Chapter 12
Applying Circular Economic Principles to Reduce Embodied Carbon

Danielle Densley Tingley, Jannik Giesekam, and Simone Cooper-Searle

Introduction

Through a series of case studies, this chapter explores the connections between the circular economy and the reduction of embodied carbon. Circular economic principles focus on maintaining the value of materials for as long as possible. A circular economy seeks to keep materials in circulation, removing the concept of waste from the system and the need for material extraction from primary sources. In a completely circular economy, all 'waste' outputs would equal system inputs; in Fig. 12.1 this means $M_{\mathrm{EoI}} + M_{\mathrm{w}} = M_{\mathrm{c}} + M_{\mathrm{m}}$. If the built environment is thought about in this way, as a system, then the inputs are construction materials; these materials accumulate in buildings, which can also be thought of as the stock. Demolition waste is the output flow of materials in this system.

The concept of a circular economy can also be extended to embodied carbon. Construction materials are input flows of embodied carbon. These emissions are new to the system. If demand for new buildings is reduced through retrofit and adaptation of buildings already in use, the input flow of embodied emissions would fall, and existing, already expended, embodied carbon would remain in stock. Another option to reduce flows of new embodied emissions is to channel demolition waste into material inputs. Steel sections, for example, can be extracted from a building at the end of its life and reused. This requires a shift in approach to building

---

D. Densley Tingley (✉)
Civil and Structural Engineering Department, University of Sheffield, Sheffield, UK
e-mail: d.densleytingley@sheffield.ac.uk

J. Giesekam
Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds, UK

S. Cooper-Searle
Department of Engineering, University of Cambridge, Cambridge, UK

F. Pomponi et al. (eds.), *Embodied Carbon in Buildings*,
https://doi.org/10.1007/978-3-319-72796-7_12

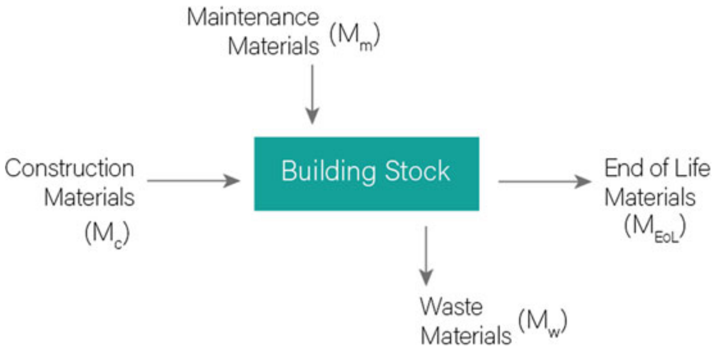

Fig. 12.1 The built environment as a system of stocks and flows

deconstruction and materials salvage. Some end-of-life buildings will be more suited to this approach than others, depending on the material composition and construction methods. Adapting the existing building stock and salvaging material at the end of a building's life will reduce, but not eliminate, the demand for new materials and the addition of embodied carbon to the building stock. Where new materials are required, strategies such as design for adaptability and deconstruction should facilitate longer building lifetimes and component and material reuse at end of life. This should enable a reduction in cradle-to-cradle embodied carbon. The following section outlines the state of the art in the area.

State of the Art

A review of the key literature on the circular economy in construction in general terms is included here, as well as an introduction and summary of some key literature for each of the four circular economic design strategies focused on in this chapter, namely, building reuse, material reuse, design for deconstruction and material reuse and design for adaptability.

The Circular Economy in Construction

Much of the literature to date that specifically focuses on the circular economy in construction or specifically buildings are industry-based reports rather than academic literature. This section provides a snapshot of some of the key documents in the area. The Ellen MacArthur Foundation has been key in increasing the profile of the circular economy, through their work to promote and progress the transition to a circular economy. Much of their work is on the benefits of the circular economy across a broad range of sectors. However, they have also compiled a report (CE100

2016), which documents a series of case studies from its CE100 network where the circular economy has been applied in the built environment; some of these case studies are explored in the case study analysis section of this chapter. Usefully this report also discusses the ReSOLVE framework in the context of the built environment. The framework sets out six strategies, which circular economic approaches can be gathered under; these are as follows:

1. *Regenerate*: which includes examples in the built environment of renewable energy, building on brownfield sites and resource recovery
2. *Share*: with examples of co-housing and office-sharing
3. *Optimise*: compact urban growth, energy and material efficiency
4. *Loop*: making use of end-of-life buildings/materials through repair, remanufacturing, upgrade and reuse
5. *Virtualise*: teleworking and smart appliances
6. *Exchange*: better performing materials and technologies (CE100 2016)

These six strategies won't necessarily reduce the embodied carbon of buildings in the design sense as some of them instead look to replace the need for additional buildings through more strategic use of existing space, e.g. teleworking. This approach would, however, reduce the embodied carbon of the broader built environment if less new buildings were required. The reduction of operational carbon is also targeted through some of the strategies, such as regenerate and virtualise.

A report on the potential of the circular economy in Dutch construction highlights four important conditions for a change to a more circular construction industry; these are as follows: minimising operational impacts, reuse of existing buildings/infrastructure, design of new buildings for circularity (including future deconstruction, adaptability and reuse) and selection of circular materials (durable, strong, light, non-toxic) (van Odijk and van Boven 2014). There are not only clear parallels with some of the strategies that will be explored in this chapter (points 2 and 3 particularly), but these ideas will also bring about reduced cradle-to-cradle embodied carbon through longer product lifetimes. The book by Cheshire (2016) explores some of these principles and the wider role of the circular economy in construction, weaving case studies throughout to demonstrate how principles can be integrated in practice. Cheshire also suggests alternative models which could be applied for additional value capture; this will likely be an important component if the circular economy is to be adopted at scale. Arup (2016) have also coalesced their ideas on the role of the circular economy in the built environment, discussing different strategies, which they categorise under the Ellen MacArthur Foundation's ReSOLVE framework. They also explore and discuss the opportunities, challenges and enablers across scales in the built environment from buildings to cities to the global scale. Another useful contribution of this report is the overlaying of the identified strategies with a layered building approach (following Brand 1994), meaning opportunities are identified across stuff, space, services, skin, structure, site and the wider system. Pomponi and Moncaster (2017a) consider the framing of the circular economy in the built environment, particularly exploring the literature that has helped to form this area. They propose a framework for circular economy research in the built environment, which considers six different dimensions: governmental, economic, environmental, behavioural, societal and technological. This brief review of literature on the circular economy in the built environment demonstrates that there are several strategies adhering to circular economic principles that would also bring about reductions in embodied carbon.

Building Reuse

Building reuse can be challenging to identify, in that buildings are frequently retrofitted to varying degrees, and there is potential for the terms building reuse and building retrofit to be used interchangeably. This chapter considers building reuse to be when a design team is presented with a site containing an existing building, and a decision is taken to reuse either all or part of the building, as opposed to demolishing the building and starting anew. Assefa and Ambler (2017) explore this, quantifying the potential life cycle impacts of repurposing and building system reuse compared to a demolition and rebuild scenario. They show an avoided impact of 33% global warming potential, purely in embodied carbon as the in-use impacts were not considered. However, in the broader context of building reuse, it is important that retrofit and improvement of the building fabric are integrated to ensure that operational carbon is also minimised. Andrews et al. (2017) debate the difficulties of energy efficient adaptive reuse of buildings, particularly considering the difficulties a change in use presents and the impacts this has on building service requirements. They suggest that regulation in the USA is a particular problem, and one potential solution would be an energy efficiency performance path rather than specific regulation in the case of building reuse. Laefer and Manke (2008) advocate building reuse, considering a number of benefits including cost savings, shorter construction times, waste management, minimised site disruptions and energy and material savings. The latter will likely result in embodied carbon savings. They propose an assessment method to apply to projects to consider the potential for reuse of an existing building's structure. In a similar vein, Langston et al. (2008) propose a framework in which to identify the adaptive reuse potential of different buildings; this considers the current age of the building as well as the predicted physical lifespan and then requires an assessment of a range of possible reasons for obsolescence, producing an index of reuse potential. The potential comparative nature of this approach would make it useful for owners with a significant property portfolio, or possibly local authorities, but it would likely be less useful for those involved in building design.

Material Reuse

Material reuse involves salvaging materials or components during retrofits or demolition. Architectural salvage occurs particularly for period pieces, although the potential for material and component reuse is much greater and could extend from floorboards and doors to structural elements such as steel or timber beams. Chau et al. (2015) have demonstrated the energy benefits of reuse at end of life, demonstrating in the modelling of a concrete frame, high-rise building that a maximum reuse scenario gives a 38.5% potential energy saving, which was higher than recycling. This, of course, translates to an embodied carbon saving as well. Pongiglione and Calderini (2014) specifically investigate the embodied carbon benefits of reusing structural steel, demonstrating a 138 tCO2e saving in the theoretical redevelopment of a train station in Italy, suggesting that 30% of the new steel could be replaced with reused steel sourced from a nearby building. This study again demonstrates the clear embodied carbon benefit of reusing materials. Inherently, if material reuse can displace the need for new material processing, then there will be an associated energy and greenhouse gas emission saving. It thus also follows that those materials with high-embodied carbon should be particularly targeted for reuse, as displacing the need for new materials of these types will yield a greater benefit. This is potentially best applied to durable materials such as steel and aluminium as they should have long enough lifespans to benefit from reuse, although they will also need to be utilised in forms where they can be salvaged with minimal damage for reuse.

There are, however, significant barriers to material reuse, particularly of structural materials; these have been explored in work by Addis and Schouten (2004), Densley Tingley and Davison (2011), Hosseini et al. (2015) and Densley Tingley et al. (2017). Commonly occurring and significant barriers include the potential cost of reuse, supply chain gaps or lack of integration (i.e. where do you source reused materials from), availability of reused materials, traceability (this is particularly an issue for structural materials where for future design, it is useful to know material properties such as steel grade) and a lack of client demand. The latter might be overcome if reduced embodied carbon becomes a client driver as reuse of materials would be an effective way to achieve this.

Design for Deconstruction and Material Reuse

Design for deconstruction and material reuse aims to facilitate future non-destructive dismantling of buildings to facilitate future reuse. Some of the barriers to this approach overlap with those outlined in the preceding section on material reuse, but another significant one is the uncertainty of the future – it is difficult to encourage clients and designers to incorporate a strategy which will see its main benefits in the future. However, work by Densley Tingley and Allwood

(2015) has shown that co-benefits such as faster construction times and greater flexibility in use can be better drivers for design for deconstruction than the environmental benefits of reuse and cradle-to-cradle embodied carbon savings. Design guides for approaches to design for deconstruction have been written by Addis & Schouten (2004) Morgan & Stevenson (2005), and Guy and Ciarimboli (n.d.), highlighting key areas such as reversible, accessible connections, non-composite design, deconstruction plans and material inventories.

Densley Tingley and Davison (2012) link design for deconstruction to embodied impacts, proposing a method to account for the embodied carbon benefits of design for deconstruction, whereby the impact is shared over the number of predicted lives. Module D of BS EN 15978:2011 Sustainability of Construction Works – Assessment of Environmental Performance of Buildings – Calculation Method would also allow for an estimate of a future benefit from reuse. Densley Tingley (2013) applies this method to series of case studies demonstrating embodied carbon savings, particularly for steel- and timber-framed structures. These construction types in particular lend themselves to reversible connections.

Delivering future reuse may require a fundamental change in perception from buildings as ‘waste in waiting’ (Giesekam et al. 2016) to valuable ‘material banks’. This idea is being explored by the ongoing BAMB (‘Buildings as Material Banks’) project which is attempting to integrate ‘material passports’ with reversible building design to optimise circular industrial value chains. Luscuere (2017) explores how these material passports can retain critical context-specific information about material health, deinstallation, disassembly, location and reverse logistics to support greater reuse at end of life. Retaining such information could support stakeholders throughout the building value chain in preserving the economic value and embodied carbon of these stocked assets.

Design for Adaptability

Pinder et al. (2017) explore what practitioners in the construction industry perceive adaptability in buildings to mean, conducting a series of unstructured face-to-face interviews. They conclude that interpretation of adaptability and indeed the vocabulary associated with adaptability is varied and suggest that this lack of clear articulation could be a barrier to the development of adaptable buildings. However, the terms ‘flexible’ and ‘resilient’ are mentioned, and more generally the discussions allude to a building’s ability to change over time. Manewa et al. (2013) discuss the role adaptable buildings play in creating a more sustainable future and explore design strategies, categorising these into themes: convertible (functions), scalable, moveable (location), adjustable (task), versatile (space) and refitable. This work demonstrates the broad nature of the term adaptable buildings.

For the purposes of this chapter, design for adaptability is taken to mean the design intention to increase the ability of buildings to change over time to suit different needs. This could be as simple as clear spans and increased floor to ceiling heights to accommodate internal reconfigurations and provision of additional services or could include sizing columns to allow for future vertical expansion of the building or increasing the design criteria for imposed loading to allow for different uses in the future. These options would likely increase the initial embodied carbon as hypothetically they will require additional material use; however, if they increase the lifespan of the building, the cradle-to-cradle embodied carbon could be reduced. There has however been little work to date which quantifies any increase in initial embodied carbon of buildings designed for adaptability and considers the potential lifetime extension that would be required to counterbalance this.

State-of-the-Art Conclusions

Of the four strategies being explored, only design for adaptability seems to have little work to date that connects this strategy with any consideration of embodied carbon, and this is an area for future work. The literature on building reuse, material reuse and design for deconstruction all demonstrate an embodied carbon saving on particular case studies. However, work on how this has been achieved in practice and project drivers has been limited. This additional knowledge would be useful in practice in order to increase uptake of circular economic strategies in the built environment.

Research Design

A series of case studies were selected to illustrate the respective strategies across a range of structure types. Each case study is used to provide practical insights on project processes, drivers and the perceived benefits and challenges of adopting circular economic approaches. These insights are drawn from semi-structured interviews with members of each design team, supplemented by supporting literature. Each case study briefly sets out the key characteristics of the project, the solutions delivered and the perceived impact on cradle-to-cradle embodied carbon. Although an attempt to precisely enumerate and compare these benefits across case studies would appear to be informative, in practice ensuring comparability of data and assumptions is challenging. As noted by De Wolf et al. (2017), Giesekam et al. (2016) and Pomponi and Moncaster (2017b), there are still numerous inconsistencies in the underlying product data and system boundaries adopted by different carbon assessors. Furthermore, although BS EN 15978:2011 Sustainability of Construction Works – Assessment of Environmental Performance of Building – Calculation Method defines a common set of life cycle stages and approaches, it does not prescribe many key parameters, such as expected lifespan, that are integral to ensuring comparability between assessments. Commonly used complementary guidance documents, such as RICS (2014), also offer minimal practical guidance on accounting for the benefits of adaptability and reuse in practice, meaning industry assessments often ignore these issues. Future guidance documents, such as the upcoming RICS professional statement 'Whole life carbon measurement: implementation in the built environment' will seek to standardise some aspects of these approaches. Without extensive retrospective gathering of comparable data, it is thus not possible to compare the strategies numerically. In the meantime, the authors have chosen to forgo quantitative evaluation of the embodied carbon benefits, in favour of qualitative statements about the life cycle stages affected.

Case Study Analysis

This section provides a series of 'good practice' case studies for each of the four strategies being discussed, exploring practical implementation of the strategy and discussing the potential scale of cradle-to-cradle embodied carbon saving. Where possible, project drivers are explored to understand if and why circular economy principles drove the approach or if other co-benefits were the primary driver, e.g. embodied carbon reduction or cost reduction. Any enabling conditions are also discussed in order to understand the key criteria for successful inclusion of these strategies in projects.

Building Reuse

A prominent example of building reuse is Quadrant 3, also known as Air W1, a mixed use complex which links Piccadilly Circus to Regent Street. Preservation of the architectural heritage was an important project driver with the building being located within a conservation area. However, with sustainability at the heart of this project for the Crown Estate, embodied carbon reduction was also targeted. Building reuse was part of the embodied carbon strategy, with over 1500 tonnes of existing steel retained in the structure. The original 1919 construction was steel frame, with the frame embedded within the facade. Three sections of the original neo-classical facades were retained and restored; the steelwork columns and beams that were attached to these facades were retained and new connections welded on so that the old steel could be connected to new steelwork. A portion of floor slab was also retained; again the steel was retained in its original form, but corrosion protection was added to certain required locations. The retention of the original facades was a key driver for the structural building reuse; certain areas in the building are Grade 2 listed; thus, an option to demolish the whole building and start again was rejected for this scheme which carefully contrasts the aesthetics of the neo-classical facades with contemporary facades. As the steelwork was embedded and supported these retained facades, there was a strong practical benefit in retaining it, beyond the environmental benefits. There were, however, also challenges when reusing the retained steelwork. In order to ensure the steelwork was of sufficient quality, thousands of 50 pence piece-sized samples were taken and tested to verify the material properties. Corrosion and lead-based paint coating also provided additional challenges. In the case of the former, certain extensively corroded elements had to be removed and replaced, and in the case of the latter, additional health and safety precautions had to be taken on-site when welding to the original steelwork. In addition, art deco interiors were restored for restaurant use, and granite kerbs and slates from the existing building were salvaged and donated to a community garden project. In total, over 1500 tonnes of embodied carbon were saved on the project, which also utilised cement replacements, designed outwaste and achieved a 20% recycled content in materials (by value) (Crown Estate 2017). As discussed in the state-of-the-art section, operational carbon is also an important consideration in building reuse projects, and this too was targeted in this project which achieved a BREEAM excellent rating (Crown Estate 2017).

There is an excellent example of the reuse of an entire structural system in a pedestrian bridge, which was on its fifth use at the time of interview with the contractor. The 30–40 tonne steel bridge was originally used by Colchester Garrison as a temporary structure to enable troop movement. By chance when it was being disassembled, Sir Robert McAlpines obtained it for reuse on the Olympic site. With original drawings, some adaptation and the addition of another tonne of steel, the bridge was redeployed in Stratford to enable pedestrians to cross a road during construction, saving time. It was later moved within the site for use during the Olympics to facilitate access to ceremonies, before then moving back to Colchester for a period, finally coming to rest in the North East as a pedestrian bridge over a dual carriage way. This is a great example of how the value of an asset was realised and maintained over a number of moves, also displacing the need for new materials to create the various temporary bridges that would have otherwise been required.

Material Reuse

It was earlier suggested that for maximum embodied carbon benefit, materials with a higher environmental impact should be targeted for reuse. Steel is a one such example, energy intensive in production and commonly used, but with a history of reuse. For this reason, steel reuse case studies are the focus of this section, although many of the benefits and barriers would also apply to other materials.

BedZED, Fig. 12.2, in the UK, is a good example of a project which prioritised reuse, with 98 tonnes of structural steel reused (Sergio and Gorgolewski n.d.). Assuming a carbon factor of 1.53 $kgCO_2e$ (Hammond and Jones 2011), this would displace 150 tonnes CO_2e that would be attributed if new steel (with an average 59% recycled content) was utilised. The majority of the steelwork was sourced locally from a redevelopment at Brighton train station, which had steel girders that were suitable for reuse. In this example, the salvage contractor stored

Fig. 12.2 BedZED (Photo Credit: Tom Chance – www.flickr.com/photos/tomchance/1008213420/)

the elements until they were required on-site. This overcomes a frequently discussed barrier to reuse, the storage of reused materials. Where and for how long materials must be stored is often perceived as a problem when reusing materials (Densley Tingley et al. 2017).

Identification of a reused material sourced during the detailed design stage can be helpful in order to ensure sufficient lead times and to take into account any potential alterations in size due to material availability. This could include reuse of elements salvaged from an existing building on-site, as in the case of the Ottawa Convention Centre, where 7, 4.5 m deep trusses were reused from the roof structure of the original Congress Centre (Canada Green Building Council 2010). The trusses weighed approximately 36 tonnes and were re-engineered to support the new roof design at a fabrication and storage facility. The enthusiasm of the building owner and engineer were both highlighted as key to achieving this component reuse.

The London 2012 main Olympic Stadium also featured steel reuse, although instead of being sourced from an existing construction site, the tubular steel was over-ordered, ex-pipeline tube. The steel had yet to be used but was considered a waste product disused in a storage yard. Five thousand tonnes of steel were reused in the roof structure. Sourcing disused pipeline steel resulted in shorter lead times than if the tube had been procured in a more traditional manner, which was perceived as a significant benefit of the approach. It is understood from discussions with those involved in the construction that testing and recertification of the tube was a relatively quick process. Coupon, sharpie hardness and chemical analysis tests were conducted on a sample from each piece of pipework. The retesting was necessary as a circumference strip of pipework would be tested to check resistance against pressure in its traditional use, whereas it needs to be tested along the length for structural use. The testing also demonstrated the quality of the steelwork, relieving fears from the client. Overall, the contractors, Sir Robert McAlpines, felt that the reuse was a positive experience and that others involved in the supply chain had similar feelings. From an environmental (displacing the need for new steel) and waste reduction perspective, it was seen as morally the right thing to do, not to mention the shorter lead times and cost savings to the project, which were significant benefits of the approach.

Design for Deconstruction and Material Reuse

Design for deconstruction and material reuse can be seen in a number of case studies around the globe, in both temporary event structures and permanent structures, including Brummen Town Hall and M&S's Cheshire Oaks store, which are explored within this chapter.

The Brummen Town Hall building in the Netherlands was designed to minimise total life costs via material and product reuse, rationalisation and renting. These actions can also deliver lower embodied carbon. BAM was the main contractor for the redevelopment of Brummen Town hall. The municipality was unsure if the building would be needed after 20 years and were looking to minimise costs and material impact. BAM, together with the architect, Thomas Rau, responded to this client brief by incorporating multiple material efficiency initiatives into the design of the building and the furnishings. As a consequence, the total costs, across the anticipated 20-year lifespan of the building were minimised, and almost all material inputs were reused and/or reusable in the future.

From the outset, the volume of construction material required was minimised by designing the new building around the existing structure. The roof was made almost entirely out of glass to minimise operational lighting costs and electricity use. This could also reduce operational carbon emissions if the electricity is generated from fossil fuels. Additional structural components were made of timber, which has a relatively lower embodied carbon than alternatives such as steel, and were designed for deconstruction. The building also included flexible walls and partitions to enable adaptability for future users. Symbolically, all materials used in the building were given their own 'passport' that details their material composition and plans for extraction at the end of the building's life (Fig. 12.3).

This commitment to reuse and cost minimisation for the building owner inspired new contracts with material suppliers. The ownership of key building components including timber, mechanical and electrical installations, lighting, tiles and flooring were retained by the manufacturer rather than the municipality. Instead, the municipality pays for the performance of these components, which goes beyond the traditional concept of product leasing. This novel approach necessitated a joint

Fig. 12.3 Brummen Town Hall during construction (Photo Credit: Royal BAM Group nv)

partnership between the designer and product manufacturers. BIM modelling was used to guarantee the performance of all components and to identify the material composition that minimised both capital and maintenance costs over the anticipated 20-year lifetime of the building since these were borne by the manufacturers rather than the building owner. An example of this type of service provision is the 'pay-per-lux' scheme from Philips (2017), where the client pays for lighting as a service and the manufacturer is responsible for maintaining the performance of the lighting – this potentially incentivises the manufacturer to ensure that the lighting operates at the lowest energy cost and thus reduces the operational carbon. Some evaluation of the capital cost of lighting replacement would be factored in here, but it is unclear if the trade-off and payback of embodied carbon would be factored into the decision (Fig. 12.4).

Since the building is still in use, it is unclear what will happen to the materials afterwards. However, the steps taken by BAM and Thomas Rau mean that there is the potential to reuse material and displace material from virgin sources. Lower demand for virgin materials can mean lower emissions generated during material production.

Marks and Spencer has introduced a number of initiatives with the aim of reducing the waste generated by product sales and construction projects. The latter aim led to a number of innovative approaches to build their 210,000 ft^2 development in Cheshire Oaks in 2012 (Datta 2012). One hundred percent of the construction waste was diverted from landfill (WRAP 2012). Many of the building materials have a high-recycled content. For example, the aluminium in the roof is 100%

Fig. 12.4 Brummen Town Hall (Photo Credit: Royal BAM Group nv)

recycled along with 60% of the high-grade aggregates. The roof is made out of glulam beams, held together with large bolts that allow for future deconstruction. Glulam has both a lower embodied energy and lower embodied carbon than steel and concrete and sequesters more carbon than is emitted in its manufacture (Hill and Dibdiakova 2016). Operational electricity use and emissions if electricity is from fossil fuels were reduced by maximising the amount of natural light in the stores. Additionally, an 80,000-l rainwater harvesting system meets around a third of the store's water requirements. The walls are cladded with a mixture of lime, water and hemp plant, known as Hemclad, which has both lower embodied carbon and delivers a better thermal performance. As a consequence of these and other initiatives, Cheshire Oaks store was estimated to be 42% more energy efficient and 40% more carbon efficient than a peer store (Faithful+Gould 2013). Marks and Spencer's commitment to 'zero waste' also extends to the end of the store's life. The building includes a disassembly and recycling guide, with details of the quantities of each "resource" element and instructions on how to reuse, resell or recycle each element. This provides an additional potential source of revenue for Marks and Spencer. The building was rated 'excellent' by BREEAM, scoring over 80% in the management, energy, water, pollution and materials and waste categories.

Lessons can also be learnt from temporary structures; two such examples were designed and constructed by ES Global for the London 2012 Olympics: the water polo arena and the shooting arena. These utilise a steel truss system, which forms part of ES Global's kit of parts for use in temporary events structures. These structures were leased for the games; in the case of the water polo arena, the lease cost amounted to approximately £1.2 million of a total £25 million project (Densley Tingley and Allwood 2015). This leasing scenario meant that the Olympic Committee had the required sports venues but removed the risk of empty, wasted stadia in the years after the games and meant that the components could then be reused again in future temporary events' structures by ES Global, lowering the wider embodied carbon arising from temporary events. With recurring sporting events being held frequently around the world, this type of approach, to design for deconstruction and reuse, is ideal to reduce the material demand and embodied carbon of the world's built environment.

Design for Adaptability

St John Bosco Arts College in Liverpool, UK used construction insights from outside the education sector to build an innovative flexible space at a lower cost than a conventional school. The new site for John Bosco Arts College in Liverpool opened in Sept. 2014. The architects, BDP, designed a three-storey, 11,100m^2, column-free, single-span steel portal frame building. A large multifunctional assembly space is in the centre of the building, circled by two floors of classrooms with 2.7 m floor-to-ceiling heights. The interior structure of columns and floors are demountable and separate to the main frame, enabling removing and dismantling of semi-permanent features in the building as the school's needs evolve. There were few precedents of this building design for schools, so the architect's reference point came more from more open-plan workplaces and commercial shopping centres.

The main reported driver for this innovative design was cost. In 2010, John Bosco Arts College was selected to receive government funding to rebuild the school buildings as part of the 'Building Schools for the Future' (BSF) programme. BDP were selected as the architect; however, the government programme was cancelled before any money was allocated to the project. This had both short-term and long-term impacts on the design of the school. In the short term, BDP developed a cheaper building design for John Bosco Arts College. Costs were £11.91/m^2 compared with the £17.50/m^2 under the original BSF-funded design and have 15% more area than a traditional BB98 compliant school (Buxton 2015). Fortunately, Liverpool City Council was able to source the £18m needed to rebuild the school in the new design. The experience with the BSF funding also prompted considerations for the longer-term future needs of the school. Liverpool City Council wanted a highly flexible building with an adaptable-changeable configuration to provide the option of changing the building's use in the future for little cost. This reduces life cycle embodied carbon through two mechanisms. First, it helps to extend the building life by ensuring it meets the evolving needs of its users. Second, the inbuilt adaptability reduces the need for extra construction materials to modify the building over time.

In the end, the experience was reportedly very positive for the key stakeholders involved, and the school was awarded a RIBA Regional Award in 2015. The head teacher, Anne Pontifex, who was also awarded RIBA 'client of the year', noted in an interview with *Architects' Journal* (Pritchard 2015):

> Our partnership with the architects developed into an open, honest and creative relationship, which enabled ideas, theory and the concept of truly 'thinking outside the box' to take place. As a result, we have what I believe is a unique, exciting and stimulating school, which supports our already outstanding teaching and learning.

Adaptable Use

At the end of 2014, Marks and Spencer opened up their first community room to the public in their Wolstanton store (Horner 2014). This initiative allows local community groups to utilise the room when it is not being used as a meeting room by the staff, thereby increasing the productivity of their capital assets. A number of stores have since followed suit, providing a free space to local charities, youth and community groups, schools and small businesses.

This initiative is aligned with the company's Plan A commitment on being in touch with the local community. The decision to offer M&S facilities is driven by the store manager, but it requires initial coordination and planning from central office. For example, a multifunctional room requires a larger floor space, needs access to washrooms and water facilities and needs to be reachable via the front of the supermarket to manage security of the store. These considerations are more easily addressed when designing and building a new store but can also be delivered through retrofits. There may be minor additional capital outlays on store branding, furniture and television screens for the community users. Staff will also need to spend a couple of extra hours a week booking out and preparing the room. However, these additional expenditures are very small relative to the total operating costs of the store.

Even though the scheme is less than a year old, a number of benefits are already emerging. The use of store space allows Marks and Spencer to be more integrated in the community and alleviates pressure on local authorities to provide equivalent services to local residents. Employees have expressed a stronger connection with their customers, public relations have improved, and there are early indications of increased footfall in stores where this service is offered. By making some of their stores multi-use, Marks and Spencer are reducing demand for new construction projects to provide equivalent services to the community, reducing the need for new material inputs and embodied emissions.

Discussion

From the exploration of the literature and the case study investigation, an understanding of project drivers and incentives to incorporate the four discussed strategies can be derived. These are split initially into lessons for each of the four strategies, with overarching lessons learnt highlighted in the 'Common Lessons' section.

Building Reuse

It is clear that buildings of historical significance, whether listed or not, will likely be prime targets for building reuse on sites where revitalisation and redevelopment are strategic priorities. This can be seen not only in the case study example discussed, Quadrant 3, but also in projects where historic facades are retained and propped during redevelopment and the remainder of the building significantly redeveloped or in some cases partially demolished and rebuilt. Another key factor is the condition of the existing structure of a building and the inherent flexibility offered by the available space. For instance, warehouse conversions are common due to large clear spans and high floor to ceiling heights offering a wide range of options for adaptation.

In order to maximise building life, and reduce embodied carbon, two steps should be carried out on existing structures on a site where redevelopment is proposed. Firstly, an assessment of whether the existing structure is fit for purpose or what alternations/additions would be required to make it suitable. Secondly, consideration of the flexibility offered and whether it is suited to the potential new building use. Even where the existing building footprint is desired, an assessment could be made to explore if vertical expansion is possible under the current load capacity of the structure or what alterations would be required to achieve this. The environmental benefits across embodied carbon reduction and waste reduction for this approach to building reuse are clear, but a more significant project driver would be the potential programme savings, in turn achieving project cost savings and earlier functional use of the building for the client.

Material Reuse

If an assessment of the viability of building reuse is found to be unfavourable, then the next step in dealing with an existing building should be to assess the material salvage and reuse potential (in conjunction with the recycling and downcycling options), essentially carrying out a demolition audit. If there are materials available for reuse on-site, then the integration of these into the new proposed project should be explored, as demonstrated by the Ottawa Convention Centre.

Another option for new projects would be to identify particular elements which would see an embodied carbon benefit from reuse and to then explore if any local demolition sites have appropriate materials available. There are also a number of online reused material marketplaces opening up, for example, Planet Reuse (2017) in the USA and Enviromate (2017) in the UK, where materials wanted and for sale can be posted. These sites could be explored to source reused materials for projects.

The earlier in the project that the materials desired for reuse can be identified, then the earlier sourcing of appropriate materials can occur. Early consideration allows for easier integration of elements into an existing design and leaves open the possibility of design alterations. The London 2012 stadium demonstrated that in cases where specialised reused materials are available that this could result in shorter lead times than ordering of bespoke fabrication, which would be a significant project benefit. Aesthetics could also drive material reuse, as well as embodied carbon reduction, particularly for those clients that are now prioritising this.

Design for Deconstruction and Material Reuse

A key factor for this approach is the longer time periods over which the benefits must be measured; a cradle-to-cradle embodied carbon measurement should result in reductions as design for deconstruction facilitates future material reuse, thus lessening the demand for new materials in the future. A move to measuring whole life costs will also yield reductions, as the approach maintains the value of future material assets. Information transfer over time is critical. Whether it be disassembly guides or material passports, having this information will facilitate future deconstruction and material reuse. Ensuring this information is preserved, accessible and passed between building owners will be important to maximising the value from this future planning strategy.

Design for deconstruction and material reuse also presents opportunities for new business models such as leasing, as the asset can be held and sold on by the leaser. The examples show that this model can also have operational carbon benefits through the delivery of services in buildings as an alternative to buying individual products. Temporary structures, or projects which are predicted to have very short lifetimes, are also likely to see significant benefits from this leasing approach, as the return on investment should be quicker on assets leased for short time periods – for example, a year to 18 months in the case of rotating sporting events. It is unclear whether current legislation sufficiently incentivises or rewards construction companies to enable future reusability or sustainable collaboration/partnerships across the construction supply chain, and this is an area to explore going forward.

Design for Adaptability

There are parallels with design for deconstruction here, as the benefits of design for adaptability will also be seen over longer, whole life cycle, time periods. Inherently, the additional adaptability and flexibility in use provided by a building that is designed considering future uses and changing requirements will only be recognised during the life cycle of the building. There can be reduced life cycle costs as the building can be easily adapted during use. If the building does successfully adapt to changing needs, then it is likely that building's life will be extended, displacing the need for future materials and buildings, and thus embodied carbon. There is a potential tension between the probable increase in carbon emissions incurred in initially enabling adaptability and the urgent need for deep carbon reductions, consistent with pathways to keep global temperature rises to below 2 °C above pre-industrial levels. This timeline suggests that short-term strategies that yield an immediate embodied carbon reduction should be prioritised first. However, these longer-term and shorter-term strategies can be integrated and complementary, for example, incorporating material reuse into a project designed for adaptability. Deployment of both will be essential in meeting the long-term goal of achieving a balance of emissions sources and sinks.

Adaptable space that can be used by different stakeholders, enabling a more intensive use of space – as in the M&S community spaces – will also largely see benefits in use. Increasing the frequency with which other stakeholders access the space can produce co-benefits, such as an increased sense of community or increased footfall with potential sales implications. This approach again potentially displaces the need for additional buildings and thus materials. As the benefits are seen during the building's life, to date, the inclusion of this strategy has largely been client driven from a practicality of use perspective rather than by an embodied carbon reduction strategy, which could be considered more of a co-benefit.

Conclusion

The four design strategies that form the focus of this chapter all aim to maintain the value of material assets, either now or in the future, making them central to a circular economic approach to the built environment. The potential benefits from these strategies are wide ranging, with the main drivers being focused on cost reductions or flexibility of use and at end of life. The cost reductions are both capital, through shorter programme times or reduced material costs, and lifetime through maintained or recovered asset value. Embodied carbon reduction should be realised through the deployment of all of these strategies, when whole lifetimes are considered, but whilst the environmental benefit is recognised, it is perhaps secondary to these other project drivers. A move to whole life costing will help a greater number of projects to see the economic benefits of these strategies. The wider exploration of opportunities to add value to projects through these strategies, the exploitation of similar niche project circumstances to increase uptake and improved quantification of the co-benefits will ultimately drive the longer-term progression of these strategies into mainstream construction. The more these strategies are explored, the more the wider industry can respond in developing the required skill sets and underpinning supply chains to enable these practices to become business as usual in the sector. The wider potential economic benefits of these strategies are likely to drive their uptake, particularly in the current marketplace, when compared to embodied carbon reduction alone. Thus these two should be considered in tandem to help drive the sector to achieving a low embodied or indeed low whole life carbon built environment.

Acknowledgements The authors would like to sincerely thank all those who gave their time up for interviews. The contribution of the second author was supported by the Research Council UK Energy Programme through the Centre for Industrial Energy, Materials and Products (grant number EP/N022645/1). The third author was supported by an EPSRC PhD studentship, grant reference EP/L504920/1.

References

Addis, W., & Schouten, J. (2004). *Design for deconstruction. Principles of design to facilitate reuse and recycling*. London: CIRIA.

Andrews, C. J., Hattis, D., Listokin, D., Senick, J. A., Sherman, G. B., & Souder, J. (2017). Energy-efficient reuse of existing commercial buildings. *Journal of the American Planning Association, 82*(2), 113–133. https://doi.org/10.1080/01944363.2015.1134275.

Arup. (2016). *The circular economy in the built environment*. Available at: http://publications.arup.com/publications/c/circular_economy_in_the_built_environment. Accessed 27/04/17.

Assefa, G., & Ambler, C. (2017). To demolish or not to demolish: Life cycle consideration of repurposing buildings. *Sustainable Cities and Society, 28*, 146–153.

Brand, S. (1994). *How buildings learn: What happens after they are built*. New York: Viking Penguin.

Buxton, P. (2015). *St John Bosco Arts College, Liverpool – Article in RIBA journal*. Available at: http://www.steelconstruction.info/St_John_Bosco_Arts_College,_Liverpool. Accessed 02/05/17.

Canada Green Building Council. (2010). *Material reuse at the Ottawa Convention Centre. Green Space, Ottawa Region Chapter Newsletter, Materials Issue, 8, April 2010*. Available at: http://static1.1.sqspcdn.com/static/f/322919/7289577/1276203149047/CaGBC_ORC_Green_Space_Issue_8_short.pdf?token=QXNNcA5t2gT9HuhpYnr2uM4wOJ8%3D. Accessed 12/07/17.

CE100. (2016). *Circularity in the built environment: Case studies. A compilation of case studies from the CE100*. Ellen MacArthur Foundation. Available at: https://www.ellenmacarthurfoundation.org/assets/downloads/Built-Env-Co.Project.pdf. Accessed 27/04/17.

Chau, C. K., Xu, J. M., Leung, T. M., & Ng, W. Y. (2015). Evaluation of the impacts of end-of-life management strategies for deconstruction of a high-rise concrete framed office building. *Applied Energy, 185*, 1595–1603. https://doi.org/10.1016/j.apenergy.2016.01.019.

Cheshire, D. (2016). *Building revolutions: Applying the circular economy to the built environment*. London: RIBA Publishing. ISBN: 9781859466452.

Datta, M. (2012). *M&S Cheshire Oaks store*. Available at: http://corporate.marksandspencer.com/blog/stories/mands-cheshire-oaks-store. Accessed 02/05/17.

De Wolf, C., Pomponi, F., & Moncaster, A. (2017). Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice. *Energy and Buildings, 140*, 68–80. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778817302815.

Densley Tingley, D. (2013). *Design for deconstruction: An appraisal* (Doctoral dissertation). University of Sheffield.

Densley Tingley, D., & Allwood, J. M. (2015). The rise of design for deconstruction – A cradle to cradle approach for the built environment. In: *International Sustainable Development Research Society conference, the tipping point: Vulnerability and adaptive capacity*, 10th–12th July 2015, Geelong, Australia.

Densley Tingley, D., & Davison, B. (2011). Design for deconstruction and material reuse. *Proceedings of the ICE – Energy, 164*(4), 195–204. https://doi.org/10.1680/ener.2011.164.4.195.

Densley Tingley, D., & Davison, B. (2012). Developing an LCA methodology to account for the environmental benefits of design for de-construction. *Building and Environment, 57*, 387–395. https://doi.org/10.1016/j.buildenv.2012.06.005.

Densley Tingley, D., Cooper, S., & Cullen, J. M. (2017). Understanding and overcoming the barriers to structural steel reuse, a UK perspective. *Journal of Cleaner Production, 148*, 642–652.

Enviromate. (2017). Available at: https://www.enviromate.co.uk/. Accessed 14/07/17.

Faithful + Gould. (2013). *Marks & Spencer Cheshire Oaks building performance evaluation first year performance summary*. Available from: http://www.greencoreconstruction.co.uk/downloads/MS_Cheshire_Oaks_Building_Performance_Evaluation_-_Summary_-_Technical_a_.pdf

Giesekam, J., Barrett, J., & Taylor, P. (2016). Construction sector views on low carbon building materials. *Building Research & Information, 44*(4), 423–444. https://doi.org/10.1080/09613218.2016.1086872.

Guy, B., & Ciarimboli, N. (n.d.). *Seattle guide: Design for disassembly in the built environment*. Available at: http://your.kingcounty.gov/solidwaste/greenbuilding/documents/Design_for_Disassembly-guide.pdf. Accessed 02/05/2017.

Hammond, G., & Jones, C. (2011). *Inventory of carbon and energy, Version 2.0*. Available at: http://www.circularecology.com/embodied-energy-and-carbon-footprint-database.html#.WWc7GojyuUk. Accessed 13/07/17.

Hill, C. A. S., & Dibdiakova, J. (2016). The environmental impact of wood compared to other building materials. *International Wood Products Journal*. https://doi.org/10.1080/20426445.2016.1190166.

Horner, R. (2014). *Our first community room – Marks and Spencers blog*. Available at: http://corporate.marksandspencer.com/blog/stories/our-first-community-room. Accessed 02/05/17.

Hosseini, M. R., Rameezdeen, R., Chileshe, N., & Lehmann, S. (2015). Reverse logistics in the construction industry. *Waste Management Research, 33*(6), 499–514.

Laefer, D. F., & Manke, J. P. (2008). Building Reuse Assessment for Sustainable Urban Reconstruction. *Journal of Construction Engineering and Management, 134*(3), 217–227. https://doi.org/10.1061/(ASCE)0733-9364(2008)134:3(217).

Langston, C., Wong, F. K. W., Hui, E. C. M., & Shen, L.-Y. (2008). Strategic assessment of building adaptive reuse opportunities in Hong Kong. *Building and Environment, 43*(10), 1709–1718. https://doi.org/10.1016/J.BUILDENV.2007.10.017.

Luscuere, L. M. (2017). Materials Passports: Optimising value recovery from materials. *Proceedings of the Institution of Civil Engineers: Waste Resource Management, 170*(1), 25–28. https://doi.org/10.1680/jwarm.16.00016.

Manewa, A., Pasquire, C., Gibb, A., Ross, A.,& Siriwardena. (2013). Adaptable buildings: Striving towards a sustainable future. *People and the planet 2013 conference: Transforming the future, RMIT University, Melbourne, Australia, 2–4 July*. Available at: http://global-cities.info/wp-content/uploads/2013/11/Adaptable-Buildings-Striving-Towards-a-Sustainable-Future1.pdf. Accessed 27/04/17.

Morgan, C., & Stevenson, F. (2005) *Design and detailing for deconstruction*. Available at: http://www.seda.uk.net/index.php?id=136. Accessed 02/05/17.

Philips. (2017). *Light as a service – UK student movement is a beacon of sustainability for wider society*. Available at: http://www.philips.com/a-w/about/sustainability/sustainable-planet/circular-economy/light-as-a-service.html. Accessed 13/07/17.

Pinder, J. A., Schmidt, R., Austin, S. A., Gibb, A., & Saker, J. (2017). What is meant by adaptability in buildings? *Facilities, 35*(1/2), 2–20.

Planet Reuse. (2017). Available at: https://planetreuse.com/. Accessed 14/07/17.

Pomponi, F., & Moncaster, A. (2017a). Circular economy for the built environment: A research framework. *Journal of Cleaner Production, 143*, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.055.

Pomponi, F., & Moncaster, A. (2017b). Scrutinising embodied car-bon in buildings: The next performance gap made manifest. *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2017.06.049.

Pongiglione, M., & Calderini, C. (2014). Material savings through structural steel reuse: A case study in Genoa. *Resources, Conservation and Recycling, 86*, 87–92.

Pritchard, O. (2015). *St John Bosco Arts College by BDP – Article in the architect's journal*. Available at: http://www.architectsjournal.co.uk/buildings/st-john-bosco-arts-college-by-bdp/8679827.article. Accessed 02/05/17.

RICS. (2014). *Methodology to calculate embodied carbon, RICS guidance note, Global 1st edition*. ISBN: 9781842197950 Available at: http://www.rics.org/Documents/Methodology_embodied_carbon_final.pdf.

Sergio, C., & Gorgolewski, (n.d.). *Reuse of structural steel at BedZED (Beddington Zero Energy Development)*. Available at: http://www.reuse-steel.org/files/projects/bedzed/bedzed%20case%20study%205-5.pdf. Accessed 12/07/17.

The Crown Estate. (2017). *Quadrant 3, modern renaissance*. Available at: https://www.thecrownestate.co.uk/media/5249/urb-quadrant-3-brochure.pdf. Accessed 12/07/17.

Van Odijk, S., & van Bovene, F. (2014). *Circular construction: The foundation under a renewed sector*. ABN.AMRO. Available at: https://www.slimbreker.nl/downloads/Circle-Economy_Rapport_Circulair-Construction_05_2015.pdf. Accessed 27/04/17.

WRAP. (2012). *Marks and Spencers sustainable learning store*. Available at: http://www.wrap.org.uk/sites/files/wrap/Refurbishment%20Resource%20Efficiency%20Case%20Study_Retail_M&S.pdf. Accessed 02/05/17.