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Review

Mining the physical infrastructure: Opportunities, barriers and interventions in promoting structural components reuse

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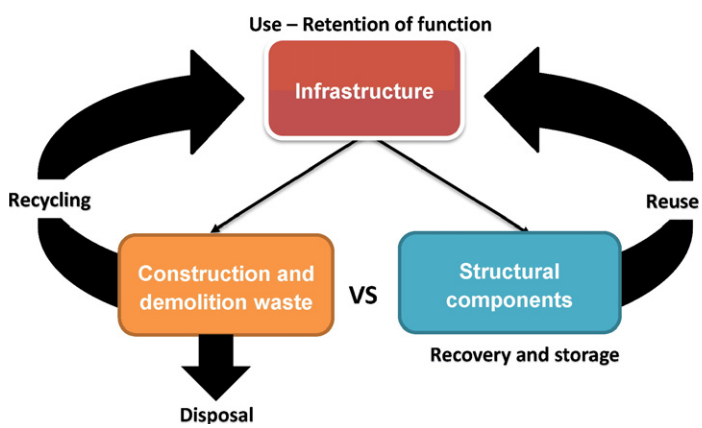
HIGHLIGHTS

- Design interventions can stimulate circularity in the construction sector.
- Interventions are not being mainstreamed due to technical/organisational constraints.
- Reuse is a win-win strategy for the construction sector.
- Typology of infrastructure components might enable the roll-out of reuse.
- Smart technologies might unlock the reuse potential of structural components.

GRAPHICAL ABSTRACT



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ABSTRACT

Construction is the most resource intensive sector in the world. It consumes more than half of the total global resources; it is responsible for more than a third of the total global energy use and associated emissions; and generates the greatest and most voluminous waste stream globally. Reuse is considered to be a material and carbon saving practice highly recommended in the construction sector as it can address both waste and carbon emission regulatory targets. This practice offers the possibility to conserve resources through the reclamation of structural components and the carbon embedded in them, as well as opportunities for the development of new business models and the creation of environmental, economic, technical and social value. This paper focuses on the identification and analysis of existing interventions that can promote the reuse of construction components, and outlines the barriers and opportunities arising from this practice as depicted from the global literature. The main conclusions that derive from this study are that the combination of incentives that promote reuse of construction components and recycling of the rest of the construction materials with the provision of specialised education, skills and training would transform the way construction sector currently operates and create opportunities for new business development. Moreover, a typology system developed based on the properties and lifetime of construction components is required in order to provide transparency and guidance in the way construction components are used and reused, in order to make them readily available to designers and contractors. Smart technologies carry the potential to aid the development and uptake of this system by enabling efficient tracking, storage and archiving, while providing information relevant to the environmental and economic savings that can be regained, enabling also better decision-making during construction and deconstruction works. However, further research is required in order to investigate the opportunities and constraints of the use of these technologies.

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Contents

1. Introduction

Our modern lifestyles are critically dependent on physical infrastructure (e.g. transport, energy, water and waste management, communications, buildings), construction and maintenance of which accounts for more than half of the total global raw resources consumed annually, and for more than one third of the total global energy use and associated emissions (Alcorn, 2003; Allwood et al., 2010, 2013; Ellis, 2011; Giesekam et al., 2014; Ness et al., 2015; Purnell, 2012). The increasing demand for housing and other services as a result of growing population requires the plan and delivery of infrastructure, at a time where resources are in decline, creating a matter of urgency in the long-term sustainability of the sector that cannot be ignored.

The production of construction materials accounts for the greatest share of carbon emitted from the construction sector, with the majority attributed to the production of steel, cement and timber. Global cement production, the main ingredient of concrete, is around 4 Gt and contributes to about 9.5% of total global carbon emissions (Olivier et al., 2014; Statista, 2015; USGS, 2015). The manufacturing of steel used for construction, contributes to about 3.3% of total global carbon emissions (Allwood et al., 2010; Cooper and Allwood, 2012; Ness et al., 2015). The global warming impact attributable to timber production is contested, but could be as high as 18% of total global carbon emissions (Purnell, 2013). In general, at least 70% of the environmental impact of an average construction material is attributed to the energy required for its production (Kay and Essex, 2009) (a notable exception being concrete, where 60% of emissions are associated with decarbonation of limestone). Concrete is the second most consumed material in the world after water (Giesekam et al., 2014) with a usage of approximately 20 Gt per annum (Behera et al., 2014). It is a composite material consisting of cement, aggregates (i.e. sand, gravel and crushed stone) and water, with aggregates occupying 65–85% of concrete's volume (Behera et al., 2014; BIO Intelligence Service, 2011, 2013; Ecorys, 2014). Aggregates and minerals such as bitumen (i.e. asphalt), clay (for bricks and tiles), limestone (for cement making), slate and gypsum, account for the largest component of construction materials used globally by mass, followed by metals (particularly steel) and wood (timber) (Ecorys, 2014; Heard et al., 2012; Horvath, 2004). In Europe, the construction sector uses by far the greatest amount of resources in the economy on a mass basis, and consumes between 5% and 10% of total energy use only for the production of construction materials (BIO Intelligence Service, 2013; EISC, 2012; European Commission, 2014; Wahlström et al., 2014).

With pressures from the Inter-governmental Panel on Climate Change (IPCC) for a 50%–85% reduction of global carbon emissions by 2050 based on the 2000 emission levels, the construction industry has become more energy efficient with regard to the processes used for the production of construction materials (Allwood et al., 2010). Yet, accelerating infrastructure development due to investment in large infrastructure in less economically developed countries, maintenance of existing stock, as well as building and retrofitting of new and existing houses results in a net increase in yearly materials and energy use and thus associated carbon emissions (Allwood et al., 2010; Couto and Couto, 2010; Durmisevic and Brouwer, 2002; Heard et al., 2012; Sassi, 2004).

A large volume of construction and demolition waste (CDW) is generated by the construction industry each year, which in industrialised countries can be up to 60% of the total amount of solid waste generated by mass (Crowther, 2014; EEA, 2012; Heard et al., 2012; Oikonomou, 2005; Sabai et al., 2013). In Europe, CDW accounts for 31% of Europe's total solid waste generated, excluding wastes from the mining and quarrying activities (BIO Intelligence Service, 2011; EEA, 2012; European Commission, 2014; Villoria Saez et al., 2013). The low cost of virgin materials, in combination with the low cost of conventional demolition and the possibility of disposing wastes to landfill, has enabled landfilling to become a popular CDW management practice in most developing counties, as well as in some European member states (BIO Intelligence Service, 2011). Pressures on limited landfill resource, and on natural resource depletion and ecological degradation caused by the increasing extraction of raw materials (Horvath, 2004; Ness et al., 2015; Sabai et al., 2013) are forcing conventional practices to be revisited, encouraging a halt to linear material flows. In Europe, the revised Waste Framework Directive (rWFD) (2008/98/EC) has mandated EU member states to implement measures in such a way as to reuse, recycle or recover of a minimum of 70% of non-hazardous CDW by the year 2020 (ETC/SCP, 2011; Office Journal of the European Union, 2008). This has led to calls for changes in both ends of the materials chain (i.e. upstream and downstream); a reduction of virgin resource demand through materials efficiency (upstream) and the proper management of the wastes generated from the construction, renovation and partial or total demolition of buildings and/or civil infrastructure (downstream) (Crowther, 2014; del Rio Merino et al., 2010; EEA, 2012; Fatta et al., 2003; Horvath, 2004; Kourmpanis et al., 2008; Pongiglione and Calderini, 2014; Symonds Group Ltd. et al., 1999; Tam and Tam, 2006b).

The need to comply with the carbon emission binding targets is also driving changes in the way construction materials and components are recovered and used at the end of their life. In terms of total energy, buildings are responsible for the largest amount of energy use (Dixit et al., 2010; Giesekam et al., 2014; Sturgis and Roberts, 2010; Weisz and Steinberger, 2010), which can be as much as 42% of total EU energy consumption, contributing to about 40% of total carbon emissions (EISC, 2012). This can be split into: the operational carbon (OC) i.e. carbon emitted by the use of energy in the form of lighting, heating/air conditioning, etc. associated with the use of the building that contributes about 80% to total carbon emissions (Ecorys, 2014); with the rest (20%) attributed to the embodied carbon (EC) i.e. carbon emitted by manufacture of construction components, including extraction, processing, transportation, site operations, etc. (Cabeza et al., 2013; Ecorys, 2014; Purnell, 2012; Sturgis and Roberts, 2010). As the OC of buildings is reduced owing to regulatory pressure, the share of total carbon attributed to EC could rise up to 50% or more (Ecorys, 2014; Grinnell et al., 2011; Ibn-Mohammed et al., 2013; Moncaster and Symons, 2013; Purnell, 2012; Sturgis and Roberts, 2010; WRAP, 2012). Therefore, substantial reductions to the EC of buildings and infrastructure will shortly be required.

As a result, incremental initiatives to implement changes that promote sustainable management of construction materials and CDW have been proposed. These include:

- promoting new ways to design buildings composed of materials with low embodied energy, or design buildings with low service frequency (i.e. high level of durability, easy maintenance, and adaptability to change of use) (Ecorys, 2011; Peris Mora, 2007);
- reducing the use of carbon-intensive materials and increasing resource efficiency in manufacturing practices (Giesekam et al., 2014; Moncaster and Symons, 2013);
- encouraging the reuse of construction components (Allwood et al., 2010; Gorgolewski, 2008) and of the waste products from other industrial processes (i.e. the use of fly ash and slag for replacing cement in concrete production reduces EC and increases durability) (Peris Mora, 2007; Purnell and Black, 2012).

The full implementation of such measures is yet to unfold. More radical analyses of the capacity to minimise the waste within infrastructure systems are possible. For example, we might recognise that recovery of the function of components – e.g. their bending moment, axial load or flow capacity – rather than simply recovering the materials from which they are made might offer a more sustainable approach, minimising the use of virgin materials, post-demolition reprocessing and downcycling. This paper examines how using waste-derived products in construction can constitute a response to improving the sustainability of the construction industry; how interventions in the design and deconstruction stages of buildings and/or civil infrastructure can make the reuse of construction components possible; and how policies and outdated standard specifications should be revised, by reviewing the global literature. This paper looks beyond the barriers and opportunities of reuse, and identifies the key changes required for the construction sector to become more sustainable, smarter and resourceful, by viewing secondary construction components as an investment opportunity rather than a waste problem.

2. Construction materials wastage and management

2.1. Waste arisings in the construction sector

Generally, the largest fraction of CDW is concrete, masonry, asphalt and other mineral waste (e.g. stones, sand, or gravel) which accounts for about 85% of total CDW (except for countries where wood is a major building material), whereas wood and steel, and other materials and products are present in smaller quantities (BIO Intelligence Service, 2011; Ecorys, 2014; Kourmpanis et al., 2008).

Data on the generation of CDW in Europe vary widely, with countries such as Denmark, Finland, France, Germany, Ireland and Luxembourg reporting a generation rate of more than 2 tonnes per capita per year, and countries such as Bulgaria, Greece, Hungary, Latvia, Lithuania, Poland and Slovakia reporting values below 0.5 tonnes per capita per year (BIO Intelligence Service, 2011; Ecorys, 2014). These discrepancies can be largely attributed to the way CDW is recorded across the European member states due to varying levels of control and reporting mechanisms, but can also be explained by the economic stagnation, historical/cultural practices, and architectural habits (Al-Sari et al., 2012; BIO Intelligence Service, 2011; Bossink and Brouwers, 1996; Fatta et al., 2003; Kourmpanis et al., 2008; Srour et al., 2012). For instance in some regions brick or concrete is the main construction material, whereas in northern countries like Finland or Sweden, etc. wood is a major construction material. Furthermore, demolition in countries such as France is seen as a failure whereas in other countries it is regarded in a more positive way (BIO Intelligence Service, 2011; Kourmpanis et al., 2008).

In developed countries, CDW from the building sector accounts for about 40% of total solid waste arisings with waste generated from demolition accounting for the biggest fraction (Behera et al., 2014; Chini and Bruening, 2003; Kourmpanis et al., 2008; Srour et al., 2012), indicating quite strongly the source of the problem. In the United States, hundreds of millions of tonnes of CDW are generated, most of which originates from the building sector (Behera et al., 2014; Srour et al., 2012). This waste consists of 90% of wastes from the demolition and renovation of buildings, with the rest (10%) attributed to waste from new constructions. In Europe, the building sector accounts for a considerable fraction of the CDW generated each year, but exact figures are not available (Ecorys, 2014). Nonetheless, knowledge of the generated quantities of CDW and its composition can provide the means to its better management.

2.2. CDW management in Europe

According to the EU Waste Strategy, CDW is considered one of the 'priority' waste streams for recycling, due to the inert nature of its components including, concrete, bricks and tiles (Fatta et al., 2003; Rodríguez et al., 2007; Wahlström et al., 2014). Hazardous materials such as asbestos, insulation materials, treated wood, glass and plastic (alone or in mixtures) that may also be present in the CDW stream require extensive safety control measures in order to properly manage the risks imposed on human health and the environment (BIO Intelligence Service, 2011; Fatta et al., 2003; Rodríguez et al., 2007; Wu et al., 2014). When hazardous materials are mixed with inert waste then the mixture should be treated as hazardous waste (Rodríguez et al., 2007).

In Europe, data on CDW management available from 18 EU member states shows that around 50% of CDW is recycled (del Rio Merino et al., 2010; EEA, 2012; ETC/SCP, 2011; Villoria Saez et al., 2013). However, recycling is not homogeneously practiced between member states (BIO Intelligence Service, 2011), and as such there are numerous inconsistencies related to the methodology and definitions used in each country. For instance, CDW composition differs from one country to another (e.g. some countries include excavation material while others do not), and clarity in the way the recycling term is used is currently lacking (Tojo and Fischer, 2011; Villoria Saez et al., 2013). More specifically, recycling in the EU can be used to mean both recycling and other material recovery[1] when the rWFD explicitly separates the two, while it is also used to refer to the collection and preparation of waste for reuse, recycling and other form of material recovery (BIO Intelligence

[1] In the rWFD recycling explicitly excludes the reprocessing into materials in a lower product quality than recycling (e.g. backfilling operations using waste to substitute other materials) as this is included in the definition of recovery (ETC/SCP, 2009b).

Service, 2011). Intrinsically, this makes the data available on the recovery and recycling of CDW highly unreliable. An attempt to estimate the amount of CDW collected and recycled in EU27 using a number of variables has been made, further details of which can be found at the Bio Intelligence Service report (2011).

In general, in countries such as Denmark, Germany and the UK recycling of CDW has been an established practice for numerous years (some have even introduced a ban on landfilling), whereas in countries such as Bulgaria, Greece, Italy and Spain landfill has been the main disposal route and only recently have measures been put in place for the treatment of that waste stream. Meanwhile, increases in the cost of commodities makes the establishment of environmentally sound and economically feasible measures for the reuse and recycling of CDW particularly important in the construction sector, and improvements are expected to be seen in the coming years (European Commission, 2014; Wu et al., 2014).

3. Mining the physical infrastructure

3.1. Recycling versus reuse

Recycling and reuse of construction materials and components at the end of their life are seen as good environmental practice because they can offer a great potential for improving and enhancing resource efficiency in the construction sector, leading to reductions in energy use and associated carbon emissions, reducing the amount of waste and of land put out of use, and can create value (European Commission, 2014; Stahel, 2013; Wahlström et al., 2014). Reuse is the process during which discarded components are recirculated (and sometimes upgraded according to the material structure) and used for the same function without destruction (Cooper and Allwood, 2012; Thormark, 2000), whereas recycling is the process during which discarded materials are reprocessed into raw materials for new products (Thormark, 2000; WRAP, 2008b).

With regard to recycling of materials, this can be separated into open-loop, also known as downcycling (e.g. steel beam turned into reinforcing bar), and closed-loop (e.g. steel beam turned into a new steel beam) recycling (Gorgolewski et al., 2006; Thormark, 2000; Webster, 2007). The environmental benefits of recycling cannot be generalised as these can vary widely from one material to another. This is largely due to the amount of energy required for the transportation and mechanical and/or thermochemical reprocessing of materials and components (Ness et al., 2015; Webster, 2007). The transport distance and mode to recycling plant, weight and type of component, reprocessing methods, and distance to raw material resource site, can affect the difference between the environmental properties of recycled vs. virgin materials (Thormark, 2000; WRAP, 2008b). Using energy consumption as an example, for some materials this can be relatively high (e.g. remelting steel) (Hradil et al., 2014), while for others it can be considerably lower (e.g. recycling of concrete on site for use as aggregates in roads construction replacing gravel) (Thormark, 2000; WRAP, 2008b).

In the case of reuse, while components may require some minimal reprocessing/fabrication the energy requirements for this are still much lower than that for recycling (Hosseini et al., 2015; Mulder et al., 2007; Sassi, 2004; Webster, 2007). For instance, the fabrication of steel sections for reuse requires a total energy consumption of 4.8 GJ per tonne, whereas recycling of the same sections requires twice the amount of energy per tonne (Geyer and Jackson, 2004). In terms of carbon emissions, the reuse of steel and glass components can save more than 60% of the carbon required for their recycling (Gorgolewski, 2008). In addition to environmental savings, reuse offers the possibility of economic and social benefits due to reductions in costs (i.e. virgin materials extraction, processing, transportation, site operations and storage), and the creation of new business models that can promote job creation and profit centres (Allwood et al., 2011; Horvath, 2004; Hosseini et al., 2015; Ness et al., 2015; Webster and Costello, 2005). Nevertheless, the transport of reclaimed components from one site to another, and the need for a materials storage site and/or a refurbishment plant for the cleaning and repairing of secondary components, are important features that have to be taken into account when assessing the environmental performance of reuse (Allwood et al., 2011; Anderson et al., 2002; Cooper and Allwood, 2012; Ness et al., 2015; Webster, 2007). According to a report by the Waste and Resources Action Programme (2008a, 2008b), the maximum transport distance by road that reclaimed tiles, bricks, slate, timber and steel can be transported before having a greater impact than their virgin counterparts made locally is 100, 250, 300, 1000 and 2500 miles, respectively (WRAP, 2008a).

On the downside, reuse can be limited by building codes and standards, the lack of confidence in the structural properties and performance of reused components, technical considerations, lack of end markets for secondary materials, but also prejudice and lack of awareness on the potential of this practice (Allwood et al., 2011; Gorgolewski et al., 2006; Horvath, 2004; Hradil et al., 2014; Ness et al., 2015; Webster, 2007). To unlock its potential, a clear demonstration of its technical feasibility and potential for recovering value is needed taking into account all the multiple aspects (i.e. environmental, economic, social and technical) of the system in which it is practiced.

3.2. Reuse potential and recyclability

A range of factors including the financial aspects, type and quality of material/component, its durability, function, fatigue loading, and projected lifetime, as well as the construction and demolition methods used govern to some extent the potential of construction components to be reused (Dorsthorst and Kowalczyk, 2005; Gorgolewski, 2008; Sassi, 2002; Thormark, 2000; Webster and Costello, 2005). However, the technical feasibility of a construction component to be reused and the EC associated with it, are the most fundamental factors in determining a component's end-of-life potential (Thormark, 2000).

To establish this potential two indicators are used; the *reuse potential* and the *recyclability efficiency metric*. Although the latter gives the impression it refers to recycling, this metric developed by the Waste and Recourses Action Programme, is used to measure the efficiency with which the EC of construction components is conserved in each of the recovery processes used that can be either reuse, recycling or energy recovery (WRAP, 2008b). To avoid confusion the term *EC reuse efficiency* is going to be used in the rest of the text to describe the benefits of construction components reuse.

3.2.1. Reuse potential

Reuse potential is a measure of the ability of a construction component to retain its functionality after the end of its primary life. This metric is difficult to define as it depends on many factors which in turn depend on cultural, historical and organisational aspects. To explain this further, the reuse potential for bricks can be somewhere between 50% and 95% contingent on the time allowed for dismantling, the care taken and the materials used for binding (e.g. cement based mortar vs. lime based mortar) (Leal et al., 2006; WRAP, 2008b). Even though the reuse potential of construction components can vary from one study to another, Table 1 aims to depict the ability of a range of components to retain their functionality over the end of their primary life, as reported in a number of studies found in the literature.

The flexibility and durability of structural steel components (e.g. beams, plates, decks and columns) create a high potential for reuse at the end of their primary life (Cooper and Allwood, 2012; Fujita and Iwata, 2008; Gorgolewski et al., 2006; Horvath and Hendrickson, 1998; Ness et al., 2015; Pongiglione and Calderini, 2014). Although, corrosion, fatigue degradation, rust formation and plasticization caused by earthquakes, fires, scouring and degradation have been reported to limit steel's potential for reuse, these can overcome with proper maintenance (Cooper and Allwood, 2012; Fujita and Iwata, 2008; Horvath and Hendrickson, 1998; Ness et al., 2015; Pongiglione and Calderini, 2014). For example, rust problems associated with steel can be resolved

Table 1
Reuse potential rates of a range of construction components.

No potential (0%)	Low (<50%)	Medium (~50%)	High (>50%)
Clay bricks (cement-based mortar)[a,f]	Mineral wool[b,e]	Steel cladding (buildings)[c]	Clay bricks (lime-based mortar)[a,b,f,o]
Steel rebar (buildings)[c]	Gypsum wallboard[a,b,e,g]	Steel cold formed sections (buildings)[c]	Structural timber[b,e,f,g,i,l]
Steel rebar (other infrastructure)[c,i]	Steel rebar in pre-cast concrete (buildings)[c]	Steel pipes (buildings)[c]	Structural steel (buildings)[c,f,j,m]
Steel connections[c,f]	Structural steel (infrastructure)[c,h]	Pre-cast concrete[a,m]	Concrete building blocks (with lime mortar)[a,f]
Structural concrete (buildings)[d,e,f,g,i,l]	Timber trusses[m]	Slate tiles[p]	Concrete paving slabs and crash barriers[j]
Asphalt (other infrastructure)[d,g,i]	Concrete in-situ[a,j,k,l,n]	Timber floorboards[p]	Clay roof tiles[j,l]
Asphalt roof shingles[e,m]	Concrete fencing, cladding, staircases and stair units[f]		Concrete roof tiles[j,l]
Plastic pipes (water and sewage), roof sheets, floor mats, electric-cable insulation, plastic windows[n]	Glass components (e.g. windows)[d]		Stone paving[f,j,p]
Concrete pipes and drainage, water treatment and storage tanks and sea and river defence units[j]			
Non-ferrous metal components (aluminium window frames, curtain walling, cladding, copper pipes, zinc sheets for roof cladding)[a,i,n]			Stone walling[f,j,p]

[a] WRAP (2008b) (figures based on buildings).
[b] Thormark (2000) (figures based on a residential building).
[c] Cooper and Allwood (2012) (figures based on global steel production).
[d] BIO Intelligence Service (2011) (figures based on European data on potential use of construction materials/components).
[e] Gorgolewski and Ergun (2013) (figures based on an archetype wartime house).
[f] Webster and Costello (2005) (based on literature).
[g] Horvath (2004) (based on literature).
[h] Pongiglione and Calderini (2014) (figure based on a railway station).
[i] Tam and Tam 2006 (based on literature).
[j] Hurley and Hobbs (2005) (based on literature).
[k] Sassi (2004) (based on literature).
[l] Sassi (2002) (based on literature).
[m] Earl et al. (2014) in Nakajima and Russel (based on literature).
[n] Leal et al. (2006) (based on management of CDW in Germany).
[o] Bohne and Waerner (2014) (based on figures from Norway).
[p] WRAP (2008a) (based on figures from the UK).

by painting; which in bridges is the most common maintenance practice (Horvath and Hendrickson, 1998), whereas plasticization can be handled by adopting damage-controlled-design. In such designs, structural members are maintained within an elastic region by specifying seismic energy-absorbing members (Fujita and Iwata, 2008). Standardised methods for assessing the properties of steel components are not available and costly tests must often be performed in order to assess their potential for reuse, especially when drawings are not available (Hradil et al., 2014). Steel components that are difficult to be recovered for reuse are those used as reinforcement in concrete buildings. The only way by which these steel components can be reused is through the reuse of pre-cast concrete modules in which they are contained. However, in most of the cases the inability to separate such steel from other materials make its *reuse potential* negligible (Cooper and Allwood, 2012).

Structural and non-structural timber components have high potential for reuse when properly deconstructed (Baiden et al., 2005). The high quality and value of large timber beams and planks, railway sleepers and floorboards offers the possibility for creating a profit at low volumes of re-sale (Hurley and Hobbs, 2005; Webster, 2007). Nevertheless, timber components can be susceptible to decay, can be difficult and dangerous to deconstruct and may require special equipment and extra care during cleaning, de-nailing and sizing to avoid damaging the members at the cost of time (Baiden et al., 2005; Nakajima and Russell, 2014; Tam and Tam, 2006b; Webster and Costello, 2005). Inevitably, this makes it attractive to burn timber for energy recovery rather than to recover its structural function, and a significant proportion of it is still being sent to landfill. Design interventions that incorporate characteristics such as holes for wiring and other services to pass through, has made timber components less sensitive to damages during construction allowing also for an efficient deconstruction. Advancements in technology such as development of the automated removal of nails and screws, metal detectors for identifying metal webbed beams, and 3D laser scanning for sorting timber components into different section sizes will further improve their reclamation and reuse (Hurley and Hobbs, 2005).

Concrete's potential for reuse is difficult to generalise due to its numerous uses, its highly variable composition (mix design) and strength, purity (based on the presence of pollutants found in e.g. paint and plaster), and form (e.g. cast-in-situ, pre-cast, or in unit materials such as blocks, tiles, stair units, etc.) (Leal et al., 2006; Nakajima and Russell, 2014). Cast-in-situ concrete is usually project specific, heavy and difficult to handle and analyse (unless information about the reinforcement is available), and has no joints between members, making it much harder to dismantle from the rest of the structure without being damaged (Dorsthorst and Kowalczyk, 2005; Hurley and Hobbs, 2005; Sassi, 2002; Webster, 2007; Webster and Costello, 2005). Sawing the construction to enable the reuse of reinforced concrete walls is possible but at the cost of time. Pre-cast concrete elements, such as girders, columns, hollow-core planks and double-tees, staircases and stair units can be recovered and reused as such in new construction, but sometimes they are likely to require small alterations in their design to enable their intact deconstruction as their connections tend to be grouted or covered with cast-in-place concrete (Hradil et al., 2014; Hurley and Hobbs, 2005; Webster, 2007; Webster and Costello, 2005). Concrete unit materials such as masonry blocks, building blocks, concrete roof tiles, and paving slabs that have no fixtures, fittings or joints are easier to dismantle and reuse (Hurley and Hobbs, 2005). Concrete fencing, cladding, concrete pipes and drainage, water treatment and storage tanks and sea and river defence units, have little potential for reuse due to difficulties in finding a comparable functional installation within a reasonable timescale (Hurley and Hobbs, 2005).

Masonry has a long history of reuse because it is durable and easy (if labour intensive) to deconstruct when sourced from buildings using traditional mortars with no Portland cement. Stones used in ancient buildings are often of great value and are reclaimed for reuse in new construction projects (Webster and Costello, 2005). Similarly, the *reuse potential* of bricks can also be high especially when not bound with Portland cement mortars and plaster that makes their separation and cleaning labour-intensive and costly (Mulder et al., 2007; Rahman et al., 2014; Tam and Tam, 2006a, 2006b). Using lime and soft mortars for binding bricks, or eliminating mortar completely by using interlocking bricks (Ali et al., 2012; Anand and Ramamurthy, 1999; Dorsthorst and Kowalczyk, 2005) can be an environmentally friendly and cost-effective way with a high reuse potential (Ali et al., 2012; Nakajima and Russell, 2014; Thormark, 2000; Webster and Costello, 2005; WRAP, 2008b).

3.2.2. EC reuse efficiency

The *EC reuse efficiency* metric is an important indicator for retaining the functionality of a construction component. Knowledge of how much carbon can be saved through the reuse of the assortment of construction components used in infrastructure can be vital in stimulating the implementation of this practice. Detailed data on the EC of construction materials can be found in a number of databases. In the UK, the most detailed open-source database is the Inventory of Carbon and Energy (version 1.6a) compiled by Hammond and Jones (2008), which can provide figures in kilograms per material use (Hammond and Jones, 2008). Although, this information is useful when accounting for the materials used in construction on a mass basis, it provides no information on the EC of components according their size and functionality. For example, while common bricks and clay tiles have the same reuse potential (>50%) (Table 1), bricks have an EC of 0.22 $kgCO_2/kg$ and tiles have an EC 0.59 $kgCO_2/kg$, respectively. Assuming that both components can have ~100% efficiency in EC savings over their reuse, the reuse of 1 kg of bricks would "save" less EC, than the reuse of 1 kg of tiles. Yet bricks are one of the dominant building materials used in traditional low-rise buildings, and hence would account for much greater proportion of the total mass of material compared to tiles. Thus, promoting reuse of bricks over tiles would most likely lead to greater EC savings considering the building as the pseudo-functional unit (Monahan and Powell, 2011). Therefore, for assessing the *EC reuse efficiency* of a construction component in addition to its mass it is also important to know its function and characteristics (dimensions, section choice, and load capacity), as well as the carbon "costs" of the treatment required for reuse (e.g. cleaning, painting, testing), transportation and construction (Dixit et al., 2010; Ibn-Mohammed et al., 2013; Petersen and Solberg, 2002; Pongiglione and Calderini, 2014; Purnell, 2012; Purnell, 2013; Thormark, 2006).

4. Interventions for promoting reuse and environmental efficiency

To unlock the reuse potential of construction components and to improve the OC and EC of existing and new structures, a number of interventions have been developed. These include the use of alternative construction materials, substitution of energy and carbon intensive materials with less-intensive ones in the production of common materials, reduction in the excess use of materials during manufacturing processes, improvements in technological design and practices (e.g. modern earth structures) and finally changes at the construction and demolition stage of a building and/or other inrastructure (Ayres, 1997; Dorsthorst and Kowalczyk, 2005; Giesekam et al., 2014; Sassi, 2002; Vaníček and Vaníček, 2013; Webster and Costello, 2005).

Research on alternative, low EC materials is on-going, with the use of natural materials such as straw, hemp and earth as alternatives to steel, concrete and masonry being gaining attention in the last decade (Giesekam et al., 2014). The production of rammed earth and unfired clay bricks, prefabricated timber and straw bale panels, and the use of sheep's wool as an insulator material are examples of alternative materials used in the construction of buildings of which structural or functional performance has been shown to be competitive with that of conventional ones (MacDougall, 2008; Giesekam et al., 2014; Sutton et al., 2011). In addition, the development of more innovative materials such as geopolymer foam concrete (Zhang et al., 2014), and hemp-based composite materials (Bevan and Woolley, 2008), which have been demonstrated to have an extended service lifetime, reduced weight, low maintenance requirements and/or low EC, is also enduring. In the coming years, it is expected that these materials will offer opportunities for replacing conventional construction components in the building sector and other infrastructure projects where appropriate.

Direct replacement of structural and non-structural components with lower carbon alternatives is not always feasible due to particular functional requirements (e.g. concrete used in foundations, steel used as reinforcement, etc.) (Giesekam et al., 2014). However, the use of waste-derived supplementary cementitious materials (SCM) (e.g. silica fume, fly ash and ground granulated blast-furnace slag) in replacing cement in concrete production (Elahi et al., 2010; Purnell, 2013; Purnell and Black, 2012) has gained pace over the last decades. Likewise, the use of recycled concrete and post-consumer plastic, glass and ceramic in the form of granules, fibres or powders in replacing virgin aggregates in concrete production (Siddique et al., 2008) has been shown to have a great potential. Furthermore, the replacement of fossil fuels with a high calorific value solid waste (e.g. meat and bone animal meal (MBM) and sewage sludge) in cement kilns (Aranda Usón et al., 2013; Rahman et al., 2015)); or the direct replacement of a component with a waste material such as the use of end-of-life tire pads as under sleeper pads in railway (Sol-Sánchez et al., 2014), are also under investigation.

Reducing excess use of material in the production of construction components is yet another resource-efficiency strategy with myriad benefits in the supply chain and the construction sector in particular. Currently, up to a third of the material used in the manufacturing of construction components can be excess to functional requirements (Giesekam et al., 2014). This is largely because a regular size is usually used to manufacture standard components such as I-beams. The use of a smaller set of component sizes to simplify site work, or the use of over-specified components copied across different projects as a way to deal with costly design time and regulatory requirements, all lead to excess material use (Allwood et al., 2012; Giesekam et al., 2014; Scott et al., 2009). Optimising construction components design could result in considerable material savings (e.g. for steel beam designs weight savings of at least 30% could be achieved) with ensuing savings in the energy use and associated emissions (Allwood and Cullen, 2011). Recently, lightweight design has gained prominence in the construction sector as a way to improve material efficiency in design and production processes. Notwithstanding its importance for the construction sector, this is not by any means a new practice as lightweight design has successful applications that date from many years back in sectors such as, the aerospace industry and automotive sector (Allwood and Cullen, 2011). A lightweight component is the one that can meet its functional requirements, retain its durability, load capacity and rigidity, while at an optimum weight. To realise the production of a lightweight component a number of challenges related to design, costs and institutional/organisational barriers have to be overcome. The advancement of computational optimisation in the design process has helped to reduce the weight, cost and emissions associated with many construction components and structures, and provides scope for further improvements (Giesekam et al., 2014).

All the above strategies are beneficial in improving the materials and carbon efficiency of manufacturing processes and of infrastructure. However, their roll-out as established practices is hindered by many cultural, economic, institutional and organisational barriers. Nonetheless, no matter how innovative some solutions can be, their whole-life evaluation is required in order to ensure that a solution to one problem does not create yet another. As further improvements in the materials production processes become incremental owing to technical and thermodynamic limits (Allwood et al., 2011, 2013; Allwood and Cullen, 2011; Allwood et al., 2012), improving components reuse and adopting design practices that minimise material use seem a more realistic and tangible solution to achieving material efficiency and improving the environmental performance of the construction sector (Schultmann, 2008).

Reverse logistics, a rapidly evolving concept in the construction sector, is aiming at controlling the flow of construction components that would otherwise end up in the CDW stream, and effectively recirculating them back to the construction stage of a new project (Aidonis et al., 2008; Hosseini et al., 2014; Hosseini et al., 2015; Nunes et al., 2009; Rogers and Tibben-Lembke, 2001). This concept has been widely practiced by the automotive sector, from where successful cases can help identify potential good practice (Schultmann and Sunke, 2007). Interventions that can promote reverse logistics (i.e. extending the life of construction components) in the construction sector, are those related to the construction and demolition stage of a structure. These are many and are presented in Table 2. The goal of these interventions is to provide the means by which an adaptable design, optimised recovery of components for reuse, and incorporation of new design methods can be ensured.

4.1. Adaptive reuse

Adaptive reuse is a method that reuses whole or part of a structure and/or building that has either been made redundant or is in a good condition, but the services and technologies within it are outdated and need to be upgraded (Bullen, 2007; Langston et al., 2008). Known also as building adaptability, this intervention constitutes a sustainable solution with direct environmental, economic and social advantages that emerge from extending the useful life of a building (Bullen, 2007; Gorgolewski et al., 2006; Laefer and Manke, 2008; Langston et al., 2008; Schultmann, 2008; Webster, 2007). Key environmental benefits include the reuse of structural components without any need for reprocessing and the reduction of CDW, which can be translated into direct and indirect resources, energy and carbon savings. In the case of old structures, a range of architectural value materials such as precious wood, marble floors and solid stone walls can display a greater useful life compared to their modern counterparts, while also adding value to the building as a whole (Laefer and Manke, 2008; Langston et al., 2008; Velthuis and Spennemann, 2007; Webster, 2007; Yung and Chan, 2012). Despite the time effectiveness of adaptive reuse, the costs of converting a building for the same or a new use can be either less or more than the costs of constructing a building from anew. Nonetheless, breathing new life into existing structures can help to retain their intrinsic heritage values, add character, and provide status to the surrounding area. Moreover, reuse of buildings that have been made redundant and revitalisation of derelict buildings, reduces crime and other unsocial behaviour, and raises living standards through added investment and added value (Bullen, 2007; Bullen and Love, 2010; Langston et al., 2008; Loures, 2015; Yung and Chan, 2012).

An exception to this generalization is old or damaged structures that cannot be upgraded due to reduced physical and structural performance (Gencturk et al., 2016; Langston et al., 2008). All old structures experience natural decay and fatigue degradation over time (e.g. roads and bridges), but in some structures this can be extended at such a degree that it may not comply with existing regulations and standards and compliance measures for reducing OC. Additionally, damaged structures may present unsatisfactory structural performance with inadequate resilience (Gencturk et al., 2016). In such cases, substantial structural changes are required, or additional protective measures have to be taken, which may be costly and material- and energy-intensive (Gencturk et al., 2016). Therefore, it is essential that prior to any building or structure being considered for major refurbishment, a thorough assessment of its structural and constructional quality and compliance with building and structural regulations should be undertaken, in order to avert risks and decide on the best sustainability practice. The location of the structure is another factor that must be taken into account. Older structures are often in advantageous locations in city centres and key transport nodes making reuse (where appropriate) more viable, whereas others can be located in less populated areas where any added investment may not return the desired benefits and value (Bullen, 2007; Langston et al., 2008; Loures, 2015; Yung and Chan, 2012).

Examples of successful implementation of adaptive reuse include the reuse of power and water plants (Loures, 2015), commercial and industrial buildings (Bullen, 2007; Gorgolewski et al., 2006; Langston et al., 2008; Yung et al., 2014), high-rise buildings, warehouses and car parks (Corus UK, 2001; Gorgolewski et al., 2006), and residential buildings (Haidar and Talib, 2015; Langston et al., 2008). More specifically, in London the redevelopment of Farrington Station has retained some of the existing façade and part of the frame, contributing to over 3000 tonnes of EC savings (RICS, 2012). In the study of Gorgolewski et al. (2006) it was reported that in Ontario, demolition contractors strip the building of its interior and/or exterior layers preserving the structural steel layer for reuse in a new building (Gorgolewski et al., 2006). In the same study it was estimated that structural steel reuse through adaptive reuse is around 2500 tonnes per year. In another study, the adoption of an old office complex into a new residential development in Oswava resulted in 90% reuse of the steel frame which generated a cost saving of 12.5% compared to constructing it from anew (Segio and Gorgolewski, 2006). These projects have highlighted a number of challenges related to the implementation of this reuse method, including the lack of information on the performance of reclaimed structure and components, and issues of legislative compliance, fire safety, disabled access and heritage constraints (such as a requirement for façade retention) (Gorgolewski et al., 2006; Langston et al., 2008). A positive and collaborative attitude between designers, developers, asset owners, and the general public, can help to overcome these challenges and help adaptive reuse to be realised. In addition, proper documentation of each structure including as-built drawings

Table 2
Interventions in the construction and demolition sector.

Intervention	References
Adaptive reuse	Webster (2007), Pongiglione and Calderini, 2014, Webster and Costello (2005), Ness et al. (2015), Laefer and Manke (2008), Gorgolewski et al. (2006), Langston et al. (2008), Velthuis and Spennemann (2007)
Deconstruction	Aidonis et al. (2008), Couto and Couto (2010), Sassi (2002), Srour et al. (2012), Schultmann (2008), Schultmann and Sunke (2007), Leroux and Seldman (2000), Leigh and Patterson (2006), Kibert et al. (2001), Guy and Gibeau (2003), Gorgolewski (2008), Schultmann and Rentz (2002), Saghafi and Teshnizi (2011), Roussat et al. (2009), Hosseini et al. (2015), Denhart (2010), da Rocha and Sattler (2009).
Design for Deconstruction (DfD)	Dorsthorst and Kowalczyk (2005); Webster and Costello, 2005; Webster (2007); Sassi, 2004; Gorgolewski, 2008; Sassi, 2008; Rios et al. (2015); Pulaski et al. (2003); Guy and Shell (2002); Durmisevic and Brouwer, 2002; Tingley and Davison (2011); Crowther, 2002; Crowther (2014).
Design for reuse (DfR)	da Rocha and Sattler (2009); Gorgolewski (2008), Berendsen (1997), Bradly and Shell (2002), Chini and Schultmann (2002), Pongiglione and Calderini (2014)
Design for Manufacture and Assembly (DfMA)	Laing O'Rourke 2013; Pasquire and Connolly (2003); Jaillon and Poon (2014)

and specifications, list of codes and standards, and inventory of the quality, size and performance of components can help to ensure that adaptive reuse can be successfully performed (Gorgolewski et al., 2006).

4.2. Deconstruction

Deconstruction is the careful dismantling of a building or structure to maximise the recovery of its components for reuse (Chini and Bruening, 2003; Geyer and Jackson, 2004; Guy and Gibeau, 2003; Guy and McLendon, 2002; Nakajima and Russell, 2014; Schultmann, 2008; Webster and Costello, 2005). It is a labour intensive and environmentally sound process (Chini and Bruening, 2003; Leroux and Seldman, 1999; Schultmann, 2008; Webster, 2007), with several advantages over conventional demolition. These include reduction of CDW and associated costs for its management, enhanced environmental protection, reclamation of construction components for reuse, recovery of materials for recycling, and preservation of the embodied energy and carbon of components and materials contingent to the reprocessing process followed (Aidonis et al., 2008; Chini and Bruening, 2003; Dorsthorst and Kowalczyk, 2005; Nakajima and Russell, 2014; Sassi 2002, 2008; Schultmann and Rentz, 2002; Schultmann and Sunke, 2007; Webster, 2007).

Deconstruction, however, does take longer than demolition and if this is part of constructing a new structure then it becomes a real challenge from an economic and time point of view. This is because the ease and speed of deconstruction are hindered by the design and techniques used at the construction stage, whereas the long lifespan of many structures makes it difficult to predict which materials will have a salvage value. For instance, the use of chemical or thermal bonding of components (e.g. in-situ cast concrete joints, adhesive bonding, welding) rather than dry mechanical ones (such as screws, bolts, or dowels) increases the cost and limits the feasibility of disassembly (Sassi, 2004; Webster and Costello, 2005). The high cost of labour and machinery required for dismantling as well as the time constraint often makes deconstruction's practicability questionable in current valuation contexts (Coelho and de Brito, 2011; Couto and Couto, 2010; Crowther, 2014; Dantata et al., 2005; Dorsthorst and Kowalczyk, 2005; Durmisevic and Binnemars, 2014; Earle et al., 2014; Gorgolewski, 2008; Horvath, 2004; Kibert, 2007; Nakajima and Russell, 2014; Webster and Costello, 2005). The presence of hazardous materials puts an additional cost on deconstruction as it requires a trained workforce for their proper removal (Geyer and Jackson, 2004; Leigh and Patterson, 2006). Likewise, the lack of secondary markets for recovered components means that the unit cost of reclaimed components fluctuates unpredictably (Geyer and Jackson, 2004). These advantages and barriers to deconstruction have been reported in many studies, and are presented in the following table (Table 3).

Examples of deconstruction can be found in many countries around the world. In the Netherlands, deconstruction has been practiced in a number of projects, and a distinct one is the disassembly of a housing block for reuse in Middelburg (Dorsthorst and Kowalczyk, 2005). In Norway, the EcoBuild group is devoted to the reduction of CDW through the promotion of deconstruction over conventional demolition, and the establishment of secondary resource markets for stimulating reuse (Nakajima and Russell, 2014). In the US, deconstruction has been successfully applied in many types of structures including closed military bases, commercial and residential buildings and churches (Horvath, 2004; Kibert, 2007). However, most of the studies are qualitative rather than quantitative, not providing figures on the economic, environmental and social values of deconstruction. Even in studies where figures are provided these are usually combined with those for recycled materials, or are based on national aggregated figures (Dorsthorst and Kowalczyk, 2005; Geyer and Jackson, 2004; Guy, 2014; Guy and Shell, 2002). Nonetheless, in the study of Geyer and Jackson (2004) a comparison between deconstruction and demolition for the recovery of steel sections showed that the cost of deconstruction per tonne of steel reclaimed was £50 higher than that of demolition. However, a whole life evaluation of the two processes showed that reuse is in fact £350 cheaper than recycling (£950), and has an *EC reuse efficiency* of approximately 80% compared to 49% for recycling. Likewise, in the study of Gorgolewski (2008) it was reported that the deconstruction of six one- and two-storey buildings was by 21% more expensive than demolition, but the net cost of deconstruction, taking into account reuse and revenue from sales, was 37% lower than that of demolition (Gorgolewski, 2008). This indicates that deconstruction and reuse offer higher environmental and economic benefits than demolition and recycling (Geyer and Jackson, 2004) when evaluated over the whole life of the structure. Aside from these findings, manifestation of the environmental, economic and social and technical values of deconstruction can diverge significantly from one study to another due to factors such as economic status, existence of secondary resource markets, technical expertise on deconstruction techniques and trained workforce.

To realise the long-term benefits of deconstruction, guidance and training on deconstruction techniques is required. In addition, political strategies that foresee the provision of incentives to boost deconstruction and reuse of construction components, and the promotion of legislation for reducing CDW, will help to realise the real potential of this method as an alternative to demolition and landfilling. Furthermore, changes in the perceived value of secondary construction components will likely put a higher demand for these in the near future. Research is critical to this end in order to provide a better understanding on the merits of deconstruction, and to explore new techniques that can enlarge its potential (Leigh and Patterson, 2006; Saghafi and Teshnizi, 2011; Schultmann, 2008; Srour et al., 2012).

4.3. Design for Deconstruction (DfD)

Design for Deconstruction (DfD) is about designing to close the construction components loops. The main principle of this intervention is to design new structures in such a way as to allow the economic recovery of structural components and their associated value (Crowther, 2002, 2009, 2014; Durmisevic and Yeang, 2009; Gorgolewski, 2008; Guy and McLendon, 2002; Guy and Shell, 2002). Through this intervention the life-cycle stages of a structure (i.e. planning, design, construction, operation, maintenance and disposal) are optimised to maximise the recovery of valuable components for reuse, and make new structures adaptable, which is why it is also referred to as Design for Adaptability and Deconstruction (DfAD) (Dorsthorst and Kowalczyk, 2005; Gorgolewski, 2008; Guy and Shell, 2002; Webster, 2007). Making structures that are easier to adapt allows a better function and configuration over time and extends the lifetime of the structure, providing economic and environmental benefits. Additionally, in such structures it is easier to locate, change and/or maintain utilities (e.g. telecom, electrical, and mechanical systems) reducing significantly the speed and cost of changes.

As with other interventions, DfD is also hindered by a number of challenges related to technical, economic and logistical barriers. For example, the financial viability of DfD may vary from one project to another due to differing monetary values assigned to different types of projects. In self-build projects, DfD is popular as the monetary value of labour in such projects is often not accounted for. The builder will own the property long-term and will benefit directly from the recovery of construction components for reuse after deconstruction. In more traditional commercial projects, the extra design time required plus the divorce in time and space between the contractor and the eventual value of recovered components require that client and/or regulatory pressures are required for commercial viability. Unless a set of contractors skilled in deconstructing buildings, the cost of deconstruction and of the recovered materials become competitive with conventional alternatives, and a market for the recovered components becomes available the economic viability of DfD will be a real hurdle in realising the

Table 3
Benefits and constraints of deconstruction.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Environmental	Reduction in the use of virgin raw resources.	x	x			x		x			x						x	x	x	x
	Reduction of waste generated.	x	x	x				x		x	x				x		x	x	x	x
	Proper removal and handling of hazardous materials.	x	x							x										
	High recovery of components for reuse and materials for recycling.	x	x	x				x		x										
	Conservation of embodied energy and carbon of materials and components.			x				x												
	Reduction of environmental impacts from minimisation of the needs for reprocessing of materials			x				x			x				x		x	x	x	
Economic	Higher costs compared to conventional demolition		x			x		x	x		x	x			x	x				
	Creation of local markets for materials recycling and components reuse	x				x		x							x					
	Lack of regional markets for reclaimed components											x								
	Opportunities for small and medium-size enterprises (SMEs) development to handle secondary components for reuse		x					x		x										
	Generation of revenue through selling salvaged components	x	x			x		x		x								x		
	Reduction of costly investments in heavy machinery and equipment	x						x									x			
	Lack of financial incentive for deconstruction	x													x					
	Increased cost of transport and storage of components	x	x		x	x														
	Lower costs of inventory, maintenance, transportation and procurement of new products																		x	
	Long-term economic benefits	x	x												x					
	Increased demand for material - low speed of deconstruction	x	x		x	x			x											
	Fluctuation of value of salvaged components			x						x										
	Reduction in the costs of waste disposal		x	x				x		x						x				
Social	Mitigation of noise, dust, and compaction associated with conventional demolition.		x												x					x
	Creation of new jobs in deconstruction sector	x	x					x		x					x		x	x		x
	Provision of low cost material to low income communities	x	x																	
	Job training in use of basic tools and deconstruction techniques	x	x					x							x					
	Cultural preservation and retention of historical significance of community infrastructure		x					x		x		x								
	Opportunities for self-employment and small business development		x					x							x					
	Consumers prejudice in using second-hand materials and preference to new		x		x							x								
	Aesthetics and commercial desirability		x		x				x											
Technical	Buildings and building components not designed for deconstruction	x	x	x	x						x	x								
	Performance guarantee for reused materials - tests needed to certify performance	x	x	x	x	x														
	Lack of experience and capability on construction techniques used, and available tools to implement deconstruction	x	x		x						x	x			x	x				
	Vast variety in quality of extracted components from buildings	x									x	x		x						
	Vast variety in the size of extracted components from buildings			x								x		x						
	Existence of hazardous substances (fire retardants, coatings, etc.)			x	x						x	x	x	x						
	Lack of information on buildings components											x	x							
	Uniqueness of each building for deconstruction																			
Organisational	Lack of standard specifications and building codes to address the reuse of building components	x		x	x	x			x		x	x			x	x				
	Excessive effort and time required				x				x			x		x	x	x				
	Lack of infrastructure for refurbishment and storage of components				x							x		x	x					
	Tight scheduling of deconstruction projects											x			x					
	Large number of parties involved in deconstruction											x		x						

(1) Couto and Couto (2010); (2) Hechler et al. (2012); (3) Kibert et al. (2001); (4) Tingley and Davison (2011); (5) Guy (2014); (6) Gorgolewski, 2008; (7) Leroux and Seldman (2000); (8) Sassi (2004); (9) Aidonis et al., 2008; (10) Dorsthorst and Kowalczyk (2005); (11) Srour et al. (2012); (12) Schultmann (2008); (13) Schultmann and Sunke (2007); (14) Leigh and Patterson (2006); (15) Sassi (2008); (16) Saghafi and Teshnizi (2011); (17) Denhart 2010 (as cited in Hosseini et al., 2015); (18) Shakantu et al. (2012) (as cited in Hosseini et al. (2015)); (19) Guy and Gibeau (2003) (as cited in Hosseini et al. (2015).

potential of this intervention due to its high costs compared to conventional practices (Crowther, 2001; Gorgolewski, 2008; Sassi, 2008).

DfD cannot be standardised as the climatic, functional, cultural, geographic and ecological aspects of each region, dictate a different approach to the selection of materials and components, as well as the form and design of the building. For instance in countries where wood is the basic construction material, DfD is going to be different than the DfD practiced in the UK where steel frames are normally used. Another example is offshore structures that can differ from one geographical region to another, due to the variety of functions (e.g. oil/gas) water depths, marine environments and climatic conditions (e.g. wind, hurricanes, etc.). Yet all DfDs share some fundamental principles and strategies that would enable the extraction and reuse of construction components at the building's end-of-life at a cost effective and time efficient manner. These are presented in Table 4.

As DfD implementation is still in its infancy, there are not many examples in the literature, and those that exist are limited to the building sector. More specifically, in the Netherlands, the Delft University of Technology has developed and constructed numerous housing projects using the DfD approach including, the MXB-5 System, Bestcon-30 System, CD-20 System, Moducon 2000 System, the SMT System and the XX Office building (Dorsthorst and Kowalczyk, 2005; Gorgolewski, 2008). Building systems such as the 'open building' approach described in Ness et al. (2015), or the 'building material level' described in Durmisevic and Brouwer (2002) are further examples of DfD, which are based on the conceptualisation of buildings as having different 'levels', namely urban tissue and infill. The urban tissue is the foundation of the building and has the longest lifetime (>200 years), whereas the infills are subject to changes every 10–20 years (Ness et al., 2015). This approach evolved from the work of Brand (1994) who established the concept of shearing layers of a building based on the frequency with which different components making up the various layers of the building are used and changed based on occupants' needs. Components with shorter

Table 4
Strategies for implementing Design for Deconstruction and reuse of materials.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Accessible information on: construction drawings; structural properties; inventory of construction components and materials, including their design life and potential for reuse.	x	x	x	x		x	x		x				x		x
3	Bar coding/labelling of materials (date of production, material grade/composition, strength and handling instructions) for ease separation, handling and storage to simplify reuse.				x	x		x			x					
4	Maximise clarity and simplicity for deconstruction at the building's end-of-life.		x				x	x				x		x	x	
5	Adaptable layering for handling utilities and envelope components without damaging structural components/allowing for parallel disassembly.	x	x	x	x	x		x						x	x	x
6	Use of a simple, regular layout to provide access to components/assemblies.		x		x	x		x			x				x	x
7	Make connections visible and accessible.			x	x			x				x	x	x		x
8	Use of mechanical connections (e.g. removable fasteners, bolts, screws) in lieu of welded joints and grouted connections, nails and chemical connections.	x	x	x	x	x	x	x	x		x	x		x	x	x
9	Minimise number of fasteners (stronger fasteners and fewer) to make disassembly faster and easier with the use of fewer types of tools and equipment.			x	x	x		x						x	x	x
10	Minimise number of components (larger components and fewer) to maximise reuse.	x	x	x	x	x		x	x		x			x	x	x
	Minimise different types of materials to maximise recycling.	x	x	x	x	x		x	x		x			x	x	x
11	Use of durable, high quality components and joints worth recovering.		x	x			x				x	x				x
12	Minimise the use of toxic materials (e.g. coatings, resins and adhesives) that can compromise the reuse potential of construction components	x	x	x	x	x	x					x		x	x	
13	Use of modular structural components and assemblies		x		x						x					x
14	Use of locally sourced and/or salvaged material.		x	x	x	x					x					
17	Design using salvaged materials, if available							x							x	
18	Lifetime of construction components to be longer than that of structure to enable their reuse								x							

(1) Guy and Shell (2002); (2) Hechler et al. (2012)); (3) Sassi (2004); (4) Crowther (2000); (5) Webster and Costello, 2005; (6) Addis and Schouten (2004) (as cited in Tingley and Davison (2011); (7) Webster (2007); (8) Dorsthorst and Kowalczyk (2005); (9) Schultmann (2008); (10) Crowther (2001); (11) Sassi 2008; (12) Morgan and Stevenson (2005); (13) Rios et al. (2015); (14) Pulaski et al. (2003); (15) Crowther (2002).

life expectancy should be easy to reach and modify without interfering with components that are expected to last longer (Fig. 1).

4.4. Design for Reuse (DfR)

Design for Reuse (DfR) incorporates the use of reclaimed components in the design of a new structure, and may include the dismantling, cleaning, testing, storage and re-fabrication of infrastructure components required for their reuse (Berendsen, 1997; Bradly and Shell, 2002; Chini and Schultmann, 2002; Gorgolewski, 2008; Pongiglione and Calderini, 2014). Despite the benefits of reusing reclaimed components accruing from retaining their value and gaining high *EC reuse efficiency*, there is an added level of complexity associated with it that needs to be tackled. This is largely due to the size, properties and availability of recovered components that strongly influence the design of a new structure. In projects where reclaimed materials and components are to be used in a similar layout to their original purpose, DfR can be successfully achieved. Even in those cases, the quality of structural components, their structural characteristics and conformity with the code standards, are critical to their successful uptake, as well as the quantity and availability of reclaimed materials available (da Rocha and Sattler, 2009; Gorgolewski, 2008; Pongiglione and Calderini, 2014). However, the latter is more easily dealt with by sourcing components from other locations and structures, or using new ones and fabricated accordingly to specific needs (Allwood and Cullen, 2011; Gorgolewski, 2008). The Mountain Equipment Co-Op in Ottawa, presents an excellent example of where structural components from the old building in place were used in the construction of the new retail facility. More specifically, existing foundations were reused in the same structural grid, and about 90% of the steel reclaimed from the original building was reused in the new structure, of which about 50% was open-web steel reused in the new roof structure. Rock and terrazzo floor salvaged from the original building were also reused in the new one. Another example in Canada, is the 740 Rue Bel-Air government building of which construction was carried out using many of the components (e.g. steel cladding, old brick, the façade and some of the timber) reclaimed from the original structure. In particular, 20% of the reclaimed open-web steel joists were reused in the new structure, whereas the rest was sold for local reuse or recycling (Gorgolewski, 2008).

Contrariwise, if the new layouts differ from the original ones, design alterations will be required to match the sizes and structure of the available recovered components. In such cases the design and construction

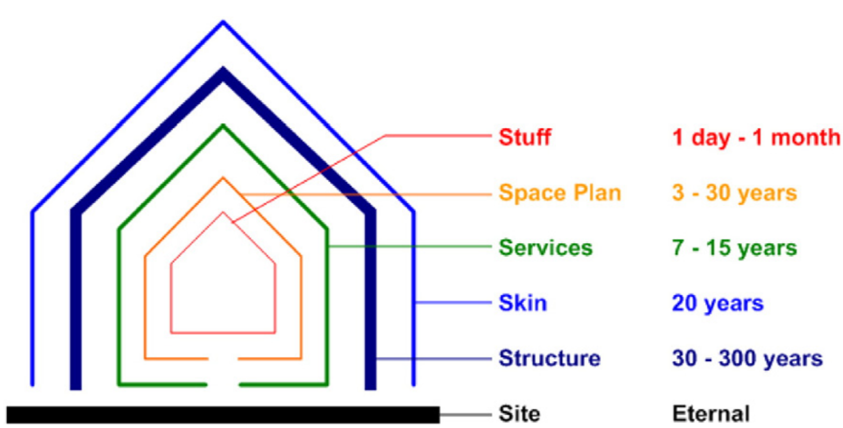

Fig. 1. Brand's 6S shearing layers theory (adapted from peterme.com).

processes must remain flexible in order to maximise reuse of construction components that are available, which can be a real challenge (Berendsen, 1997; Gorgolewski, 2008). A successful case study were reclaimed components were incorporated in the new design, is the Beddington zero energy development (BedZED) in Surrey, which comprises 82 homes and 3000 m^2 of commercial live/work space (Lazarus, 2003). For this construction, 95% (98 tonnes) of the structural steel used in the building came from reclaimed sources, 1862 tonnes of sub-grade fill was reclaimed on-site, whereas large amounts of timber (number not available) used for the interior partitions and some flooring, were sourced from a large reclamation yard with extensive timber stock (Addis, 2006). In Italy, the construction of a new railway station using reclaimed steel from an old industrial complex presented in the study of Pongiglione and Calderini, 2014, explained the importance of being flexible during the design process. In particular, they reported that roof trusses that were under tension in the original building would be under compression in the new configuration, and this would have been critical for wind lateral loads. Therefore, a change in the structural scheme allowed for the trusses to be rested on three new central struts, leaving the trusses that were under tension in the old structure to remain under tension in the new one (Pongiglione and Calderini, 2014). In the same study, it was concluded that the reuse of steel sections resulted in 30% savings in the energy and carbon emissions compared to a construction using only new components.

From both reuse conditions it can be generalised that the close collaboration between designers, structural engineers, traders and constructors is critical for the successful realisation of efforts to promote reuse of construction components and the recovery of value from infrastructure (Gorgolewski, 2008; Ness et al., 2015; Pongiglione and Calderini, 2014). Coordinated actions for the sourcing, testing and incorporation of reclaimed components in new structures are necessary for successful implementation of this intervention.

4.5. Design for Manufacture and Assembly (DfMA)

An emerging novel approach to material efficiency and ability to deconstruct a building at the end of its useful life is the Design for Manufacture and Assembly (DfMA). This intervention, inspired by its use in the automotive and consumer-products sector, focuses on the off-site design and manufacture of high-quality construction components with the technical capabilities, surface finish, overall shape and tolerances required for the structure in which they are intended to be used (e.g. concrete floor-slab elements, structural columns or modular plant rooms), which are then assembled into the completed building or infrastructure asset on-site (Kalyun and Wodajo, 2012; Laing O′Rourke, 2013; Boothroyd, 1994). Assembly is a crucial aspect of DfMA that has to be taken into account during manufacturing, in order to design the connections and joints of the construction products up to the required standards necessary for the structure. In the UK, Laing O′Rourke is practicing DfMA for projects including offices, schools, hospitals and hotels (e.g. Tootley building in London, Dagenham Park Church of England School and The Leadenhall Building project in the City of London) (Laing O′Rourke, 2013).

A major benefit of DfMA is that it enables an easy assembly and disassembly in a time-effective and cost-wise manner, promoting deconstruction and recovery of components at the end of a structure's lifetime, hence improving the overall sustainability of products and structures (Laing O′Rourke, 2013; Pasquire and Connoly, 2003). This technique ensures that components recovered have a greater potential to be in a good physical and technical condition for reuse than those recovered from traditional sites. However, an implication of this intervention is that components will have specific dimensions and moulding, creating barriers in their reuse, unless they are used under a similar context and function as before. Additionally, the variety of principles and guidelines that govern the manufacture and assembly of these components constitute a real barrier to the full implementation of this intervention. Once these are established and used, they can bring substantial benefits in achieving long term sustainable development in the construction sector (Lahtinen, 2011; Kalyun and Wodajo, 2012; Pasquire and Connoly, 2003).

5. Discussion

The construction sector demands more resources and produces more waste than any other sector in the world. The need to move towards a low carbon economy requires major transformations in the way production and consumption systems are perceived and realised. This places the construction sector in the spotlight as changes in the production, use and end-of-life management of construction components and structures can result in significant improvements in the overall sustainability impact of the sector. To that end, it has been increasingly advocated that CDW contains a variety of valuable resources that should be returned back to the economy instead of being wasted or downgraded. This concept of circularity dictates that a system should strive to retain products' value at the longest possible, preventing its wastage and promoting the creation of further value (Stahel, 2013; Hislop and Hill, 2011; European Commission, 2014). Henceforth, rethinking construction to make it more resource efficient and reduce its carbon footprint, by introducing new ways of designing, planning, constructing and deconstructing infrastructure, has a key strategic role in achieving sustainability in the long-term.

Mining existing infrastructure to reclaim the function of construction components is a promising route towards achieving these objectives, as it can address both resource efficiency and carbon emissions reduction targets. Nevertheless, the real potential of this practice has not yet been fully realised because of the lack of proper mechanisms; to achieve reuse, construction components have to be reusable. Although there is guidance on the theoretical reuse potential of construction components, on-site assessment of the reusability of construction components is currently the only way to evaluate their physical performance and ability for reuse. This time-consuming on-site assessment could be avoided if the reuse potential and lifetime of construction components was assessed and documented during the production and construction stage of projects that would enable their recovery and reuse at the end of a structure's life.

Efforts must be made to introduce new measures that associate *reuse potential* indicators with construction components during manufacturing and construction, to enable their ease identification and recovery for reuse, preserving their value in the system for longer. This will require a better understanding of how reuse potential values should be accounted for, which necessitates a better understanding of the materials used in the manufacturing of construction components, their mixtures, material grade, material strength, properties, etc., as well as the construction techniques used and the way components are connected with other components. To include this information, labelling of components would be a useful innovation for both adaptation (e.g. evaluation of member capacity for change of use) and resale (Webster, 2007). This can be a time-consuming and challenging task to achieve for the many of the component types used in the construction sector, but the potential value recovered from such practice could be so substantial that it would offset any of the time and effort 'costs' involved. Research in this area should be undertaken as current work is not coherent enough to support any suggestions on the *reuse potential* of construction components.

Determining the *reuse potential* of different construction components can also enable the determination of the EC savings that can achieved by their reuse, creating a stimulant for retaining components in the economy for longer. However, the *EC reuse efficiency* is not easy to decipher as it can vary depending on the size, dimension, and the functional unit of a construction component used in different contexts. Nonetheless, understanding EC would have a substantial impact on the willingness of the industry to take action as recovery of the "carbon value" embedded in each component will become an easy route towards achieving sustainability targets. In this regards, the EC of new construction components selected in new structures is also important in ensuring the long-term sustainability of the construction sector. The design parameters (dimensions, section choice, and load capacity), energy mix, material design and recycled content (e.g. typical steel has 60% recycled content, 40% virgin) (Dixit et al., 2010; Petersen and Solberg, 2002; Purnell, 2012; Purnell, 2013; Thormark, 2006) have to be taken into account for determining the EC of a construction component (Ibn-Mohammed et al., 2013). For example, lightly loaded timber columns, and long beams (<6 m) are found to be more efficient in terms of EC than other materials of the same functional unit (Purnell, 2012); whereas reinforced concrete beams with optimised strength and mix design can have a lower EC than steel or timber composite beams over the entire range of permissible concrete section sizes in large-scale construction (Purnell, 2013). Moreover, a comparison of steel and timber beams used at the construction of the new airport outside Oslo showed that the efficiency in the manufacturing of glulam beams is two to three times higher than that of steel beams (Petersen and Solberg, 2002). However, the scientific and technical literature is unclear on how EC should be measured and reported for the different types of components that are available in the market. Clarifications in this area are required to promote a mutual understanding and a common consensus on the way EC is accounted for. This would provide the means for the development of a framework that would contribute in the assessment of the real value of a component after recovery and create a taxonomy of materials based on their *EC reuse efficiency* potential.

Exploiting "smart" technologies such as Radio Frequency Identification (RFID) and Building Information Modelling (BIM) for tagging and archiving the properties of construction components based on their *reuse potential*, *EC reuse efficiency*, and other specifications required for enabling their reuse, would be an innovative disruption in the construction sector. This could help to enable and standardise the efficient tracking, handling and reuse of infrastructure components promoting their circularity in the supply chain (Ness et al., 2015). RFID tagging has been shown to be particularly useful in holding data, such as expected life-span in situ, EC, warranty limitations and data and place of manufacturing. Stress sensors combined with RFID can monitor physical parameters and the structural performance history of structures, such as bridges, providing further opportunities for establishing the suitability for reuse (Cheng and Chang, 2011; Ness et al., 2015). BIM has the potential to digitally represent the physical and functional characteristics of a structure by retrieving data from a database, forming a reliable basis for decision-making (Cheng and Chang, 2011; Ness et al., 2015). A combination of RFID with BIM holds much promise for the construction of sustainable infrastructure both in terms of minimising materials and waste and of retaining the functionality of existing secondary construction components. The unique RFID tag assigned to a construction component can be linked to a BIM database. This can enable the recovery and organisation of information during all building project phases incorporated into a 3D information model. In that way reclaimed construction components, archived in the BIM database, can find their way in being reused into new structures at a much effortless, cost-efficient and accurate way (Cheng and Chang, 2011). This technology is still in its infancy but if it becomes mainstream it will allow a big transformation in the construction sector and will unlock value and promote circularity with multiple benefits for the environment, economy and society.

In the shorter- and medium-term, the implementation of interventions in the planning, construction and deconstruction of a structure are more likely to help promote the recovery and reusability of construction components. These interventions (adaptive reuse, deconstruction, DfD, DfR and DfMA) as shown herein, have evidently many benefits to offer, but short-term economic issues, time constraints and a lack of appropriate skills in the industry, leave at present little space for the expansion of reuse in the construction sector. Challenges and issues that are worth to be explored further include: the heterogeneity of structural designs and construction practices; inherent variability in construction materials used; existence and efficiency of reclaimed materials end markets; and standards and specifications of materials used in construction.

As the price of fossil fuels inevitably begins to inflate, extraction of raw materials for use in the production of construction components will become more costly, enforcing a shift to material conservation and implementation of more resourceful practices. Amongst these practices is the dismantling of structures at their end-of-life for the recovery of construction components that can be reused, and the recovery of damaged components and other materials for recycling. As of today, existing markets for reclaimed materials are limited, because design interventions that utilise reclaimed components have only recently gained sufficient pace to create the initial conditions for the development of such markets. This creates difficulties in the implementation of any of the design interventions, which not only delays their uptake by the construction sector but also negatively impacts the deconstruction activities and further development of secondary markets.

An additional hurdle to this slow development is the price of reclaimed materials. Currently, newly manufactured components and materials are readily available and generally at much cheaper prices than reclaimed materials (except for certain high-value heritage materials), rendering the reclaimed materials market uncompetitive. The only way for secondary markets to become competitive is by offering low prices and high quality standards for reclaimed components and materials, while liquidity requires that the quantity, availability, size and properties of components are properly inventoried and communicated to ensure the success of the market. The need for co-ordination and collaboration amongst different parties in the construction supply chain for the provision, accreditation of performance and marketing potential of the reclaimed materials is critically required, in order to enable those markets to become established against virgin material markets.

A typology system that would assist contractors and designers to account for the selection and performance of recovered construction components with confidence would be a key tool in unlocking their reuse potential. This typology system would be largely focused on:

- The properties of the component (dimensions, material, nominal loading capacity, expected residual capacity (including the methods by which this was determined and the confidence therein), connection details etc.
- The nature of the recovery process (general demolition, controlled demolition protocol, specific recovery, or implementation of DfD, DfR or DfMA processes) including details of the methods used to extract the component and the associated likelihood of damage or contamination caused.
- The nature of the original use (e.g. magnitude, frequency and duration of loading), exposure conditions (e.g. wind, snow, high temperatures, coastal or marine environments) and the match thereto for the proposed new structural form, loading, exposure etc.

A table (Table 5) has been developed to list the classifications required for developing a coherent and consistent typology system.

The classifications in Table 5 are not definitive, and more or less may be required for a generic typology or a specific project respectively. A framework and methodology would be required for typologies of

Table 5
Proposed classifications for a typology of recovered structural components.

Level I classifications		Description and example level II+ classifications
1	Action	The physico-mechanical role of the component in its previous deployment, e.g. 1.1 structural (primary load bearing, such as beams or columns), 1.2 semi-structural (secondary load-bearing such as cladding, roofing), 1.3 modular (such as bricks, tiles), 1.4 functional (such as staircases, windows, lighting).
2	Material	The material from which the component is made, e.g. 2.1 concrete (plain or reinforced), 2.2 steel, 2.3 timber, and 2.4 glass. In each case, a quality would need to be specified, especially strength grade for the structural materials.
3	Deployment	The structural form or class in which the component was previously used, e.g. 3.1 domestic housing, 3.2 high-rise housing, 3.3 commercial, 3.4 industrial, 3.5 infrastructure.
4	Exposure	The environmental conditions to which the component has been subjected, e.g. 4.1 outdoor, 4.2 indoor, 4.3 marine, 4.4 chemical/corrosive, 4.5 high temperature. These conditions would be associated with quantifications (e.g. weather records, detail of chemical environments, Eurocode EN1992 exposure classes) where appropriate.
5	Loading	The loading history of the component, e.g. 5.1 static loading (live and/or dead), 5.2 fatigue loading, 5.3 impact or transient loading. Each would be associated with a quantification of the loading history where appropriate. For functional components, loadings might be expressed in other terms (e.g. electrical, traffic).
6	Recovery	The methods used to recover the component, e.g. 6.1 general demolition, 6.2 recognised demolition protocol, 6.3 component-specific recovery, 6.4. DfD/DfR/DfMA process. In each case, a likelihood of damage or contamination should be associated or specified.
7	Residual	The structural and functional properties of the component remaining, e.g. 7.1 dimensions, 7.2 structural capacity, 7.3 functional capacity. In each case, it should be specified whether the residual has been directly measured (and how) or inferred from nominal capacity adjusted for age, exposure and loading.
8	Connections	The capacity of the component to be connected to other structural and/or functional components and artefacts, e.g. 8.1 standard connections (bolt or dowel holes, recognised electrical/hydraulic/communications connector), 8.2 no connector (e.g. where component has been sawn from a monolithic connection, or otherwise removed from a non-disassemblable original connection).
9	Availability	Details of when and where a component is likely to be available, and in what quantity, e.g. 9.1 time arising, 9.2 place arising, 9.3 amount arising, 9.4 market maturity.
10	Generation	The number of times the component has already been reused, and whether the proposed new use would represent upcycling, recycling or down-cycling/cascading.

components available to be matched against the proposed application; essential and desirable characteristics would have to be identified (and minimum performance standards quantified) in each case. Further research is required to establish these.

Standardisation of the size and connection details of structural components used would simplify the typology. This in turn would greatly limit the risks and hurdles associated with the reclamation and resale of construction materials and increase the likelihood of these materials to be reused in a variety of applications in the construction sector. While this is already partially in place in some systems (e.g. standard steel beam and column cross-sections with associated structural properties, see Tata Steel, 2016) in most cases (particularly for reinforced concrete) key properties such as section capacity, component length and connection details are usually bespoke for each structure. To achieve that however there is a need for policy makers, guided by architects and engineers, to revisit and revise building codes, specifications and standards in order to provide guidance to promote both new construction approaches based on e.g. DfMA, DfR and DfD to ensure that new components introduced into infrastructure are reclaimable and that reclaimed components are reusable, in order to enable the better management of resources and structures.

Therefore, policy has a key role to play in governing the transformation of the construction sector from being a heavy consumer to a custodian of resource. Incentives for e.g. carbon emissions reductions and inflation in e.g. landfill tax rates will drive reuse, and bring major reforms in the way construction materials are used, both upstream and downstream in the construction supply chain. Designing new infrastructure and redeveloping the existing with sustainability in mind can bring long-term benefits not only in terms of reduced material use and associated environmental issues, but also in long-term economic and social welfare. The role of policy will be to direct the generation and appropriation of this added value to spawn a new generation of business models, that seek to generate profit from innovative practices with sustainability at their core, hence setting the pathway for the development of secondary markets. A conceptual framework for preliminary guidance to the promotion of sustainability in the construction sector has been developed and presented below (Fig. 2).

A key aspect that must be addressed in promoting reuse is a change in the cultural mind-set towards reusing construction components, and the wider collaboration between all actors involved in the planning, construction, maintenance, refurbishment or deconstruction of a building. Both these are critical in making an impact through reuse. Independent, individual actions are proved unable to solve any of the problems that the construction sector currently faces, let alone the reuse issue. Only by taking a whole life perspective and understanding the problems from their many angles, and by tackling issues in collaboration can real transformations in this sector be achieved.

6. Conclusions

The potential for reusing construction components is acknowledged by the construction sector. Economic, organisational, political and technical factors currently impede this potential from being realised, rendering reuse largely unexploited. Despite a number of initiatives to unlock reuse being widely documented in the global literature, a lack of quantitative information restricts the demonstration of the real advantages to be gained. Research that can better highlight the economic, environmental, technical and social benefits of reuse would enable designers and contractors to get a better understanding of how changes in their current practices could optimise the recovery of value for their businesses through deconstruction and reuse. Education and training in the wider skillset associated with sustainable construction/deconstruction, combined with the right policy incentives and opportunities for market development would empower their active participation in reusability schemes. This would provide the right conditions for reuse to become a mainstream practice and for secondary markets that are vital for those practices to flourish, to be developed. But, while there is such lack of clarity on the properties and simplicity of form in the types of construction components used in the sector, there will be significant barriers to reuse. The development of a typology system is suggested as a way to provide some guidance when it comes to the specification of reusable components at the design stage, and the sorting and reuse of construction components at the recovery stage. Smart technologies carry the potential to help by providing efficient tracking, storage and archiving of component properties, but further research is required in order to investigate the opportunities and constraints of the use of these technologies.

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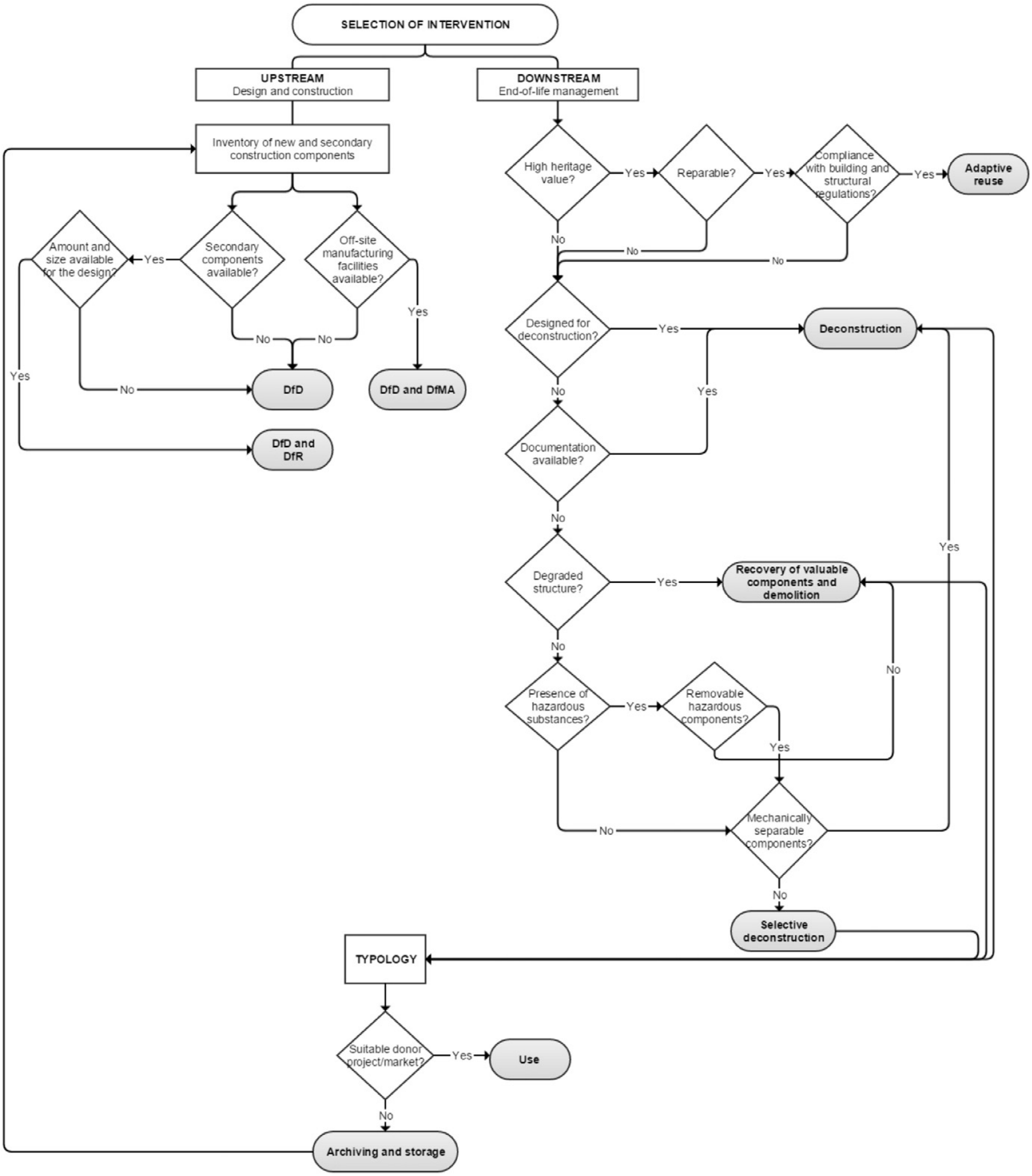

Fig. 2. Conceptual framework for intervention selection to promote sustainability in the construction sector.

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