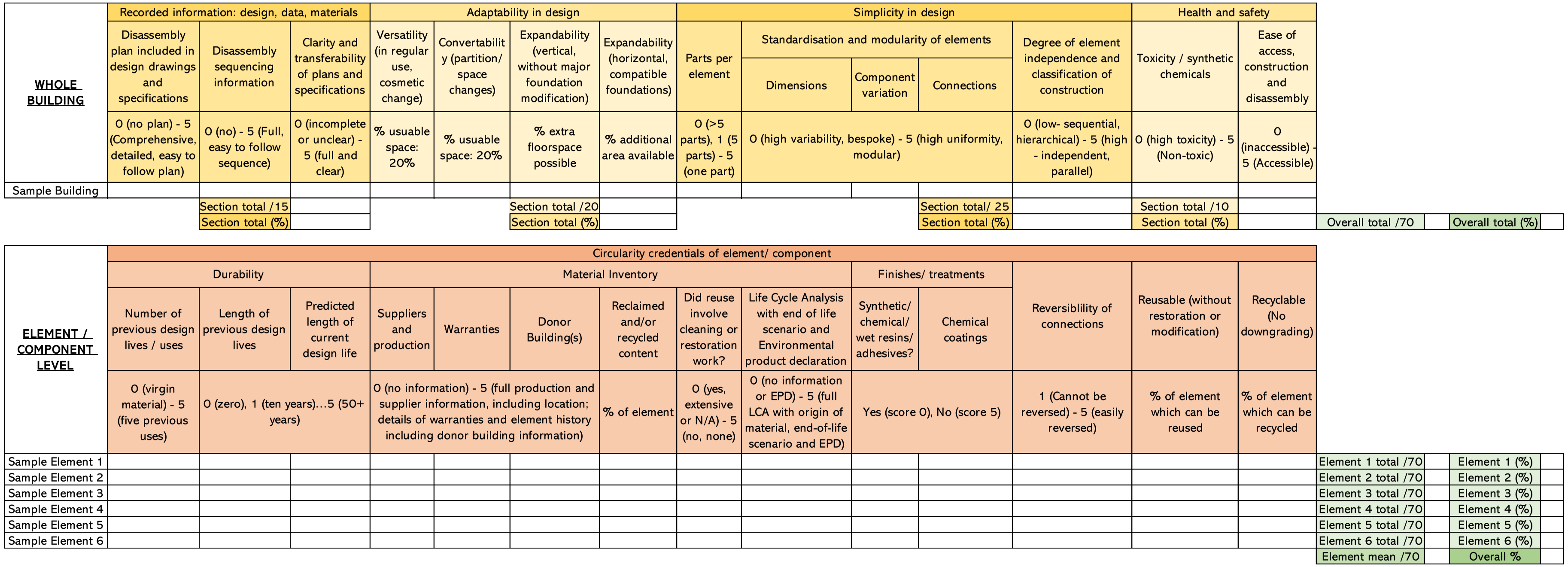
3 Results

3.1 Visual and numerical format of the CCEF

The CCEF, as shown in Figure 3, is formed of two sub-sections; the upper section deals with the overall construction project/building and the lower section covers element or component level. Whole building criteria were developed to cover the potential of the building to be adapted and expanded, including consideration at the design and planning stage. Simplicity, standardisation and modularity in design are evaluated, along with health and safety. Element level criteria were developed to evaluate and document the history, current status and potential future of the element, with criteria considering whether any treatments or finishes have been applied, the extent of donor-building element information and the end of design life potential for disassembly, reuse or recycling. Criteria are unified by the theme of a lower score denoting lesser circularity in design, material use and construction; likewise, a higher score denotes greater circularity. The numerical valuations therefore indicate, according to the applicable parameter, as shown in Table 1 for whole building level and Table 2 for element level.

The CCEF also rewards reuse of reclaimed materials from donor buildings following little to no cleaning or restoration work, effectively awarding extra points for this scenario as being even better than recycled material (which is, in turn, preferable to use of new, fresh source material), thus placing particular emphasis upon material reuse. An extensive discussion regarding the range of LCA standards, methods and consistency in dealing with embodied carbon, global warming potential and long-term carbon emissions, is outside the scope of this paper. However, the CCEF is designed to incorporate key LCA considerations such as known origins and end of life scenarios in relation to material reuse, within the overall focus of the framework in providing a consistent numerical summation of circularity in construction projects in accordance with BS ISO 20887:2020.

Both upper (building) and lower (element) sections result in a final, numerical value for a building - a maximum score would be 70, which can easily be converted to a percentage score. It is possible that there may be an element of bias in the estimation of stakeholders in a direction which reflects their position. Stakeholders should adhere to the table guides (Table 1 and Table 2) as closely as possible and there is potential that weighting for different sections could be introduced allowing for any bias to a sections' importance to be incorporated according to the perspective of the evaluator or stakeholder. For example, contractors may view the health and safety section with greater significance, whereas clients may focus on adaptability and durability of their assets from an economic perspective. Weighting will inherently introduce unavoidable subjectivity, but consistency and transparency in the weighting will allow for appropriate auditing of the decision maker (Maskell et al., 2018).



	Recorded information: design, data, materials			Adaptability in design				Simplicity in design					Health and safety					
WHOLE BUILDING	Disassembly plan included in design drawings and specifications	Disassembly sequencing information	Clarity and transferability of plans and specifications	Versatility (in regular use, cosmetic change)	Convertability (partition/ space changes)	Expandability (vertical, without major foundation modification)	Expandability (horizontal, compatible foundations)	Parts per element	Standardisation and modularity of elements			Degree of element independence and classification of construction	Toxicity / synthetic chemicals	Ease of access, construction and disassembly				
									Dimensions	Component variation	Connections							
	0 (no plan) - 5 (Comprehensive, detailed, easy to follow plan)	0 (no) - 5 (Full, easy to follow sequence)	0 (incomplete or unclear) - 5 (full and clear)	% usuable space: 20%	% usuable space: 20%	% extra floorspace possible	% additional area available	0 (>5 parts), 1 (5 parts) - 5 (one part)	0 (high variability, bespoke) - 5 (high uniformity, modular)			0 (low- sequential, hierarchical) - 5 (high - independent, parallel)	0 (high toxicity) - 5 (Non-toxic)	0 (inaccessible) - 5 (Accessible)				
Sample Building																		
		Section total /15				Section total /20					Section total/ 25		Section total /10					
		Section total (%)				Section total (%)					Section total (%)		Section total (%)		Overall total /70		Overall total (%)	

	Circularity credentials of element/ component																	
ELEMENT / COMPONENT LEVEL	Durability			Material Inventory						Finishes/ treatments		Reversiblility of connections	Reusable (without restoration or modification)	Recyclable (No downgrading)				
	Number of previous design lives / uses	Length of previous design lives	Predicted length of current design life	Suppliers and production	Warranties	Donor Building(s)	Reclaimed and/or recycled content	Did reuse involve cleaning or restoration work?	Life Cycle Analysis with end of life scenario and Environmental product declaration	Synthetic/ chemical/ wet resins/ adhesives?	Chemical coatings							
	0 (virgin material) - 5 (five previous uses)	0 (zero), 1 (ten years)...5 (50+ years)		0 (no information) - 5 (full production and supplier information, including location; details of warranties and element history including donor building information)			% of element	0 (yes, extensive or N/A) - 5 (no, none)	0 (no information or EPD) - 5 (full LCA with origin of material, end-of-life scenario and EPD)	Yes (score 0), No (score 5)		1 (Cannot be reversed) - 5 (easily reversed)	% of element which can be reused	% of element which can be recycled				
Sample Element 1															Element 1 total /70		Element 1 (%)	
Sample Element 2															Element 2 total /70		Element 2 (%)	
Sample Element 3															Element 3 total /70		Element 3 (%)	
Sample Element 4															Element 4 total /70		Element 4 (%)	
Sample Element 5															Element 5 total /70		Element 5 (%)	
Sample Element 6															Element 6 total /70		Element 6 (%)	
															Element mean /70		Overall %	

Figure 3: The circular construction evaluation framework developed in this study, showing evaluation criteria at both whole building and element/ component levels.

Table 1: Indications of numerical scores from zero to five within the CCEF - whole building level.

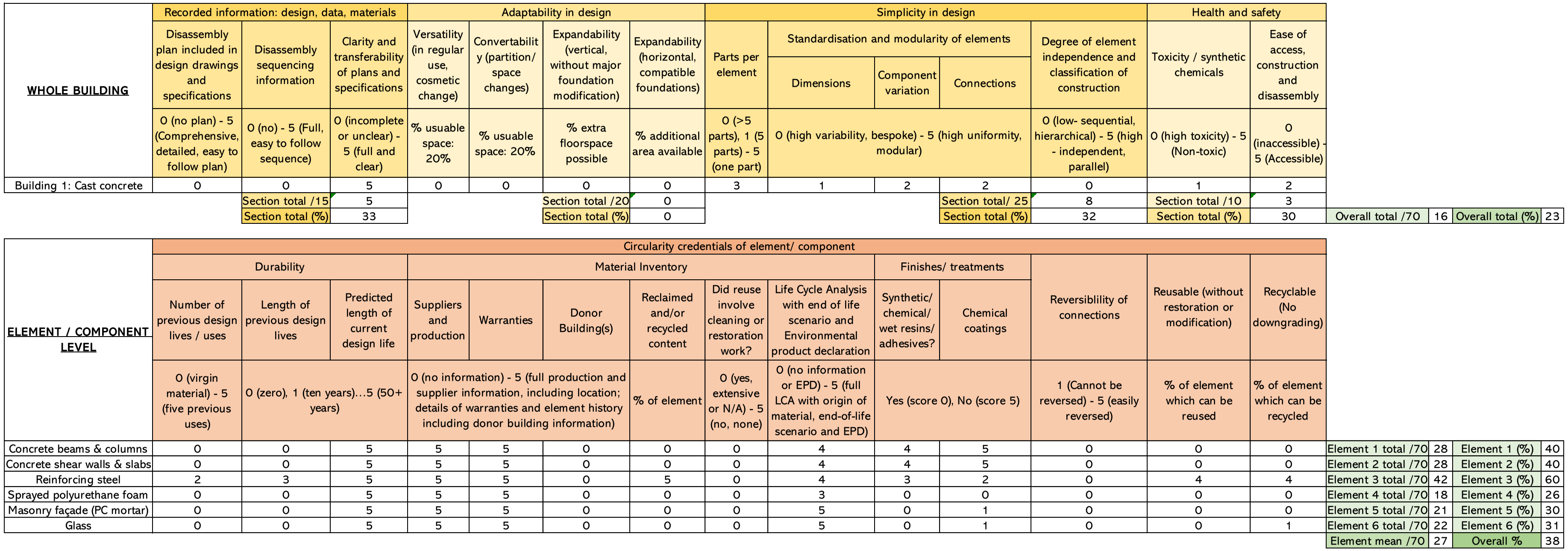
Score /5	**%**	**Whole building level indicators**
Zero	less than 10%	A 'No' answer; no disassembly plan or sequence; No scope for converting, adapting or expanding; highly complex or bespoke design with sequential construction required; non-reversible connections; monolithic construction; no accessibility or disassembly without significant damage to surrounding materials; Very high use of synthetic chemicals, resins, finishes and treatments.
One	10% - 29%	Minimal consideration for disassembly in design and plans; Minimal scope for converting, adapting or expanding; complex design with varying elements requiring sequential construction; limited accessibility or scope for disassembly without significant damage to surrounding materials; high use of synthetic chemicals, resins, finishes and treatments.
Two	30% - 49%	Some consideration for disassembly; Some scope for converting, adapting or expanding; moderately complex design with variability in parts and sequential construction required; limited accessibility or scope for disassembly without some damage to surrounding materials; significant use of synthetic chemicals, resins, finishes and treatments.
Three	50% - 69%	Moderately detailed and clear disassembly plans; scope for modest adaptation or expansion; some simplicity in design, moderate variability in elements, some parallel construction possible; reasonably accessible, scope for disassembly with minor damage to surrounding materials; moderate use of synthetic chemicals, resins, finishes and treatments.
Four	70% - 89%	Reasonably comprehensive disassembly plan and sequence; scope for adaptation and/or expansion; simplicity and/or standardisation in design, moderate component variation; parallel construction possible; mostly accessible, disassembly possible with only very minor damage to surrounding materials; little use of synthetic chemicals, resins, finishes and treatments.
Five	90% or higher	A 'Yes' answer; Comprehensive, clear disassembly plan and sequence prepared during design stage with clear specifications; Extensive scope for adaptation and/or significant expansion without significant modification to foundations; simplicity, standardisation and modularity in design with minimal variation in components; independent, parallel construction entirely possible; reversible connections; full accessibility with minimal work and scope for full disassembly with no damage to surrounding materials; No synthetic chemicals, resins, finishes or treatments.

Table 2: Indications of numerical scores from zero to five within the CCEF - element level.

Score /5	**%**	**Element level indicators**
Zero	less than 10%	A 'No' answer; no reuse or recycling of elements at the end of the first design life; No material inventory, no recorded details of elements; virgin materials; missing or incomplete life cycle analysis (LCA), no environmental product declaration (EPD); materials may be durable but there is no scope for reuse or recycling within construction, therefore significant downgrading, landfill or incineration will take place at the end of the first design life; No expansion without significant and expensive modification to foundations; A 'no' answer.
One	10% - 29%	Very little reuse or recycling of elements at the end of design life; minimal material information, minimal reclaimed or recycled material; largely incomplete LCA, no EPD; materials may be durable but very little scope for reuse or recycling, downgrading, landfill or incineration expected at the end of the first design life.
Two	30% - 49%	Little reuse or recycling of elements at the end of design life; little material information, little reclaimed or recycled material; partially incomplete LCA, no EPD; materials may be durable but minimal scope for reuse or recycling with potential requirement for landfill or incineration; limited scope for additional design lives; minimal use of sustainably sourced materials.
Three	50% - 69%	Some reuse or recycling of elements at the end of design life; basic material information, some reclaimed or recycled material; partially incomplete LCA, possible EPD; reasonably durable materials with scope for reuse or recycling; scope for a second design life; sustainably sourced materials.
Four	70% - 89%	Considerable reuse or recycling of elements at the end of design life; material inventory, significant use of reclaimed or recycled material; complete LCA with end-of-life scenario, complete EPD available; long design life with durable, reusable materials; scope for subsequent design lives; sustainably sourced materials.
Five	90% or higher	A 'Yes' answer; full reuse or recycling of elements at the end of design life; comprehensive material inventory stating content and origin, extensive use of reclaimed or recycled materials; complete LCA with end-of-life scenarios, extensive EPD available; long design life with durable, reusable materials; scope for multiple design lives; sustainably sourced materials.

3.2 Implementation of the CCEF

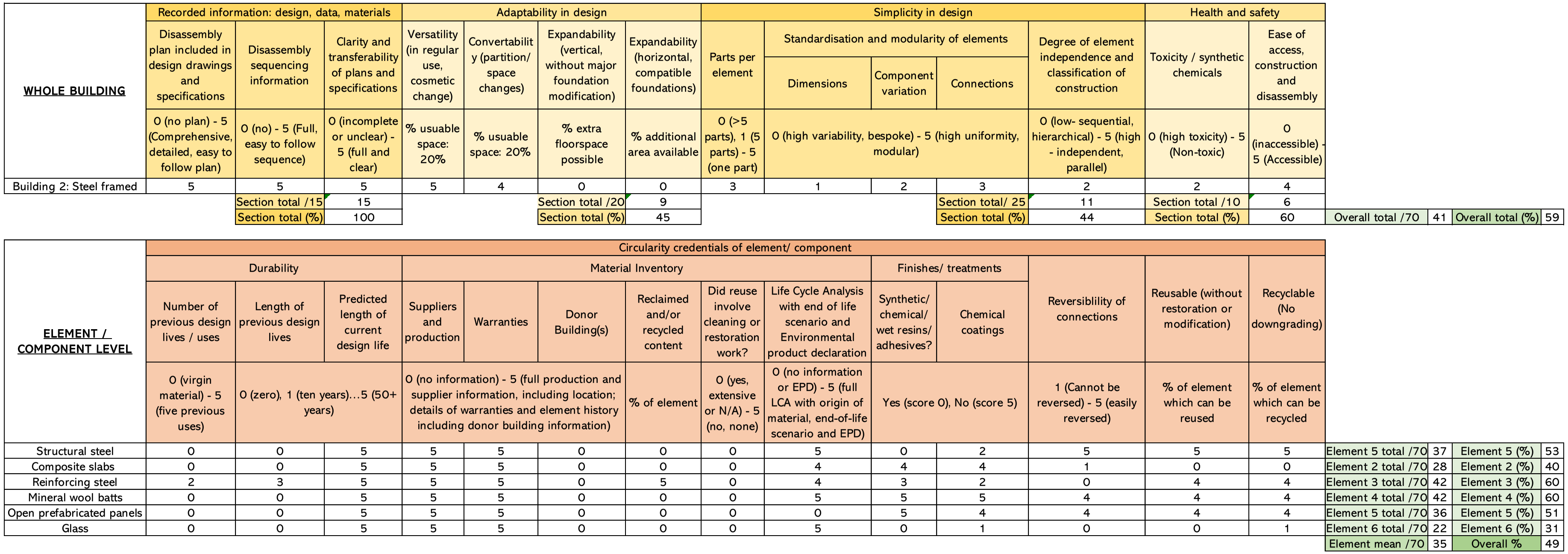
To demonstrate how the CCEF may be implemented and a construction project may be assigned a score at both whole building and element level, four example buildings are presented and the resulting ratings compared. For consistency, no weightings have been applied to the different categories in this assessment. Figure 4 shows the CCEF as applied to building 1. Figure 5 shows the CCEF as applied to building 2; the steel frames can be disassembled, which is a major factor in building 2 achieving a higher rating using the CCEF than the cast concrete example in building 1. Figure 6 shows the CCEF as applied to building 3 and Figure 7 shows the CCEF as applied to building 4. The CCEF assessments of buildings 1 to 4, presented in column chart form in Figure 8, show the difference that choice of material, and material history, can make as well as the overall design approach in addition to designing for disassembly and adaptability, which increases whole building scores.



WHOLE BUILDING	Recorded information: design, data, materials			Adaptability in design				Simplicity in design					Health and safety					
	Disassembly plan included in design drawings and specifications	Disassembly sequencing information	Clarity and transferability of plans and specifications	Versatility (in regular use, cosmetic change)	Convertability (partition/ space changes)	Expandability (vertical, without major foundation modification)	Expandability (horizontal, compatible foundations)	Parts per element	Standardisation and modularity of elements			Degree of element independence and classification of construction	Toxicity / synthetic chemicals	Ease of access, construction and disassembly				
									Dimensions	Component variation	Connections							
	0 (no plan) - 5 (Comprehensive, detailed, easy to follow plan)	0 (no) - 5 (Full, easy to follow sequence)	0 (incomplete or unclear) - 5 (full and clear)	% usuable space: 20%	% usuable space: 20%	% extra floorspace possible	% additional area available	0 (>5 parts), 1 (5 parts) - 5 (one part)	0 (high variability, bespoke) - 5 (high uniformity, modular)			0 (low- sequential, hierarchical) - 5 (high - independent, parallel)	0 (high toxicity) - 5 (Non-toxic)	0 (inaccessible) - 5 (Accessible)				
Building 1: Cast concrete	0	0	5	0	0	0	0	3	1	2	2	0	1	2				
		Section total /15	5			Section total /20	0				Section total/ 25	8	Section total /10	3				
		Section total (%)	33			Section total (%)	0				Section total (%)	32	Section total (%)	30	Overall total /70	16	Overall total (%)	23

ELEMENT / COMPONENT LEVEL	Circularity credentials of element/ component																	
	Durability			Material Inventory						Finishes/ treatments		Reversiblility of connections	Reusable (without restoration or modification)	Recyclable (No downgrading)				
	Number of previous design lives / uses	Length of previous design lives	Predicted length of current design life	Suppliers and production	Warranties	Donor Building(s)	Reclaimed and/or recycled content	Did reuse involve cleaning or restoration work?	Life Cycle Analysis with end of life scenario and Environmental product declaration	Synthetic/ chemical/ wet resins/ adhesives?	Chemical coatings							
	0 (virgin material) - 5 (five previous uses)	0 (zero), 1 (ten years)...5 (50+ years)		0 (no information) - 5 (full production and supplier information, including location; details of warranties and element history including donor building information)			% of element	0 (yes, extensive or N/A) - 5 (no, none)	0 (no information or EPD) - 5 (full LCA with origin of material, end-of-life scenario and EPD)	Yes (score 0), No (score 5)		1 (Cannot be reversed) - 5 (easily reversed)	% of element which can be reused	% of element which can be recycled				
Concrete beams & columns	0	0	5	5	5	0	0	0	4	4	5	0	0	0	Element 1 total /70	28	Element 1 (%)	40
Concrete shear walls & slabs	0	0	5	5	5	0	0	0	4	4	5	0	0	0	Element 2 total /70	28	Element 2 (%)	40
Reinforcing steel	2	3	5	5	5	0	5	0	4	3	2	0	4	4	Element 3 total /70	42	Element 3 (%)	60
Sprayed polyurethane foam	0	0	5	5	5	0	0	0	3	0	0	0	0	0	Element 4 total /70	18	Element 4 (%)	26
Masonry façade (PC mortar)	0	0	5	5	5	0	0	0	5	0	1	0	0	0	Element 5 total /70	21	Element 5 (%)	30
Glass	0	0	5	5	5	0	0	0	5	0	1	0	0	1	Element 6 total /70	22	Element 6 (%)	31
															Element mean /70	27	Overall %	38

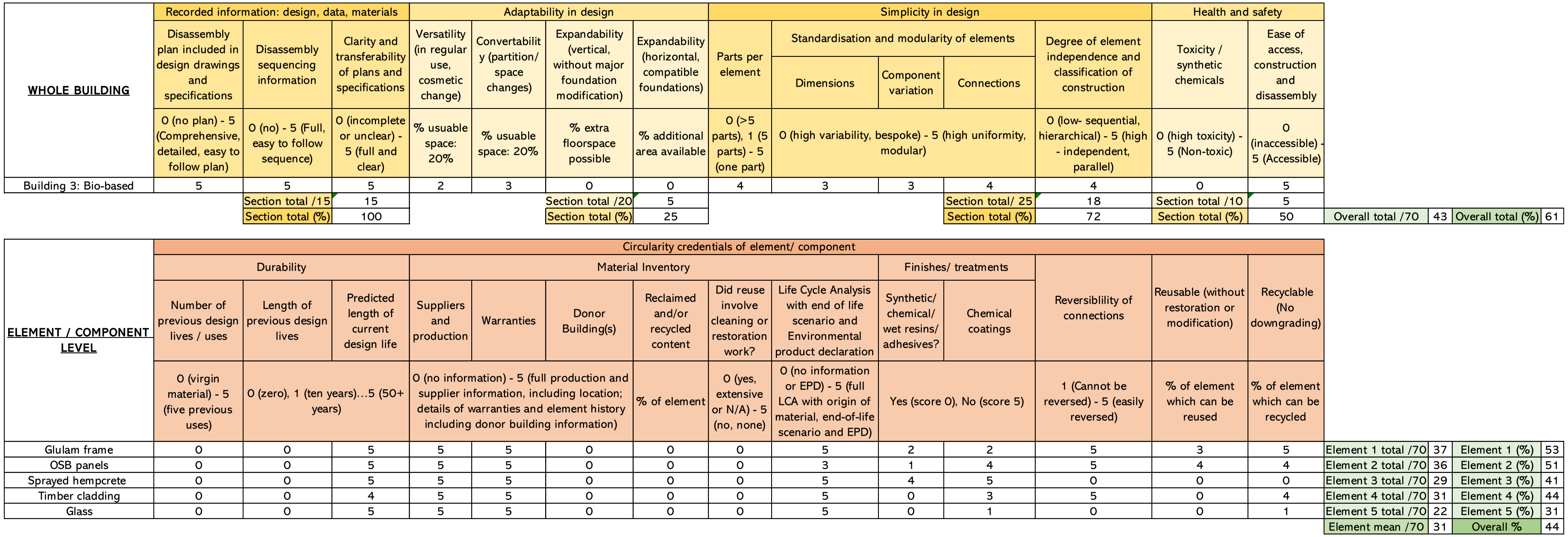
Figure 4: Building 1: A cast concrete framed building with masonry cladding and sprayed polyurethane insulation, assessed for circularity using the circular construction evaluation framework.



WHOLE BUILDING	Recorded information: design, data, materials			Adaptability in design				Simplicity in design					Health and safety					
	Disassembly plan included in design drawings and specifications	Disassembly sequencing information	Clarity and transferability of plans and specifications	Versatility (in regular use, cosmetic change)	Convertability (partition/ space changes)	Expandability (vertical, without major foundation modification)	Expandability (horizontal, compatible foundations)	Parts per element	Standardisation and modularity of elements			Degree of element independence and classification of construction	Toxicity / synthetic chemicals	Ease of access, construction and disassembly				
									Dimensions	Component variation	Connections							
	0 (no plan) - 5 (Comprehensive, detailed, easy to follow plan)	0 (no) - 5 (Full, easy to follow sequence)	0 (incomplete or unclear) - 5 (full and clear)	% usuable space: 20%	% usuable space: 20%	% extra floorspace possible	% additional area available	0 (>5 parts), 1 (5 parts) - 5 (one part)	0 (high variability, bespoke) - 5 (high uniformity, modular)			0 (low- sequential, hierarchical) - 5 (high - independent, parallel)	0 (high toxicity) - 5 (Non-toxic)	0 (inaccessible) - 5 (Accessible)				
Building 2: Steel framed	5	5	5	5	4	0	0	3	1	2	3	2	2	4				
		Section total /15	15			Section total /20	9				Section total/ 25	11	Section total /10	6				
		Section total (%)	100			Section total (%)	45				Section total (%)	44	Section total (%)	60	Overall total /70	41	Overall total (%)	59

ELEMENT / COMPONENT LEVEL	Circularity credentials of element/ component																	
	Durability			Material Inventory						Finishes/ treatments		Reversiblility of connections	Reusable (without restoration or modification)	Recyclable (No downgrading)				
	Number of previous design lives / uses	Length of previous design lives	Predicted length of current design life	Suppliers and production	Warranties	Donor Building(s)	Reclaimed and/or recycled content	Did reuse involve cleaning or restoration work?	Life Cycle Analysis with end of life scenario and Environmental product declaration	Synthetic/ chemical/ wet resins/ adhesives?	Chemical coatings							
	0 (virgin material) - 5 (five previous uses)	0 (zero), 1 (ten years)…5 (50+ years)		0 (no information) - 5 (full production and supplier information, including location; details of warranties and element history including donor building information)			% of element	0 (yes, extensive or N/A) - 5 (no, none)	0 (no information or EPD) - 5 (full LCA with origin of material, end-of-life scenario and EPD)	Yes (score 0), No (score 5)		1 (Cannot be reversed) - 5 (easily reversed)	% of element which can be reused	% of element which can be recycled				
Structural steel	0	0	5	5	5	0	0	0	5	0	2	5	5	5	Element 5 total /70	37	Element 5 (%)	53
Composite slabs	0	0	5	5	5	0	0	0	4	4	4	1	0	0	Element 2 total /70	28	Element 2 (%)	40
Reinforcing steel	2	3	5	5	5	0	5	0	4	3	2	0	4	4	Element 3 total /70	42	Element 3 (%)	60
Mineral wool batts	0	0	5	5	5	0	0	0	5	5	5	4	4	4	Element 4 total /70	42	Element 4 (%)	60
Open prefabricated panels	0	0	5	5	5	0	0	0	0	5	4	4	4	4	Element 5 total /70	36	Element 5 (%)	51
Glass	0	0	5	5	5	0	0	0	5	0	1	0	0	1	Element 6 total /70	22	Element 6 (%)	31
															Element mean /70	35	Overall %	49

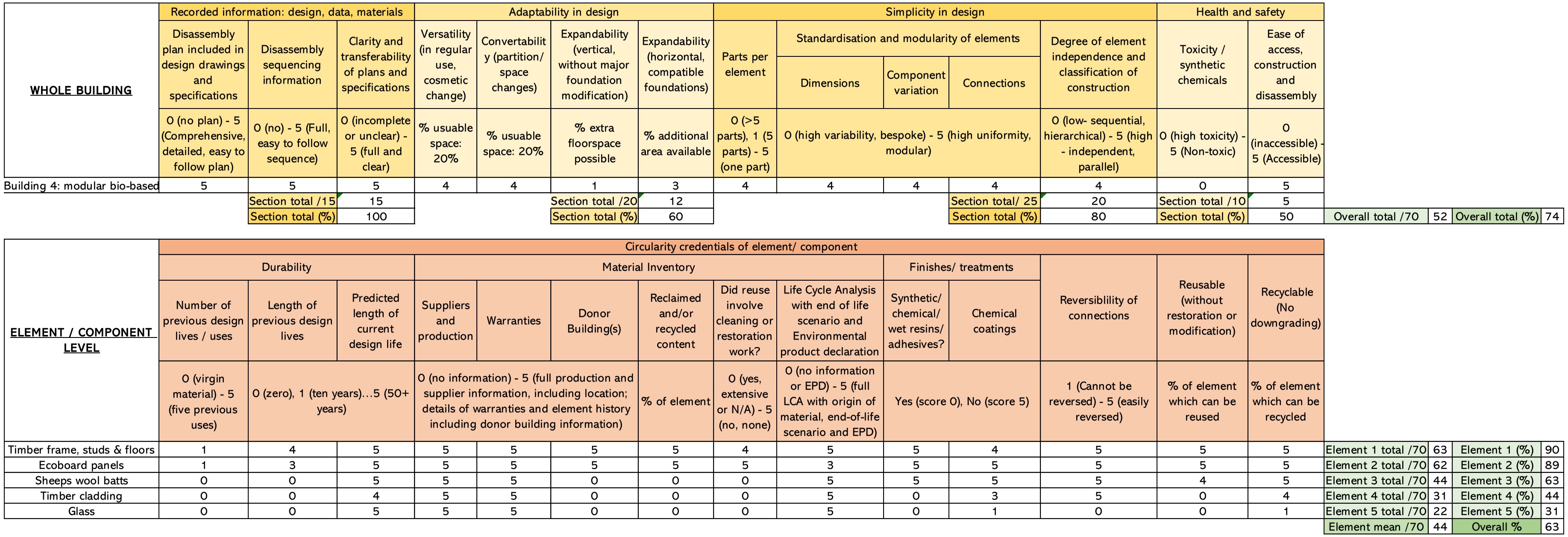
Figure 5: Building 2: A steel framed building using mineral wool insulation, lightweight steel open prefabricated panels and steel-concrete composite floors, assessed for circularity using the circular construction evaluation framework.



WHOLE BUILDING	Recorded information: design, data, materials			Adaptability in design				Simplicity in design					Health and safety					
	Disassembly plan included in design drawings and specifications	Disassembly sequencing information	Clarity and transferability of plans and specifications	Versatility (in regular use, cosmetic change)	Convertability (partition/ space changes)	Expandability (vertical, without major foundation modification)	Expandability (horizontal, compatible foundations)	Parts per element	Standardisation and modularity of elements			Degree of element independence and classification of construction	Toxicity / synthetic chemicals	Ease of access, construction and disassembly				
									Dimensions	Component variation	Connections							
	0 (no plan) - 5 (Comprehensive, detailed, easy to follow plan)	0 (no) - 5 (Full, easy to follow sequence)	0 (incomplete or unclear) - 5 (full and clear)	% usuable space: 20%	% usuable space: 20%	% extra floorspace possible	% additional area available	0 (>5 parts), 1 (5 parts) - 5 (one part)	0 (high variability, bespoke) - 5 (high uniformity, modular)			0 (low- sequential, hierarchical) - 5 (high - independent, parallel)	0 (high toxicity) - 5 (Non-toxic)	0 (inaccessible) - 5 (Accessible)				
Building 3: Bio-based	5	5	5	2	3	0	0	4	3	3	4	4	0	5				
		Section total /15	15			Section total /20	5				Section total/ 25	18	Section total /10	5				
		Section total (%)	100			Section total (%)	25				Section total (%)	72	Section total (%)	50	Overall total /70	43	Overall total (%)	61

ELEMENT / COMPONENT LEVEL	Circularity credentials of element/ component																	
	Durability			Material Inventory						Finishes/ treatments		Reversiblity of connections	Reusable (without restoration or modification)	Recyclable (No downgrading)				
	Number of previous design lives / uses	Length of previous design lives	Predicted length of current design life	Suppliers and production	Warranties	Donor Building(s)	Reclaimed and/or recycled content	Did reuse involve cleaning or restoration work?	Life Cycle Analysis with end of life scenario and Environmental product declaration	Synthetic/ chemical/ wet resins/ adhesives?	Chemical coatings							
	0 (virgin material) - 5 (five previous uses)	0 (zero), 1 (ten years)…5 (50+ years)		0 (no information) - 5 (full production and supplier information, including location; details of warranties and element history including donor building information)			% of element	0 (yes, extensive or N/A) - 5 (no, none)	0 (no information or EPD) - 5 (full LCA with origin of material, end-of-life scenario and EPD)	Yes (score 0), No (score 5)		1 (Cannot be reversed) - 5 (easily reversed)	% of element which can be reused	% of element which can be recycled				
Glulam frame	0	0	5	5	5	0	0	0	5	2	2	5	3	5	Element 1 total /70	37	Element 1 (%)	53
OSB panels	0	0	5	5	5	0	0	0	3	1	4	5	4	4	Element 2 total /70	36	Element 2 (%)	51
Sprayed hempcrete	0	0	5	5	5	0	0	0	5	4	5	0	0	0	Element 3 total /70	29	Element 3 (%)	41
Timber cladding	0	0	4	5	5	0	0	0	5	0	3	5	0	4	Element 4 total /70	31	Element 4 (%)	44
Glass	0	0	5	5	5	0	0	0	5	0	1	0	0	1	Element 5 total /70	22	Element 5 (%)	31
															Element mean /70	31	Overall %	44

Figure 6: Building 3: A bio-based material example using new glulam beams and sprayed hempcrete insulation assessed for circularity using the circular construction evaluation framework.



	Recorded information: design, data, materials			Adaptability in design				Simplicity in design					Health and safety					
WHOLE BUILDING	Disassembly plan included in design drawings and specifications	Disassembly sequencing information	Clarity and transferability of plans and specifications	Versatility (in regular use, cosmetic change)	Convertability (partition/ space changes)	Expandability (vertical, without major foundation modification)	Expandability (horizontal, compatible foundations)	Parts per element	Standardisation and modularity of elements			Degree of element independence and classification of construction	Toxicity / synthetic chemicals	Ease of access, construction and disassembly				
									Dimensions	Component variation	Connections							
	0 (no plan) - 5 (Comprehensive, detailed, easy to follow plan)	0 (no) - 5 (Full, easy to follow sequence)	0 (incomplete or unclear) - 5 (full and clear)	% usuable space: 20%	% usuable space: 20%	% extra floorspace possible	% additional area available	0 (>5 parts), 1 (5 parts) - 5 (one part)	0 (high variability, bespoke) - 5 (high uniformity, modular)			0 (low- sequential, hierarchical) - 5 (high - independent, parallel)	0 (high toxicity) - 5 (Non-toxic)	0 (inaccessible) - 5 (Accessible)				
Building 4: modular bio-based	5	5	5	4	4	1	3	4	4	4	4	4	0	5				
		Section total /15	15			Section total /20	12				Section total/ 25	20	Section total /10	5				
		Section total (%)	100			Section total (%)	60				Section total (%)	80	Section total (%)	50	Overall total /70	52	Overall total (%)	74

	Circularity credentials of element/ component																	
	Durability			Material Inventory						Finishes/ treatments		Reversiblility of connections	Reusable (without restoration or modification)	Recyclable (No downgrading)				
ELEMENT / COMPONENT LEVEL	Number of previous design lives / uses	Length of previous design lives	Predicted length of current design life	Suppliers and production	Warranties	Donor Building(s)	Reclaimed and/or recycled content	Did reuse involve cleaning or restoration work?	Life Cycle Analysis with end of life scenario and Environmental product declaration	Synthetic/ chemical/ wet resins/ adhesives?	Chemical coatings							
	0 (virgin material) - 5 (five previous uses)	0 (zero), 1 (ten years)...5 (50+ years)		0 (no information) - 5 (full production and supplier information, including location; details of warranties and element history including donor building information)			% of element	0 (yes, extensive or N/A) - 5 (no, none)	0 (no information or EPD) - 5 (full LCA with origin of material, end-of-life scenario and EPD)	Yes (score 0), No (score 5)		1 (Cannot be reversed) - 5 (easily reversed)	% of element which can be reused	% of element which can be recycled				
Timber frame, studs & floors	1	4	5	5	5	5	5	4	5	5	4	5	5	5	Element 1 total /70	63	Element 1 (%)	90
Ecoboard panels	1	3	5	5	5	5	5	5	3	5	5	5	5	5	Element 2 total /70	62	Element 2 (%)	89
Sheeps wool batts	0	0	5	5	5	0	0	0	5	5	5	5	4	5	Element 3 total /70	44	Element 3 (%)	63
Timber cladding	0	0	4	5	5	0	0	0	5	0	3	5	0	4	Element 4 total /70	31	Element 4 (%)	44
Glass	0	0	5	5	5	0	0	0	5	0	1	0	0	1	Element 5 total /70	22	Element 5 (%)	31
															Element mean /70	44	Overall %	63

Figure 7: Building 4: A bio-based material example using reclaimed timber beams and posts, sheeps wool batts and modular design, assessed for circularity using the circular construction evaluation framework.

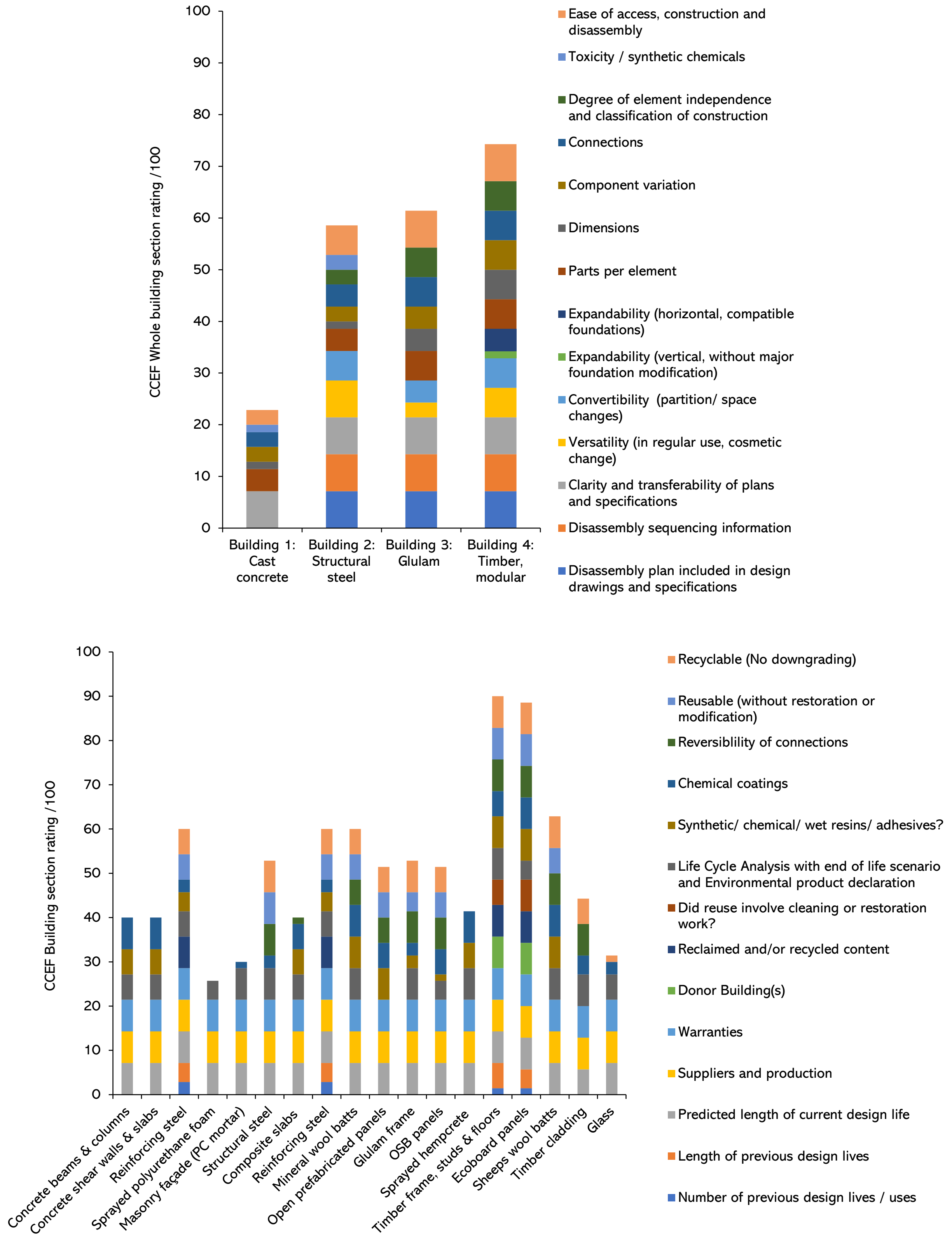


Figure 8: Application of the Circular Construction Evaluation Framework, showing percentage ratings for building level (above) and element level (below) for the four example buildings.

4 Discussion

4.1 Implementation of the CCEF

Figure 8 demonstrates the significant difference that reclaimed, previously used material can make in promoting circularity in construction. It can be seen that a bespoke, in-situ monolithic structure using material which cannot be readily reused or recycled scores significantly less than a simple, modular construction with reversible and reusable connecting components.

4.1.1 Whole building level

Whilst cast concrete Building 1 is strong, stiff and constructed to a high quality, it has not been designed for future adaptation or expansion. There are no disassembly plans and adaptation or alteration would not be economically viable. Therefore, the building and elements do not score well using the CCEF and this stands as an example of a construction method not readily compatible with circular economy principals.

Building 3 scores comparably with Building 2 - both the steel and glulam frames are sourced from new material but both can be fully dismantled and reused again for a further design life. Hemp possesses hygric and thermal properties which makes it very suitable as an insulation product; however, the wet spraying method is less suitable for circularity, as both the material itself and the base on to which it is sprayed cannot be readily disassembled or adapted at the end of the design life, thus there is less scope for reuse and reduced circularity. Building 4 has the highest rating and serves to demonstrate the advantage of combining reusable materials with a standardised, reversible modular design approach using reclaimed materials with a known history already used in the design life of a previous project - a cornerstone of circularity in construction. On the whole building level, using these examples it can be categorised that a rating of 60% is good and a rating above 70% is an excellent example of circular construction and a level to be aimed for on a building project.

4.1.2 Element level

Examining the element level, the previously used timber and ecoboard elements score the highest at nearly 90%; this demonstrates the major difference that having just one previous design life can make in circular construction. Taking a long-term view, it is the structure rather than the façade which will have the longest design life - as highlighted by Figure 2. This is reflected in the CCEF for Building 4, where the structural frame uses material sourced from a donor building, but it is not expected that the external timber façade can be reclaimed and reused without extensive restoration or member size reduction (if indeed at all), after already serving a design life in a previous building and being exposed to the elements. Figure 8 illustrates that it is challenging for an element to exceed 60% on the CCEF, therefore 60% can be taken as a benchmark of circularity, with the reusable, reclaimed elements scoring notably in excess of this, signifying a high level of circularity.

4.2 Construction systems

When considering MMC, it can be identified that the prefabricated off-site creation of pre-cast volumetric modular units, planar or linear elements, which can be simply connected together with visible, accessible connections, is readily compatible with circular construction. In-situ construction can be inherently problematic beyond first use as exemplified by the challenge of disassembling and reassembling structural reinforced concrete. Off-site prefabrication of three-dimensional modular units which can be assembled into a variety of design configurations and the category concerning linear members such as columns and beams which may be assembled into a dis-mountable frame using visible, robust connections is suggested to be particularly compatible with the concept of circular construction.

It was considered to have an explicit foundations category within the CCEF, scoring highly for pad foundations and lower for strip or trench foundations. However, it was decided to leave foundations incorporated by vertical and horizontal expansion categories - if a building can be expanded vertically without major foundation modification, this is deemed compatible with designing for adaptability, and if a building can be expanded horizontally, this is also compatible and suggests modular, rectilinear design with pads or piles which can be continued laterally at the same intervals. Furthermore, foundation choices can be governed by ground conditions which are beyond design control, for example pile or raft foundations may be necessary, rather than chosen.

4.3 Material choice and LCA

Material choice is highly important and good quality, durable materials promote re-use in a circular economy and a departure from the established linear method of demolition at the end of a building's initial functional period. The inherently high initial costs of durable, quality materials is an issue for clients and market-driven forces traditionally driven by cost and time and focused upon the realisation of a single-use static building quickly and cheaply. Although high quality materials possess an initial price premium, they yield long term potential for reuse and can promote material reclamation markets (Guy and Ciarimboli, 2005). This is particularly important with bio-based materials as higher quality elements are more likely to be structurally sound, possess high durability and be free of defects resulting from insect attack or hygrothermal processes such as wetting/drying, heating/cooling and freeze/thawing than cheaper, lower quality materials.

A challenge for emerging materials, in particular composite materials, is whether the product has an Environmental Product Declaration (EPD). An EPD is a summary of a life cycle assessment and EPD documents themselves have limitations. Although the documents are subjected to external peer review, manufacturing companies will have commissioned the document with a view to increasing awareness and ultimately sales of the product. It can be challenging to compare products and different international regulations concerning the production, scope and application of the declarations (Del Borghi, 2013). For materials which contain bio-based constituents, current LCA practice in standards do not take into account variable timings of biogenic carbon emissions during and post-design life and further research into the development and application of dynamic LCA for circular construction is required to address this. An EPD can, however, be considered as a guide to the environmental impact of a product and as a source of information regarding the constituents and properties of a material, thus making a positive contribution towards the aim of circular construction.

Material reuse with the aid of database-held information is a particular theme of the CCEF. It should also be stressed that while the CCEF scores materials of simple composition with minimal or no synthetic additions such as treatments, coatings or matrix resins or binders, the CCEF may still be applied to buildings which use composite materials, and the use of durable, whole elements which can be reused will also aid a higher score.

4.4 Upscaling design for disassembly and adaptability

The upscaling of circular construction requires three key developments. Firstly, economic viability, which should be achieved with savings on construction speeds, materials being re-used in multiple future design lives and reduced labour-related associated risks and costs, rather than looking to try and reduce initial material costs (which can be inherently high for quality, durable materials). The fact that reinforced concrete remains the most widely used construction material in the world (Gurumoorthy and Arunachalam, 2019), with demolition typically the economically driven end-of-life option, highlights this and a cultural shift towards using materials in reversible configurations would need to be demonstrated through further case studies and be shown to be economically viable. Secondly, a change to a more manufacturing-related mindset is required, which promotes the development of standardised pre-fabricated components and thirdly, the establishment of comprehensive match-making databases consisting of previously used elements in donor buildings.

Designing for disassembly and adaptability is an established concept in manufacturing sectors such as automotive, where designers were motivated by legislation to ensure materials and components can be recycled (Arup and Reifer, 2019) and aerospace, which develops standardised components for mass deployment (Wood, 2017). These sectors introduced industry-wide international quality standards including Advanced Product Quality Planning (APQP) and Production Part Approval Process (PPAP) to facilitate quality standardised, repeatable components with interchangeable parts which can be adapted and disassembled, and platforms evaluating manufacturing processes down to the component level (Wood, 2017; Rydström and Viström, 2019). Evaluation methods are valuable tools in educating and promoting the development of design for disassembly and adaptability, prefabrication and modularity in the construction industry, and the required bridging of the gap between construction and manufacturing, as the adoption of manufacturing standardisation platforms offers scope for improved circularity and productivity in construction. The CCEF is a novel tool which takes inspiration from the manufacturing sector platforms in assessing a larger product at the component or element level, but also being tailored for construction in considering the whole design, building and construction-scale elements. The CCEF is also designed to be accessible for all stakeholders to evaluate both the whole project and the component level without requiring prior knowledge in particular fields such as LCA, probability theory or statistical analysis.

It is suggested that circular construction, in addition to strategies involving promotion, regulation and education, should be driven by a culture of incentivisation. One option is to develop a systematic approach where the material supplier has the obligation, or opportunity depending upon the value of the material used, to take back the products after use (Bruce, 2019). Another approach is to place the condition of the owner of a building being able to prove the building is no longer fit for purpose before permission to demolish is legally granted. A further option suggested by this study is to develop and ultimately establish a system for governing bodies to offer financial incentives such as subsidies or reduced levels of taxation to clients or developers to use reclaimed elements with reversible connections and design dynamic buildings for future disassembly or adaptability.

Architects and Engineers able to access databases can endeavour to design using the full dimensions of available materials, promoting a practice of the design of new buildings adhering to circular principals being informed and directed by circular software tools.

4.5 Future use and validation considerations

It is envisaged that the design categories in the CCEF will become more relevant and applicable over long time scales and will not be at risk of becoming anachronistic. Material reuse, with particular reference to the attention given to design lives, previous material use and material information and designing for disassembly and adaptability are all envisaged to be perpetually relevant topics in the future of the construction industry; after all, the profile of climate change, use of finite natural resources and embodied carbon will continue to be high on the international agenda on an ongoing basis (Giesekam et al., 2018; Gallego-Schmid et al., 2020; Röck et al., 2020; D'Amico et al., 2021). Additionally, the future use of bio-based materials to complement traditional materials may play a role in reducing the carbon footprint of construction (Amziane and Sonebi, 2016; Jones and Brischke, 2017). However, it is possible that the relative importance of the categories within the CCEF may change over long periods of time. Future changes can be accommodated by the CCEF; the categories should remain but transparent weightings may be introduced – and modified over time as environmental, societal and technological developments occur. The approach of transparency allows this framework to be effectively adjusted by others.

Validation for a model can be defined as deciding whether it is acceptable for its intended use, or whether it represents real world practice well enough for its stated purpose (Giere, 1991). The purpose of the CCEF is to evaluate the degree of circularity in a proposed or extant construction project. The performance criteria are contained within the whole building and elements tables with scores of zero to five, increasing with circularity. The criteria for validation for the model would consist of evaluating the extent of circularity in extant building projects. As circular building is very much in its infancy, there is an absence of accessible observed case study data, and data concerning motivation and drivers for stakeholders to incorporate circularity into design, for such a validation. Absence of data is understandable due to the challenge of systematically collecting and analysing detailed demolition and adaptation project data (Rockow et al., 2019). The objective performance outcome would be the level of circularity of a construction project; can you reuse or recycle 1D, 2D and/or 3D elements of known source and constitution? Based upon Caswell (1988) and Rykiel Jr (1996) it is submitted that when the principal purpose of a formulated framework, model or theory is to systematise, develop or progress, the framework/model is indeed a scientific contribution in itself, notwithstanding the absence of, and challenge of gathering, additional real-world data validation.

5 Conclusions

A Circular Construction Evaluation Framework (CCEF) has been developed and presented which can quantify the level of circularity in a construction project using criteria specified in an accessible tabulated format. The CCEF is formulated to be specifically for design and construction projects, with sections evaluating the building as a whole, and taking an influence from the manufacturing sector also evaluating at the element/component level. The evaluation of the extent of circularity early in project planning can be used to inform and promote designing for disassembly and adaptability, and serve as an accessible, transparent method suitable for early-project use to complement pay-to-use specialist LCA software tools, labels from awarding bodies and adaptability evaluations of extant buildings. The CCEF framework encompasses the use of catalogued elements from donor buildings, reversible interlocking and gravity connections through to whole building design considerations such as standardisation of design, modularity and the scope for adaptation or expansion.

Circular construction is promoted by visible, transparent and accessible mechanical or interlocking connecting components and prefabricated standardised elements. Designing for disassembly and adaptability should be incorporated at a very early stage in a project, with architectural design, disassembly plans and diagrams being aided by inventories of reusable materials and connections from donor buildings and simple rectilinear design informed by the availability of reusable elements. Re-use and re-arrangement of building elements and configurations as a sustainable alternative to demolition would be promoted by the use of high quality, durable materials capable of reuse in multiple design lives. Known material constituents and properties will aid future reuse, although issues exist regarding accurate, consistent LCA and the development of EPDs for products.

With demonstrated example applications of the CCEF, it has been shown that the use of reused durable materials in conjunction with modular, demountable and adaptable design is an effective combination in achieving high levels of circularity in a construction project. Over long time scales, the design categories within the CCEF may be subject to transparent and modifiable weightings to reflect changes and future developments.

6 Acknowledgements

Circular Bio-based Construction Industry (CBCI) is an Interreg 2 Seas 2014-2020 project. Interreg 2 Seas is a European Territorial Cooperation programme. The authors of this paper and the partners within the CBCI project gratefully acknowledge the funding from the Interreg 2 Seas programme 2014-2020 co-funded by the European Regional Development Fund (ERDF) under subsidy contract No 2S05-036.

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