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**Manuscript title:** Recovery and Re-Use of Structural Products from End of Life Buildings

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## Abstract

Buildings and construction have been identified as having the greatest potential for circular economy value creation. One source of value creation is to recover and re-use building products from end of service life buildings, rather than destructive demolition and downcycling. Whilst there is a trade in non-structural and heritage product recovery and re-use, the largest volume, mass and value of most buildings comprises structural elements - concrete, brick and masonry and steel, present many challenges. A comprehensive literature review confirms limited attention to innovation and advanced techniques to address these challenges and therefore the potential re-use of the stocks of accumulated building products globally and associated environmental benefits. Potential techniques being tested in an EPSRC circular economy research programme are referenced as a key building block towards circular economy building system re-design.

## Introduction

In a circular economy, growth comes from 'within', by increasing the value derived from existing economic structures, products and materials (EMF, 2015a) and innovation. Increased value in a circular economy, it is argued, derives from maintaining the integrity of a product at a higher level (technical and economic durability), using products longer (repeat use), cascading use in adjacent value chains and creating pure, high quality feedstock (avoiding contamination and toxicity). Various reports have identified construction and buildings as having the highest potential for circular economy innovation, value retention and creation opportunities (EMF, 2015b).

To achieve this industrial take-up, circular economy business models and product flows need to be more cost effective, deliver superior revenues or improve capital and resource productivity to beat the linear model.

In a future circular economy, all end of service life (EoSL) buildings will be material and product banks and deconstructable to retain high value materials and products and, given their bulk/value ratio, repair and remanufacture of products from EoSL buildings would be carried out and stored locally and then blended into new builds also locally to minimise cost. All this will create value, promote innovation and attract investment.

A major immediate seemingly intractable challenge however is that there is a huge legacy of materially intensive buildings and infrastructure not designed for the recovery and re-use of products due to technical, economic barriers including a lack of market mechanisms (Adams et al., 2017). This question then arises of whether it is 1) possible to extract more products and value from the stocks of such buildings at the end of their service lives and 2) whether the products can be re-manufactured and re-used in future buildings. If this is possible then the final question is 3) how to translate the potential of mining such buildings to create a new circular building construction system that co-ordinates and integrates key players and activities including, building and product design, dismantling and separation, high value remanufacture and market place exchange. The questions form the first part of a new EPSRC project **REgenerative BUILDings and products for a circular economy** - REBUILD (EPSRC EP/P008917/1) which is investigating novel techniques to the recovery of the most common building products from load-bearing structures: structural concrete components from reinforced concrete structures, steel from steel-concrete composite structures, bricks from masonry walls bonded by cement-based mortar. A fuller description of the project and some early findings is presented towards the end of the paper.

This paper reviews the state of the art on the topic and is structured as follows: Section 1 of the paper highlights the resource intensity of building and construction materials demand within the economy. Section 2 summarises the current state of the art and evidence on the feasibility of recovery and direct re-use of building structural products within new builds, key barriers and potential environmental benefits.

## Literature review method

A review of the academic literature was conducted with the *Web of Science* online database using search terms including ‘circular economy’, ‘steel’, ‘bricks’, ‘masonry’, ‘concrete’, ‘re-use’, ‘remanufacture’ and ‘recycling’ for articles between 2010-2017. These articles were examined for how the three core structural materials and their accompanying terms were presented in terms of their specific research context. The papers were then systematically grouped by frequency and key terms. The review generated produced 241 articles on aspects of brick recycling, 26 on direct brick recovery (mainly heritage bricks) and re-use, 6 related specifically to steel recycling from buildings, 13 on steel recovery and re-use and 188 articles on aspects of concrete recycling, 9 on direct concrete recovery and re-use.

### *Building and material stocks and flows*

Buildings and construction are major sources of economic activity, employment and material throughput globally. The sector is also very wasteful, with estimates in the UK for example of between 7-15% products not being used in the final construction, much of it landfilled (Adams, 2013).

Over the past century the overall use of construction materials has increased by a factor of 42, the same period has seen a 23 fold increase in the accumulation of materials (792 Gt) within stocks of buildings and infrastructure (Wiedenhofer et al., 2015; Krausmann et al., 2009, 2017). In China for example stocks increased by a factor of 5 between 1978-2005 accounting for 55% of global production of cement in 2010, and will likely double in the next 30 years (Ecorys, 2014). In-use stocks of non-metallic minerals are also high for example 294 tonnes per capita population (t/cap in Japan and 337 t/cap in USA. In Japan 43% of in use stocks are contained within buildings (Hashimoto et al., 2009). Studies at European scale shows non-metallic minerals in UE25 building stocks are 72 t/cap whilst in and outflows of construction materials remain significant (e.g. 2.6 t/cap in Paris, 6.5 t/cap Vienna) and stock accumulation remain high (1.1 t/cap Paris, 5.5 t/cap Vienna).

Globally, around 65% of total aggregates (sand, gravel and crushed rock) and approximately 20% of total metals are used by the construction sector to create the built environment. Within construction, concrete, aggregate materials (sand, gravel and crushed stone) and bricks make up to the 90% (by weight) of all materials used. Around 25% of all steel, 75% all concrete, 65% all aggregates, 70% all bricks are used for buildings (Ecorys, 2014). In Europe between 30-50% (different sources give different numbers) of total material use goes to housing and mainly consists of iron, aluminium, copper, clay, sand, gravel, limestone, wood and building stone (Herczeg et al., 2014).

Construction materials in many parts of the world are also increasingly scarce. For examples, the world demand for sand is outstripping supply leading to ‘peak sand’ and concerns about the damage to river and ocean eco-systems in Africa and elsewhere from illegal or poorly managed sand dredging to supply global markets (UNEP, 2014).

The UK is largely self-sufficient in certain building materials, such as sand, which may contribute to the lack of incentives to address resource scarcity and promote reclaim and re-use models. Reclaim and re-use could contribute to the UK demand of around 400 Mt of new materials each year for new, replacement or maintenance of infrastructure and buildings. Approximately 50,000 buildings are demolished each year, generating 45 Mt of construction and demolition (C&D) waste, the majority of this are concrete, masonry, bricks, and steel (Adam, 2013). However, market conditions, low productivity and lack of capabilities and skills contribute to the downcycling of materials and destruction of potential value at the end of service life.

Three recent studies, one in Melbourne (Stephan and Athanassiadias, 2018), Rhine Maine (Schebek, Schnitzer, Blesinger et al., 2017) and Rhien Ruhr region (Oezdemir et al., 2017), offer detailed analysis of buildings at city and regional scale. In the case of Melbourne, across 14,385 buildings concrete dominates the mass of material stock (92%) and also C&D waste (78%). In the Rhine Main region, a detailed study of 19 typical examples of 6,000 non-residential buildings, showed concrete and bricks combined account for approximately 73% of material composition. The Rhine-Ruhr study comprised 179 residential buildings with a building gross area of 25,985 $m^2$ and total material stock of 2,315 tons per capita consisting of 48.5% concrete, 22.2% bricks, and 3.5% metal. A further material analysis calculated sand and gravel contributed 70.3%, marl and clay 14.75%, and cement approximately 9.3% of the mass.

The figures confirm buildings as a major stock of materials, which continues to accumulate. These materials will be released through time as buildings come to their end of service lives. However, recycling of construction materials will downgrade performance (Augiseau and Barles, 2017). The challenge then is to find different ways to meet the future demands for construction products by reusing existing products to reduce pressure on supplies and externalities. Some high-level principles, key building blocks and spatial configurations for systems level re-design for buildings and construction have been set out in Growth Within (EMF, 2016) and Amsterdam City study (Circle Economy, 2016). A better approach higher up the value chain is to reclaim and remanufacture products and re-design the construction system to achieve superior economic, material and social value against a base linear case.

*Recovery and re-use of building products*

The potential benefits of recovering and re-using building structural products is an attractive proposition, for a variety of reasons. Building products are a high percentage of construction cost and have high embodied energy (Bribian et al., 2011). Steel and aluminium together are responsible for approximately 51% of the total embodied energy in building materials with concrete responsible for another approximately 17% (Diener and Tillman, 2015). Whilst the direct maintenance and re-use of products has significant environmental benefits over recycling only a small percentage in the UK (approximately 3 Mt) are reclaimed for direct re-use, mostly for heritage products or easily demountable structures such as steel sections from portal frames (around 4% of all steel in buildings is re-used vs 92% recycled). In the case of brick, concrete, other masonry, the figures for direct re-use are even lower.

If building product could be recovered directly and re-used cost-effectively, rather than recycled, it could offer both cost and multiple resource and environmental benefits. As an example, steel re-use in the UK is profitable at recovery cost below £200-400 per tonne (Newman, 2016). The challenge however is that the majority of existing buildings were not designed for adaptation, dis-assembly, or high value re-use. Whilst renovation and refurbishment is usually preferable from an overall materials or energy perspective (Crawford et al., 2015), there is a huge legacy of buildings where this may be technically difficult or not cost effective. Where a building is judged to be at the end of its useful or service life, demolition of buildings is often considered a cost to be minimized with speed of site clearance commercially critical. Moreover, despite having many innovative companies and products, the building and construction sector lack confidence in the performance of re-used product, such as steel (Dunant et al 2017) and cost of recertification, leading to limited demand and a business as usual approach. Given the majority of structural materials would be under working (elastic) load during their working life, they are fully capable of meeting engineering requirements and being re-used as new. Industry codes of practice or standards do not prohibit use of reclaimed products but without such a specific code or industry standard, designers and specifiers do not know how to deal with them.

There is a growing interest and practice in methods of design for deconstruction to ensure future circularity, although much of this focuses on using new materials and products, instead of using EoSL buildings as potential feedstock. In combination, these and other factors mean that the building and construction sector will continue to opt for demolition and recycling end of service life wastes (usually to create aggregate for on site back fill) unless new techniques and approaches to demolition and recovery become technically feasible and most importantly commercially viable.

The following section summarises some of the key challenges that need to be overcome for steel, concrete, brick and masonry recovery and the potential for new or novel techniques and system enablers that could create re-use of higher value.

## Steel

The issue of steel re-use and recycling have been increasingly addressed by researchers worldwide, especially in the steel industry (Broadbent, 2016; Wang et al., 2017), and manufacturing industry (Diener and Tillman, 2015; Dunant et al., 2017). However, whilst the combined rate of re-use and recycling of steel in the UK increased from 93% to 96% over the period from 2000 to 2012 (Sansom and Avery, 2014) this is dominated by recycling, with re-use being less than 4%. Although structural steel elements are inherently reusable with minimal reprocessing, reclaiming structural steel elements from existing buildings pose significant technical challenges. Structural elements where steel is used are rarely made of steel only and are usually composite steel/concrete construction. Webster and Costello (2005) suggested that composite construction is a barrier to deconstruction and recommended that it should be avoided in design for deconstruction. In this type of construction, the steel product is connected to the concrete via welded shear studs. Separating structural steel elements from concrete requires further research (Rehman et al., 2017), however, it is expected that re-use would change the way the construction sectors operate and create new business developments (Lacovidou and Purnell, 2016).

For steel re-use to become widespread and scale, various practical barriers have been identified, i.e., cost of recovery, availability/storage, demand, traceability and supply chain gaps/lack of integration (Tingley et al., 2017). Dunant et al. (2017) highlighted similar issues and the importance of collaboration between contractors, stockists and fabricators to facilitate steel re-use economically. They also pointed out that a market for reusing steel can exist on condition that the selling reused steel is more profitable to stockists than selling scrap. Dunant et al. (2018) highlighted that the supply chain should include specialised stockists to make the market for steel reuse more favourable. Techniques such as semi-automatic geometric characterization have also been proposed as key requirements to increase steel re-use (Yeung et al., 2015). Smarter technologies and alternative business models have also been recognized as key to support the practice of steel re-use (Ness et al., 2015). A core challenge in steel building product re-use is testing and verification of material properties. Research in this field is limited. Fujita and Masuda (2014) proposed a non-destructive evaluation procedure for determining the steel grade to re-use steel structural members. Through a case study, it was shown that accurate tensile strength and chemical compositions could be derived from non-destructive tests. These values were evaluated against the Japanese codes, and found to be consistent with the design specification.

### Brick

It is estimated that around 2.5bn bricks in the UK (Bioregional and Salvo LLP, 2008) are demolished annually, although <5% of these are reclaimed for re-use. Many of these bricks are crushed long before the end of their technical life losing their embodied energy and other natural resources (Thormark, 2000). Approximately 50% are under hybrid recycling i.e. crushed along with other masonry materials and used in hardcore and fill.

Brick construction is typically made of bricks bonded by mortar. The two mortar types are lime-based mortar and ordinary Portland cement (OPC)-based mortar. Lime-based mortar is commonly used in historical masonry buildings. It also degrades over time. Therefore, after a long period of time in use, lime-based mortar will have little residual bond strength and it is relatively easy to separate bricks with lime-based mortar. The majority of research papers on brick re-use address the dating, recovery and re-use of heritage bricks from lime-based mortar (Cristini et al., 2014; Serlorenzi et al., 2016; Bouvier et al., 2013; Pesce et al., 2013; Quagliarini et al., 2014; Gorgolewski, 2008; BDA, 2014). Sisti et al. (2016) has introduced a retrofitting technique for masonry buildings by a ring beam made of re-used bricks. Thormark (2000) reported that about 85% of the bricks with lime-based mortar can be perfectly separated. The rest can be assumed to be damaged and therefore only suitable for material recycling as a substitute for natural gravel. The ICE Demolition Protocol (2008) states that bricks have a recovery potential of 10% - rising to 100% in some buildings. BDA (2014) concluded that 'the use of reclaimed bricks should not be discouraged provided that users are conscious of their qualities and the associated property testing of re-used bricks is required…. Their high cost is a reflection of demand and the cost of reclamation…'. Currently, the removal techniques of lime-based mortar are mostly manual, using a heavy/brick hammer and broad cold chisel or bolster (BDA, 2014), demolition hammer, or brick cleaner machines (Paoloni, 2017). Although these methods are very time-consuming, they are at least technically feasible, even though it is not practical for them to reclaim on a brick-by-brick basis (Yeap et al., 2012). Recent projects such as REBRICK (2013) have shown the potential for recovery of bricks from lime mortar by an automatic brick-cleaning system.

The above methods will neither be possible nor ideal to reclaim bricks with ordinary Portland cement (OPC)-based mortar commonly used in contemporary masonry buildings because the mortar retains very high bond strength and is much harder to be removed (Hobbs and Hurley, 2001).

Concrete

As previously described concrete forms the largest proportion of building stocks. The current dominant end of life scenario for concrete buildings and its elements is demolition well before the material technical end of life (Asam 2007). Concrete structural elements are difficult to reclaim (Durmisevic, 2010) hence there has been a greater focus on recycling rather than re-use. In some cases the demolished concrete passes through a recycling process in which it is crushed to separate reinforcing steel, the resulting crushed material is used for example for road beds. Methods and techniques to increase the quality, durability, and tension stiffening properties of recycled concrete is widely researched, (Kisku et al., 2017; Rangel et al., 2017; Xiao et al., 2016). The applications of recycled concrete blocks, characterized by larger size than conventional recycled aggregates, in composite structures have also been investigated (Chen et al., 2016). Reusing larger sized recycled concrete blocks is a half-way house between the conventional use of recycled aggregates and the ideal situation of using complete recovered concrete products. Given the current situation of relatively mature methods of recovering materials and challenges of reclaiming complete structural products, this may represent an immediately achievable practice of obtaining higher value use of recycled concrete.

To shift from recycling to reclaim and direct re-use requires new techniques. There are two generic types of RC structures: in-situ construction and pre-cast construction. In in-situ construction, the concrete of the building is cast together to form a monolithic mass. The only means of separating structural elements in such construction would be to cut through the structure. A further issue with reclaiming RC structural elements is their re-use. Due to flexibility of changing dimensions and the amount of reinforcement, RC structural elements do not have standard dimensions and standard reinforcement amount and layout. This makes it difficult to join reclaimed RC structural elements.

In contrast, it is possible to reclaim RC structural elements from prefabricated concrete structures because the prefabricated elements were assembled together in the first cycle of construction. Huuhka et al. (2015) has reviewed the re-use potential of over 26,000 prefabricated concrete wall panels and nearly 14,000 hollow-core slabs in Finnish 1970s mass housing, along with the review of technical prerequisites for re-use. The panels are found to be still usable in architectural (plan) design of detached houses, which form one third of annual residential production in Finland. In addition to having a very low carbon footprint, re-use of concrete panels reduced the cost of new construction by 20–30% (Huuhka, 2010a & b; Huuhka et al., 2015). Yeap et al. (2012) however highlights the costs of handling and storing concrete building components, which could make recovery and re-use uneconomic. To overcome this would require matching supply of reclaimed product with demand at local or regional level. One example of how this might be achieved is currently taking place in Kerkrade, Netherlands. This innovation project is aimed at 100% reusing and recycling of materials acquired from the demolition of an outdated 100 person social housing high-rise flat to create four new units co-designed with residents (UIA 2018).

In summary the review of the literature reveals much less attention has been given to structural product recovery and re-use compared to recycling. The available re-use literature has often considered structural elements to present intractable challenges hence little promotion of technical innovation and novel techniques. Early results from REBUILD are promising in showing the potential to reclaim structural elements. The shift from recycling to re-use however is not just simply a technical challenge but requires analysis of whether the effort is justifiable in terms of environmental savings.

### Environmental impacts

The reduction, re-use, recovery and recycle of EE/EC (embodied energy/embodied carbon) intensive construction materials/products was one of the main embodied carbon mitigation strategies proposed by Pomponi and Moncaster (2016). However, research on the comparative environmental performance of the re-use of structural building materials versus recycling and virgin product is fragmented and sparse. In contrast there is a strong research literature comparing recycled versus new with mixed conclusions, depending on the nature of the product. It is not always the case, for example, that recycling has a better overall energy and carbon performance than using virgin materials such as the case with recycled concrete (Huuhka et al., 2015), although much effort is exploring new techniques to improve processes. Other studies however have shown the life cycle impacts of recycled concrete to be lower compared to conventional concrete (Knoeri et al., 2013).

Virgin steel, brick and concrete are energy and carbon intensive products which have used a great deal of energy during manufacture (Berge, 2009). Table 1 illustrates the range in embodied energy in MJ/kg from selected studies for these products, which vary significantly around the overall average. The percentage contribution of total embodied carbon and energy attributable to each life cycle stage of the products and the building can be identified by a new designed tool (Moncaster and Symons, 2013).

The number of studies comparing steel re-use to recycling is limited. A case study of re-use of steel structures without melting, demonstrated that this re-use of steel could allow for 30% saving in energy and $CO_2$ reduction (Pongiglione and Calderini, 2014). A complete 3250 $m^2$ steel frame warehouse relocation in the UK demonstrated both the technical feasibility of deconstruction and re-assembly and an overall 38% carbon reduction compared to a benchmark building (SEGRO, 2013), a figure similar to an earlier steel re-use study (Gorgolewski et al., 2006). Studies on re-use of bricks are equally limited. The REBRICK study estimated each re-used brick will save 0.5 kg of $CO_2$ emissions compared to building with new bricks (REBRICK, 2013). A US study estimated that the percentage of source reduction of bricks that occurs when reusing bricks can be 0.0788 MTCE (Metric Tons Carbon Equivalent) per ton (U.S. EPR, 2003).

Environmental life cycle assessment of concrete is more widespread. Concrete has relatively high embodied energy due to the use of clinker in its component which creates one ton of $CO_2$ per each ton of clinker (Cabeza et al., 2013). A study comparing new versus re-used precast double-T concrete reported 1.23 GJ of energy savings, 147 kg reduction in $CO_2$ production, 50% reduction in water and air emissions per $m^3$ product (Catalli, 2009). Glias (2013) compared re-used concrete components compared to recycling or virgin sources (Figure 1).

In Figure 1, recycling concrete 1,2,3 refer to 3 types of mix for recycled concrete; Gravel concrete, Crushed stone, and Site-mixed concrete refer to 3 types of new concrete; Re-used concrete component refer to re-used concrete prefabricated part. When comparing the recycled concrete mix 3 with the new concrete a 50% reduction in primary raw materials is observed for the recycled concrete but on the other hand there is no improvement on the energy values. Re-use is between 92-97% lower than recycling in primary energy and global warming potential (Glias, 2013).

## REBUILD

The REBUILD project is designed to translate the potential of building product re-use to reality. Funded by EPSRC this project seeks to connect two ends of the buiding and construction value chain to overcome many of the barriers previously cited. Achieving this requires a new circular building construction system that co-ordinates and integrates key players and activities including building and product design, dismantling and separation, high value remanufacture and market place exchange at a regional scale to capture the potentials for circular economy innovation, value retention and creation opportunities (see Figure 1). REBUILD focusses on the major challenge of legacy buildings and the potential to create value from remanufacturing products of buildings at end of service life (EoSL) into high value durable products with minimal re-processing for new builds, which themselves should be designed for future deconstruction and product re-use, and the system innovations required at regional scale. The focus of the project is three Northern Cities, Manchester, Leeds and Bradford.

The objectives of the project are:

1) Systematic understanding and modelling of the quantities of building product within current and future EoSL building stocks and barriers to re-use (WP1); 2) New demolition, separation, repair and remanufacture techniques(e.g 3D printing) that lead to the maximum amount of reusable components at the highest value (WP2); 3) Quantify the re-use potential, material and environmental impact, cost avoidance and value creation potential for each category of re-usable product against new product for different categories of new build (WP2 and 3); 4) Define and optimise circular system elements (building design techniques, product choices, fabrication centres, upcycling facilities, logistics, resource bank storage, market-places, and future construction locations, locations of product repair and re-manufacture techniques) configurations and arrangements that will create opportunities for value creation and capture, and how this affects decisions about the pathways of re-usable product and their impacts (WP3).

The project is at an early stage. Table 2 summarises some of the key year 1 activities and early findings to asses the potential stocks of reclaimable products and address the technical challenges for reclaim and re-use of steel, concrete and brick. The analysis and innovation of economic, legal, environmental and wider system requirements to make the shift to a circular economy system will build on these stages.

## Conclusions

Construction minerals account for the highest extraction rate of raw materials worldwide and buildings present the largest material stock. To create a circular economy building system requires an ability to closely couple the recovery and re-use of products from end of life buildings to stock replacement and maintenance. The majority of research on the re-use of structural materials from end of life buildings has focussed on methods to improve quantify of recycling rates and quality, rather than product recovery and direct re-use. As a result, little attention has been given to the LCA environment benefits of re-use rather than recycled or new product (Tingley and Davidson, 2012). Where studies have been conducted the evidence demonstrates the significant energy, carbon and resource benefits of re-use.

In a circular economy building and construction system demand will be created through a combination of factors including efficient and proven techniques for selective deconstruction and segregation of products, cost-effective remanufacturing and re-use certification processes that creates competitively priced products, and breeds confidence coupled with building designs that are better equipped to incorporate re-used products and shifts in procurement policies and regulation to stimulate re-used product. Individual innovations such as on-line market places and exchanges for building wastes and products (e.g. Enviromate, RECIPRO, Construction Material Exchange), product tracking and monitoring such as material passports, amended LCA tools (e.g. EN 15804), and BIM for manufacturing and manufacturers (BIM4M2), have a contributory role in accelerating an effective end-to-end product re-use system.

The focus of this paper has been concrete, brick, masonry and steel which represent the largest mass of structural products in the majority of buildings globally and by far the largest percentage of C& D waste, much of it downcycled at the end of building service life. For high volume and high value structural product re-use to become mainstream in the UK building construction industry, it is imperative that the barriers to deconstructing EoSL buildings, including masonry with cement-based mortar, reinforced concrete, steel/concrete composite structures, which account for the vast majority of UK building construction tonnage and cost, must be overcomed.

For reinforced concrete structures, reusing larger recovered concrete blocks may solve the problem of labour intensity and downgraded performance associated with recycling and overcome the technical challenges associated with recovering and reusing complete structural products.

Further converting the current linear life cycle model of structural elements to a circular one requires new ways of designing structures and buildings to support disassembly potential for re-use and adaptation, where elements such as frames, wall panels, roof slabs, and even columns and beams can be disassembled without material loss or pollution to be re-used in extending existing building or in the production of new ones. (Salama, 2017)

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**Table 1.** A comparative embodied energy analysis of virgin steel, brick and concrete

| **Selected source** | **Embodied energy: MJ/kg** | | | **Region** |
|---|---|---|---|---|
| | **Steel** | **Brick** | **Concrete** | |
| Australia Government, 2018 | 38 (Galvanised) | 2.5 | 1.5-2.0 | Australia |
| Tectonica-online, 2018 | 35<br>(20% recycled) | 2.9-3.0 | 1.0-1.1 | - |
| Hammond and Jones, 2011 | 35.4 | 3.0 | 0.7-1 | UK |
| Arc Architects Ltd., 2006 | - | 3.8<br>0.5 (unfired) | - | UK |
| Berge, 2009 | 25 (Galvanised) | 3 | 1.5 | Norway |
| Alcorn, 2003 | 31.3 | 2.7<br>0.1 (unfired) | 0.9–1.4 | New Zealand |
| All database sources | 25-38 | 0.1-3.0 | 0.7-2.0 | |

**Table 2.** Summary of key activities from REBUILD project

| Challenge | Activity and potential solution |
|---|---|
| Evaluting total stocks and flows of structural construction materials | Local authority data sets, land-use statistics, google earth, 4D visualisation modelling and building typopolgies are being used to estimate total stocks of brick, steel, concrete at regaionla scale and small scale sample sites for most common building types/ages |
| Overcoming the challenges of steel reclaim and re-use | Using laser to cut the welded shear studs to separate steel and concrete in composite construction. |
| Reuse of reinforced concrete elements | Technical feasibility of joining reclaimed RC elements, e.g. by cutting slots in reclaimed RC elements to accommodate reinforcement link bars. |
| Repair of concrete elements | 3D printing |
| Overcoming the challenges of brick/concrete masonary recovery | Lab scale development of punching and saw cutting to reclaim cement bonded bricks has demonstrated the technical feasibility of these approaches. The next step is to prove their commercial viability by improved design and machinery implementation. |
| Creating new products to facilitate deconstruction of future composite steel and concrete construction. | A new form of demountable shear stud to replace the traditional welded stud is being investigated and tested. |
| Creating higher value products to improve economics of reclaim. | Technical options for remanufacturing the brick into higher value products such as brick slips as facades for modern construction systems. |
| Comparative environmental assessment of virgin versus recycled versus re-used products at regional scale | Initial work on product versus product LCA comparison is underway. Novel regional scale LCA and circularity metrics are being developed to enable regional, whole system comparisons. |
| New codes and industry standards to build confidence | Mechanical and durability properties of reclaimed materials will be compared to new ones and draft design codes and standards produced. |

**Figure 1.** Environmental impact comparison of the production (up to the factory gate) of a cubic meter of building material of new, recycled and re-used materials (Glias, 2013)

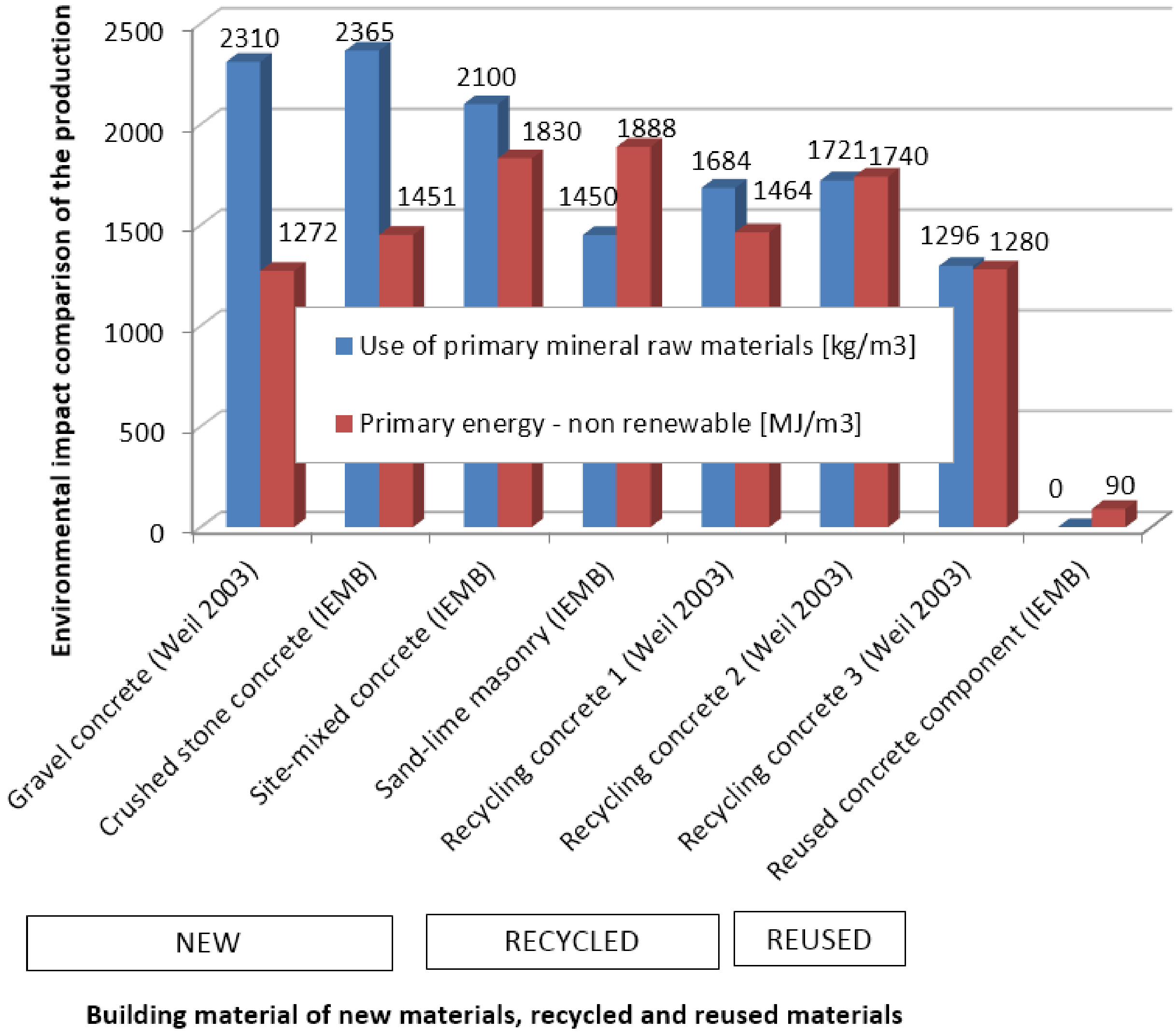

**Figure 2.** Visual overview of REBUILD project