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# Cradle to Cradle and Whole-Life Carbon assessment – Barriers and opportunities towards a circular economic building sector

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**Abstract.** The general awareness of climate change has been increasing steadily while buildings continue to be the main contributors to greenhouse gas emissions. To address the need for change in the building industry and transform its hazardous impacts on the environment to a positive footprint, circular economic design approaches and Whole-Life Carbon (WLC) assessment have been introduced. This paper analyses the main barriers for a successful implementation of the regenerative Cradle to Cradle (C2C) concept and WLC evaluation, identifying the lack of unified and measurable framework along with the deficiency of detailed case studies and post occupancy evaluation. In the context of the increasing demand for carbon accounting, obtaining comprehensive information on embodied carbon in buildings is challenging despite the existing Life Cycle Assessment structure. To link theory with practice, the paper discusses the London School of Economics Centre Buildings Redevelopment by RSH+P as case study. It reveals barriers and opportunities for WLC evaluation as well as the potential of life cycle cost optimization in environmental and economic terms.

The paper concludes with a reflection on how the certification of materials through material passports may not only achieve a higher transparency but lead to a circular economic building industry by comprehensive WLC assessment and a closer implementation of reversible building design corresponding to the C2C principles. The potential of combining WLC evaluation with C2C strategies and translating them into a comprehensive, unified assessment framework for a circular building sector is identified.

**Keywords:** Reversible Building Design, Cradle to Cradle, Materials Passport, Whole-Life Carbon, Embodied Carbon, Circular Building Sector



## 1. Introduction

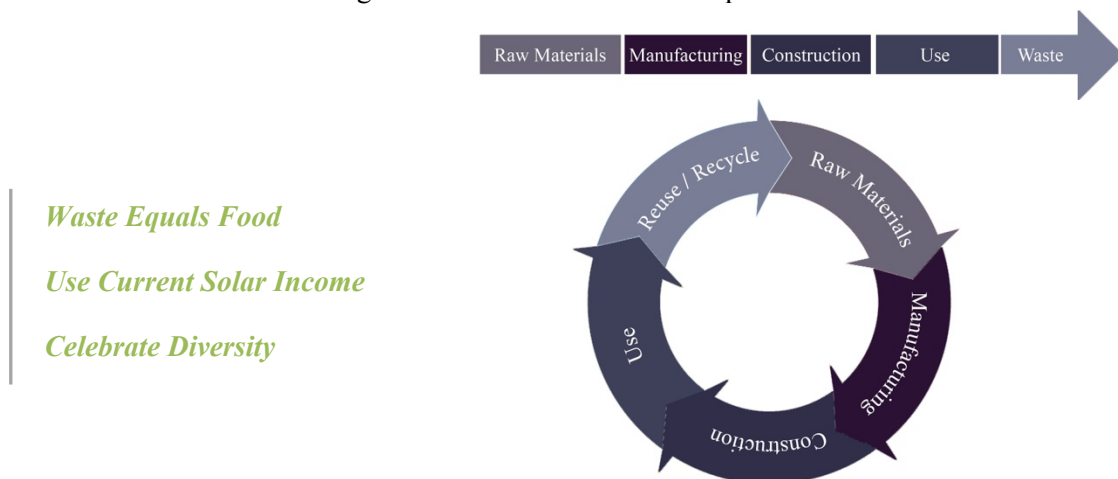
Over the last few years, environmental awareness has been increasing steadily as global warming results in occurring natural catastrophes and economic crises. According to the United Nations Environment Programme (UNEP), buildings accounted for at least one third of the total global final energy demand, resource consumption, waste production and CO<sub>2</sub> emissions in the year 2013 [1]. These numbers prove evidence of a systemic shift in the building industry.

### 1.1 Circular Economy, Cradle to Cradle and reversible building design

To design in a more resource efficient manner and to reduce or eliminate the carbon footprint of buildings, different concepts have been developed in the last decades. *Circular Economy* and *Cradle to Cradle* (figure 1) aim to replace the linear *Cradle to Grave* system with a circular model and achieve a 'positive footprint' of all industries (figure 2). Reversible building design facilitates maintenance, adaptation, extension, reuse and relocation. Materials and products are the key factors in closed-loop, regenerative design, hence they should be recyclable and reusable without losing quality. In 2015, the Horizon 2020 project *Buildings as Material Banks* (BAMB) has been launched to enable the shift to a circular built environment through reversible building design tools and material passports [2].

### 1.2 Embodied carbon in buildings

While demand for carbon accounting of buildings is undoubtedly increasing, there is still a very limited sample of buildings in the public domain with which to compare (i.e. under 250 projects in the WRAP Embodied Carbon Database). Additionally, it is difficult to get information on the break-down of the embodied carbon in these buildings and further on the related impact of the materials used.



**Figure 1.** C2C main principles.

**Figure 2.** From linear to circular.

### 1.3 Aims and Methodology

The paper aims to illustrate the importance of linking theory and practice for a successful implementation of Cradle to Cradle principles, reversible building design and Whole-Life Carbon accounting, while pointing out related difficulties and opportunities. A thorough literature review, interviews with practitioners and in-depth analysis of the London School of Economics – Central Building Redevelopment (LSE-CBR) in the City of London, designed by RSH+P, was conducted.

In the LSE-CBR case study, an embodied carbon assessment has been undertaken to a significant depth by a team including one of the authors of this paper, who is working for the project environmental consultants (ChapmanBDSP), in order to inform the design. The paper aims to analyse the current best practice Life Cycle Assessment (LCA) and suggest the way-forward to include more complex parameters and analysis such as material qualities, project stage or C2C methodology.

To conclude, the paper provides necessary steps in order to achieve closed-loop design processes as well as effective carbon accounting and presents an outlook on the requirements and possibilities of a zero-carbon future.

#### 1.4 Background: Policies, carbon assessment and materials passports

As a reaction to the increasing frequency of extreme weather events, governments have been implementing policies for environmentally sustainable and resilient urban development. In their most recent report [3], the IPCC suggests limiting the increase in global average temperature below 1.5°C above pre-industrial levels, instead of 2°C, as adopted in the 2015 Paris Agreement [4].

To provide guidance and consider further aspects, the European Union and United Kingdom have set up own legal requirements for the building sector, in which environmental and economic benefits are targeted; focusing on carbon reduction and life cycle issues such as durability and circular economic solutions for end-of-life future reuse. An important asset on the way to a zero-carbon building industry is *Life Cycle Assessment* (LCA), which is more and more emphasizing the *Whole-Life Carbon* (WLC) assessment of buildings (figure 3). Certification systems such as *BREEAM 18* require a form of LCA, including both operational and embodied carbon analysis, which returns the WLC cost of the project.

“Whole-Life Carbon emissions are directly related to the type and quantity of the resources used to create, maintain and use a building. This means that whole-life assessments are as much about resource efficiency as they are about carbon emissions. This makes whole-life assessments extremely relevant to tackling two key relevant environmental problems: global warming and resource depletion” [5].

At present, it is difficult to precisely evaluate the embodied carbon of building materials, as it depends on many variables, which will be further explained in *section 2.2*.

Moreover, seriously health-threatening ingredients in many products as well as the increasing importance of health and well-being contributed to the demand for more transparency from the building industry regarding material qualities. The Environmental Protection Encouragement Agency (EPEA) has developed the *Cradle to Cradle Certified™* Program. This contains the *C2C Circularity Passports®* and the *C2C Certified™* products. The latter has been introduced in several bigger (certification) systems, such as LEED, BREEAM, DGNB and BAMB. During the certification process, the materials and manufacturing practices of each product are assessed in five categories: Material Health, Material Reutilization, Renewable Energy & Carbon Management, Water Stewardship and Social Fairness [6]. Further material passports exist, for instance developed by the BAMB project [2].

Building Assessment Information	Life Cycle Stages				Included in Assessment
Building Life Cycle Information	Product Stage		A1	Raw material supply	Yes
			A2	Transport	Yes
			A3	Manufacturing	Yes
	Construction Process Stage		A4	Transport	Yes
			A5	Construction Installation Process	Yes
	Use Stage (60 years)		B1	Use	Yes
			B2	Maintenance	Yes
			B3	Repair	Yes
			B4	Refurbishment	Yes
			B5	Replacement	No
			B6	Operational Energy Use	Yes
			B7	Operational Water Use	Yes
	End of Life Stage		C1	De-construction/Demolition	Yes
			C2	Transport	Yes
			C3	Waste Processing	Yes
			C4	Disposal	Yes
Beyond Building Life Cycle	Benefits and Loads		D	Reuse - Recovery - RecyclingPotential	No

WLC Potential

**Figure 3. LSE-CBR – LCA Criteria.**

## 2. Cradle to Cradle and Life Cycle Assessment in the building sector

In the following sections, the barriers and opportunities of C2C and LCA in the building sector are analysed, resulting from literature review, interviews and evaluation of case studies.

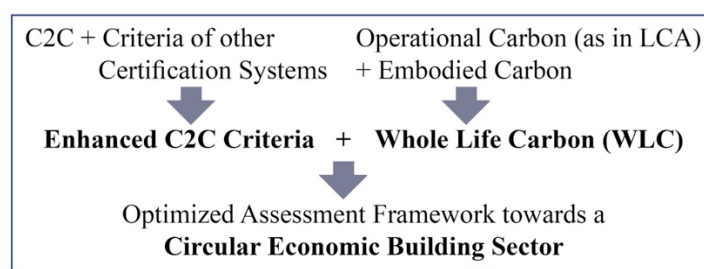
### 2.1. Cradle to Cradle

Whereas the C2C materials certification program (*see section 1.4*) is more and more established in the building sector, the implementation of C2C principles in the design of buildings remains difficult. A thorough literature review and interviews with practitioners (conducted by the main author) revealed the following possible reasons for the barriers towards a regenerative, C2C-inspired building sector:

1. a conservative, slowly changing building industry with many actors and no unified supply chains
2. the lack of one thorough, practicable framework with comprehensive case studies
3. the “prototype-characteristic” of building developments with time and cost pressure

Concerning the comprehensiveness of C2C, Toxopeus et al. [7] argue that the C2C evaluation process, in contrast to LCA, does neither consider the use phase of a material or product nor its operational energy consumption. Furthermore, other circular system concepts (e.g. *Regenerative Design*, *Biomimicry* and *Blue Economy*) call for an efficient energy consumption to reduce fossil fuels and minimise the use of resources. In contrast, “Cradle to Cradle propounds that solar energy is abundantly available and reduction is therefore not needed, except for energy use in production processes” [7].

The approach of comparing the Cradle to Cradle principles to the guidelines of other existing systems and concepts could be used to derive, adapt and complement basic indicators and measurable units according to C2C. Complementing the enhanced C2C system with WLC assessment would provide an optimised evaluation system, given that criteria is unified and comparable (figure 4). This is further elaborated in *section 3*.



**Figure 4.** C2C + WLC = CE.

### 2.2 In-depth carbon accounting – Case study London School of Economics

Whereas Whole-Life Carbon evaluation considers both operational and embodied energy during the entire life cycle of buildings, standard Life Cycle Assessment does not necessarily cover all aspects. Consequently, the amount of energy consumed to extract, process, transport, fabricate, maintain and reuse or dispose a material or product is not always calculated.

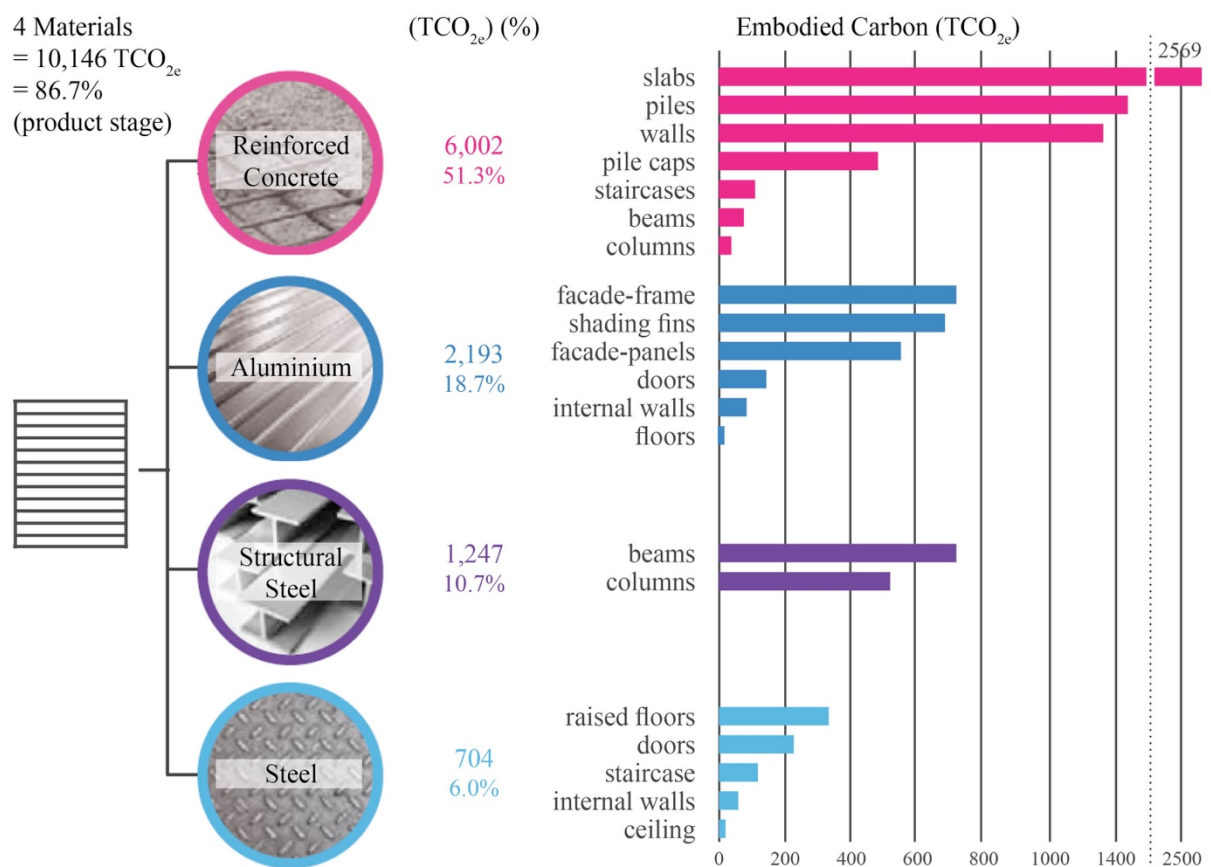
The LSE-CBR case study points out that lifetime costs in carbon and financial terms can be reduced by a regenerative and genuinely sustainable design approach supported by thorough carbon accounting.

The comparability of numerical LCA or WLC results is difficult due to individual considerations of assessors, despite same initial information, such as quantities and technical drawings. The barriers and opportunities of current LCA methods such as the challenge of comparing like-for-like is shown in the following sections on the case study of LSE-CBR, where the assessment of operational and embodied carbon was undertaken by a team including one of the papers’ authors to inform the design.

**2.2.1 Material qualities.** The Environmental Product Declaration (EPD) provides comparable information about the life cycle environmental impact. However, as it is not always issued individually for different manufacturers, information on some materials and products are generalised. Thus, the variable primary energy demand, e.g. due to different processing methods, is not considered. LCA assessors rely on standard EPDs, what results in inaccurate numeric outcomes. Unitized material certification systems and C2C Circularity Passports® could provide a reliable source for comparability to inform the material selection.



**2.2.2 Material quantity.** LCA does usually not consider where and therefore to what extent the material is applied in a building; even though the break-down of embodied carbon to building elements and materials could help to identify potential of carbon-saving and inform the design. The most 4 carbon critical ‘materials’ in the LSE-CBR project are highlighted in figure 5. Together, these account for 87% of the product stage embodied carbon. “It can be seen that the (reinforced concrete) slabs in the building are the biggest contributor, followed by piles and walls. The aluminium used in the façade (frame, panel, fins) is also very significant, as is the steel used in the structural beams and columns. Hence, material efficiency in terms of the design of the super-structure and sub-structure can have a major impact on overall embodied carbon, particularly when combined with specifications of ‘products’ with even slightly lower Global Warming Potential, kgCO<sub>2</sub>equivalent” [8]. If all aspects are considered during material selection, reduced lifetime costs in carbon and financial terms can be achieved. C2C certified materials combined with LCA could provide useful information for informed decisions.



**Figure 5.** LSE-CBR – Carbon critical materials.

**2.2.3 Benchmarks and Project Stage.** Depending on the benchmarks used for reference and the project stage in which LCA is conducted, the outcome varies significantly. The LSE-CBR case study shows, that benchmarking of the LCA product stage (A1-A3) according to Atkins Carbon Critical tool for medium rise office block varies from 650 to 1600 kgCO<sub>2e</sub>/m<sup>2</sup>. The study also highlights the importance of assessing the embodied carbon according to the project stages through which meaningful steps can be taken in reducing carbon impact: At stage 2 (concept design) 1037 kgCO<sub>2e</sub>/m<sup>2</sup> are assumed for Gross Internal Area (GIA), whereas stage 5 (construction) predicts only 823 kgCO<sub>2e</sub>/m<sup>2</sup> [8]. Reduction in non-usable areas, improvements in material efficiency based on stage 2, 3 and 4 designs, sensible façade module design, influencing piling design leading to significant reduction in volume and detailed information on quantity and quality are some reasons. Different assumptions for material compositions and specifications at different project stages can also generate considerable variances in the carbon

impact. For example, the percentage of concrete and steel (and hence of virgin or recycled steel) in reinforced concrete elements can lead to major differences in the LCA. “1 kg of virgin steel has an average embodied carbon content of 2.113 kg CO<sub>2e</sub> which drops to 0.462 kg CO<sub>2e</sub> when 1 kg of recycled steel is considered” [9].

*2.2.4. Further aspects.* Additionally, the source of fabrication energy, distance travelled, production method (precast or in-situ), maintenance and refurbishment effort, lifespan, ease of disassembly or carbon set free through final disposal are difficult to consider, due to variety or lack of information. Comparing the LCA of buildings with different lifespans, the use phase becomes much more substantial over 100 than 60 or 20 years of life. Thus, low initial embodied energy does not necessarily have low whole-life embodied energy and vice versa.

### 3. How to overcome the identified barriers towards a circular building sector?

Simon Sturgis rationalizes the challenges of LCA as follows: “Notwithstanding the limitations, life cycle assessment (LCA) remains at present the best approach to guide towards an assessment, and a subsequent mitigation, of the carbon emissions and environmental impacts caused by buildings” [5]. Nevertheless, it is important to further develop the current methodologies and overcome the barriers of C2C implementation and WLC assessment, as suggested in the following sections.

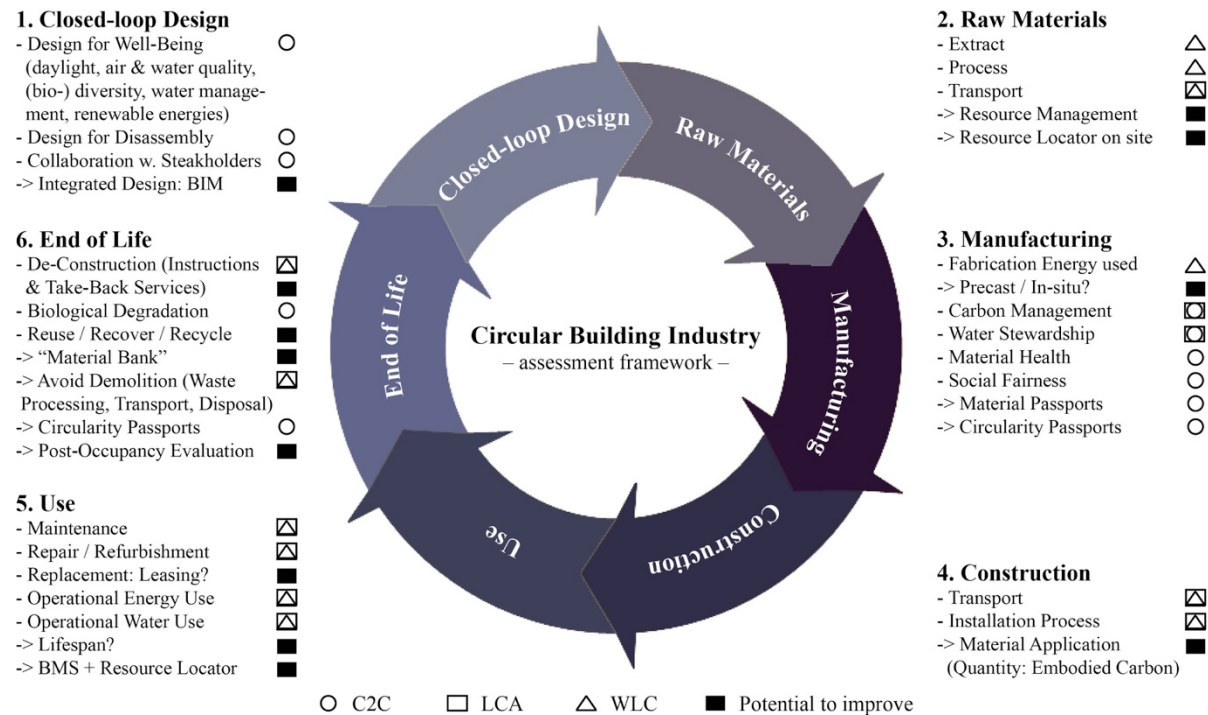
#### 3.1 An integrated framework for a circular building sector – Combining WLC and C2C

To attain regenerative design processes, as intended by Circular Economy and Cradle to Cradle, the choice of materials and structures which do not produce much waste during sourcing and construction but are recyclable with minimum waste and use of energy in order to reduce need for new materials is essential. Measuring the resulting carbon impacts of all construction related aspects and elements, hence expanding the current LCA method, allows us to compare the relative environmental performance of new and reused building components.

The LSE-CBR case study illustrates likewise that holistic WLC assessment could play an important role on the way towards a genuinely circular design model. So far, the stage beyond a building's life cycle (*stage D*) has usually not been considered (figure 3). In extending and promoting *stage D* lies enormous potential for recycling and reusing building components and thus closing the gap between end-of-life and new design stage. Additionally, materials certification and comparable benchmarks need to be further developed in order to achieve higher transparency. Further research and development of certification systems' operating mode as well as the evaluation of embodied carbon, material health and capability for reversible building design is recommended.

Considering the above, the huge potential of combining WLC and C2C principles becomes evident. Figure 6 illustrates the aspects currently considered by LCA, WLC and/or C2C and highlights the potential for a comprehensive, unified assessment framework by complementing LCA/WLC with C2C and further developing linked criteria and principles:

1. The *Design process* (1.) itself is missing in LCA, whereas C2C criteria consider aesthetic, adaptive design that provides good daylight, air and water quality for the occupants' well-being, celebrates diversity and is easy to disassemble.
2. Regarding the *Product stage* (2. & 3.), C2C evaluates the material qualities and considers aspects which are neglected by LCA; such as ingredients hazardous to health and social fairness, e.g. by supporting local jobs and providing fair working conditions. However, LCA considers resource efficiency, as opposed to C2C. WLC evaluates energy used for production.
3. The *Construction and Use stage* (4. & 5.) along with energy efficiency and transportation are neither considered in C2C certification, contrary to LCA/WLC.
4. Respective the *End-of-Life stage* (6.), C2C aims for a closed-loop design process by using 100% recyclable or biodegradable materials, whereas LCA examines de-construction, demolition, waste processing and disposal but does not consider the potential for reuse, recovery or recycling.



**Figure 6.** Potential of combining LCA with C2C and developing a circular assessment framework.

To finally overcome the identified barriers, the suggested new WLC assessment methodology implementing the C2C principles, needs transparent and comparable benchmarks regarding fabrication energy, manufacturing method (e.g. precast or in-situ) and considered lifespan.

Furthermore, the new framework needs to be further elaborated by integrated design processes and detailed post occupancy evaluation. Therefore, close cooperation of interdisciplinary teams as well as development of Building Information Modelling (BIM) for reversible building design is essential.

Next to the high-volume, low-cost approach towards reduced energy use and greenhouse gas emissions by retrofitting the existing building stock, the reuse potential of buildings, components and materials as suggested by BAMB [2] combined with take-back services provided by manufacturers and suppliers and a building management system (BMS) that includes a resource locator to track available materials for reuse will complement the framework.

### 3.2. Supporting growing awareness

The growing trend of healthy lifestyle, the success of sustainable certification systems and the Ellen MacArthur Foundation along with other international projects, such as BAMB, will help to increase the number of Cradle to Cradle certified materials on the market and facilitate transition towards a circular economic building sector. Consequently, the network will grow and provide the needed platform for knowledge exchange and material pooling.

### 3.3. Planners, clients and other stakeholders

In order to convince designers and clients, the social, environmental and economic benefits of a circular economic building industry should be promoted. As disclosed in research and the LSE-CBR case study, lifetime costs in carbon and financial terms can be reduced through resource efficiency, durability and a construction type which allows easy maintenance and dismantling for adaption or reuse. Fines due to legal requirements can be avoided through anticipation, as downward pressure on carbon emissions will increase [5]. Supporting the development of nonlinear but circular processes, such as 3D printing, self-assembly and a material bank seems indispensable on a way to zero carbon and zero waste buildings.



#### 4. Concluding remarks and outlook

To overcome the current in-depth limitation of carbon accounting and facilitate reversible building design as well as the implementation of Cradle to Cradle strategies, a unified, integrated Whole-Life Carbon assessment framework which incorporates and enhances C2C criteria is instrumental.

Furthermore, stronger interdisciplinary cooperation among stakeholders and supply chains, in-depth research on case studies and post occupancy evaluation, innovative market incentives and strategies as well as comprehensive material certification, e.g. through materials passports, is needed in order to achieve higher transparency on materials qualities and their embodied carbon. This in turn can foster validated and better comparable Whole-Life Carbon assessments.

Another key factor to achieve a significant cultural shift by understanding our (individual) impact on climate change is education. Clients, investors and occupants will have to understand and ‘feel’ the benefits of buildings with lower whole-life embodied carbon. At the same time, financial benefits should be increased and accentuated whereas the concern of potential risks when investing in reversible design solutions should be alleviated.

A holistic sustainable approach considers the wellbeing of the occupants by creating a healthy environment through healthy materials. This fact has been used successfully for promotion and will hopefully facilitate a shift in people’s mindset. Along with the integrated Whole-Life Carbon assessment framework as introduced above and focus on reversible building design, we can hopefully not only target but achieve a zero-carbon building industry – to meet the 1.5°C target set by the IPCC and save our planet.

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Note: All figures are by the authors.

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