PAPER • OPEN ACCESS

REBUILD: Regenerative Buildings and Construction systems for a Circular Economy

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 642384.

REBUILD: Regenerative Buildings and Construction systems for a Circular Economy

Atta Ajayabi[1], Han-Mei Chen[2], Kan Zhou[3], Peter Hopkinson[1,4], Yong Wang[2] and Dennis Lam[3]

[1]Exeter Business School, University of Exeter, United Kingdom
[2]School of Mechanical, Aerospace and Civil Engineering, University of Manchester, United Kingdom
[3]School of Engineering, University of Bradford, United Kingdom
[4]Author to whom any correspondence should be addressed

p.hopkinson@exeter.ac.uk

Abstract. Buildings and construction have been identified as having one of the greatest potential for value creation and capture from the application of circular economy principles. To achieve this requires a fundamental transformation in the recovery, remanufacture and re-use of end of service life structural products such as steel, bricks, concrete which make up the largest proportion of materials. At the same time these products must be re-used in new buildings and infrastructure designed for subsequent deconstruction and disassembly. REBUILD is a 3 year way UK research project to address this challenge. Initial findings on quantifying the material intensity of buildings (stock and flow assessment) are presented based on one of our case study cities. Results from new techniques to separate and reclaim bricks from cement mortar shows technical feasibility and ability to retain structural performance. Details on the next stage of scaling this work and techniques for separating and reclaiming steel and concrete are briefly described. Subsequent stage of life cycle assessment, value stream mapping and creating products for new forms of circular building and construction systems are also described. The paper concludes that whilst there are considerable challenges in reclaiming structural products that re-designed circular building and construction system could transform the value of end of service life buildings and the offers new opportunities for circular innovation and the circulation of materials and products at their highest value for the longest period.

Keywords: Circular Economy, Buildings, Stocks, Structural products, Re-use

1. Introduction

This paper presents the findings from the first stage of a 3 year UK National Engineering and Physical Science and Research Council project, focussing on the major challenges of translating the principles of circular economy into the building and construction sector. The focus of this paper is 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 to achieve this. This will require new approaches to product reclaim and remanufacture and demonstration of the technical feasibility and superior economic, material and social value from such a re-design against the base linear case. The paper presents initial findings from city scale case studies including:

- Systematic understanding and modelling of the quantities of building product within current and future EoSL building stocks and barriers to re-use,
- Initial results from Lab scale demonstration of new demolition techniques for separation, repair and remanufacture of building components that lead to the maximum amount of reusable components at the highest value,
- The next stage challenge of quantification of 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.

In a circular economy, growth comes from 'within', by increasing the value derived from existing economic structures, products and materials [1]. Increased value in a circular economy 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). To drive value and support 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. Construction and buildings have the highest potential for circular economy innovation, value retention and creation opportunities [1]. To translate potential to reality 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. REBUILD responds to the challenge to bring together key players in building construction and ownership e.g. design, demolition, finance, maintenance, manufacture etc., at a regional scale to capture potential for circular economy innovation, value retention and creation opportunities. REBUILD focusses on the major challenge of legacy buildings and the potential to create value from remanufacturing products of buildings at 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. For the majority of key building structural and non-structural products (concrete, brick, composites, masonry, and steel) many challenges have to be overcome in order to realise this vision.

This project aims to bring together key players in building construction and ownership e.g. design, demolition, finance, maintenance, manufacture etc., at a regional scale to capture potential for circular economy innovation, value retention and creation opportunities. The underpinning logic of this project is identification of new deconstruction techniques combined with technological developments allowing immediate "on site" or local re-manufacture of new products (concrete, brick and steel) for new buildings coordinated within a circular building-for-deconstruction system, where the key elements are arranged at a variety of spatial scales. REBUILD addresses the following four major technical and system design challenges: 1) Systematic understanding and modelling of the quantities of building product within current and future EoSL building stocks and barriers to re-use; 2) New demolition, separation, repair and remanufacture techniques that lead to the maximum amount of reusable components at the highest value; 3) Quantification of 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; 4) Defining and optimising 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.

2. Estimating Stocks of buildings and structural products

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 [2].

Buildings are a major stock of materials, which continues to accumulate.

The estimation of stocks of building products and their potential release rates is a fundamental first stage element of a circular building and construction system re-design. It requires estimations of building numbers, their ages, construction type and product/material choices. REBUILD focuses on two building types - commercial office (steel frame, masonry) and housing (brick and masonry) that form approximately 80% of UK floorspace and contain large quantities of our three primary building products. Material and product intensity is estimated using approaches adapted from previous studies such as [2], coupling typical structural details and material intensities per floor space and period (for example see [3]) and spatial databases of building and settlement patterns. Several recent studies have shown the potential volume and proportion of materials within building stocks [3,4,5]. A study of 14,385 buildings in Melbourne has shown that concrete dominates the mass of material stock (92%) and also construction and demolition (C&D) waste (78%) [34]. A more granular assessment of 19 archetype non-residential buildings in the Rhine region found that concrete and bricks combined accounted for approximately 73% of material composition [4]. A further study in the Rhine region analysed 179 residential buildings in the area Rhine-Ruhr and found a total material stock of 2,315 tons per capita consisting of 48.5% concrete, 22.2% bricks, and 3.5% metal [5]. None of these studies considered the technical feasibility of whether those building products could be reclaimed and re-used in subsequent structure.

REBUILD has adapted and integrated the methods used in these and related studies [6,7] with data sets to model and estimate building volumes, surface areas and material intensity at scale (Figure 1). The Spatial analysis involves integrating the Ordnance Survey (OS) dataset of buildings, heights and addresses into Historic Landscape Classification (HLC) dataset of sequential land use model. This would render a dataset of growth of stocks over time. The dataset in enhanced by 3D visualization to facilitate understanding the quantities and their locations, as well as management of the data (Figure 2). Initial analysis was performed for the metropolitan city of Bradford (population 550,000) and the HLC and OS datasets were integrated in order to create a spatio-temporal dataset. The data was then projected on a spatial map and building height data added in order to create a 3D map. Fig 4 shows the 3D visualization of the model for a brick housing estate.

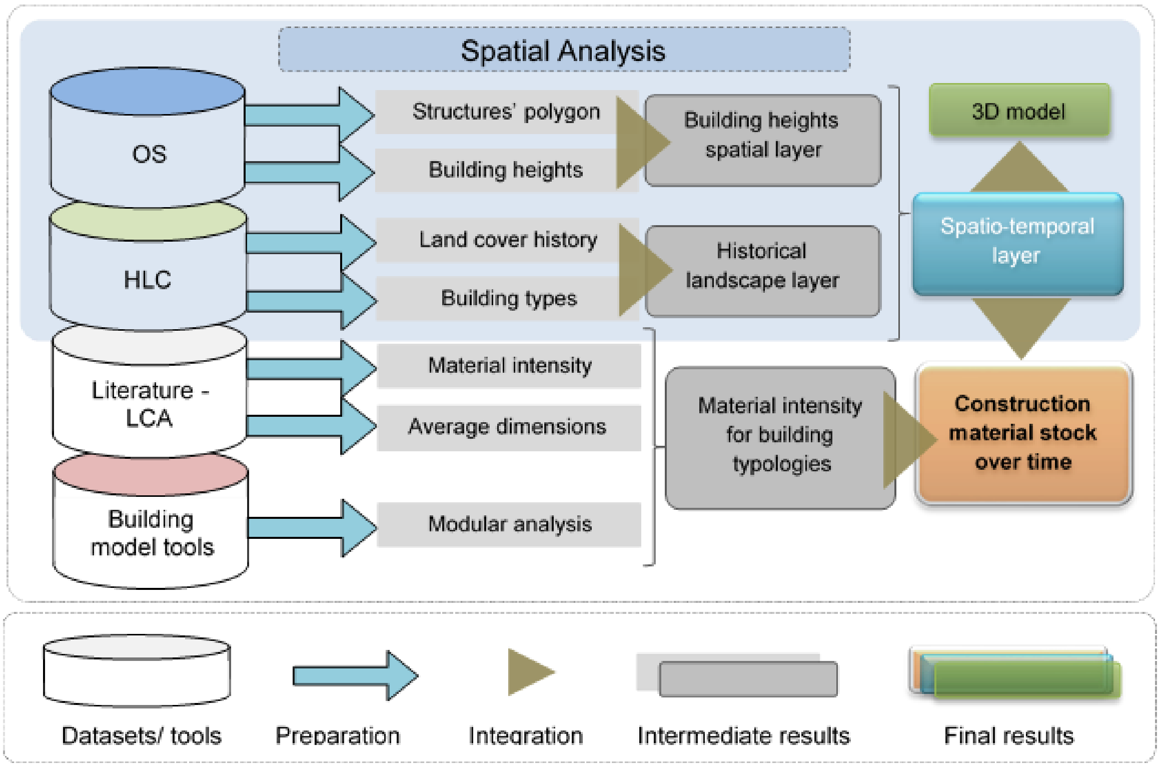

Figure 1. Structure of the methodology of dataset development of REBUILD construction material stocks.

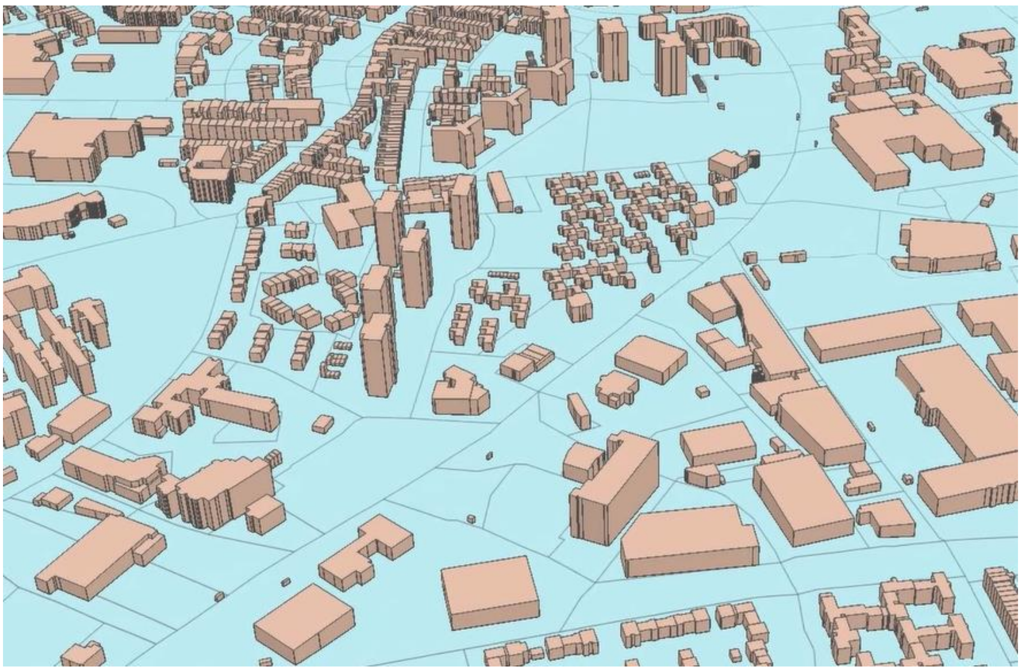

Figure 2. A snapshot of the REBUILD 3D model from central Bradford.

IOP Conf. Series: Earth and Environmental Science 225 (2019) 012015 doi:10.1088/1755-1315/225/1/012015

A case study of a semidetached house on a large social housing estate (Canterbury, BD5 9LR) has been studied. Most of the buildings in this estate were constructed between 1933 and 1938. The dimensions as measured from the OS map are as follows: Area: 68.54 m^2, Perimeter: 34.24m, Relevant height: 7.6 m, Maximum relevant height: 9.6 m. Subsequently, the area of the external walls is estimated to be 260.2 m^2. 3D images are also extracted from the Google 3D model and the dimensions are spatially compared to the REBUILD's 3D model and the dimension are validated (Figure 3).

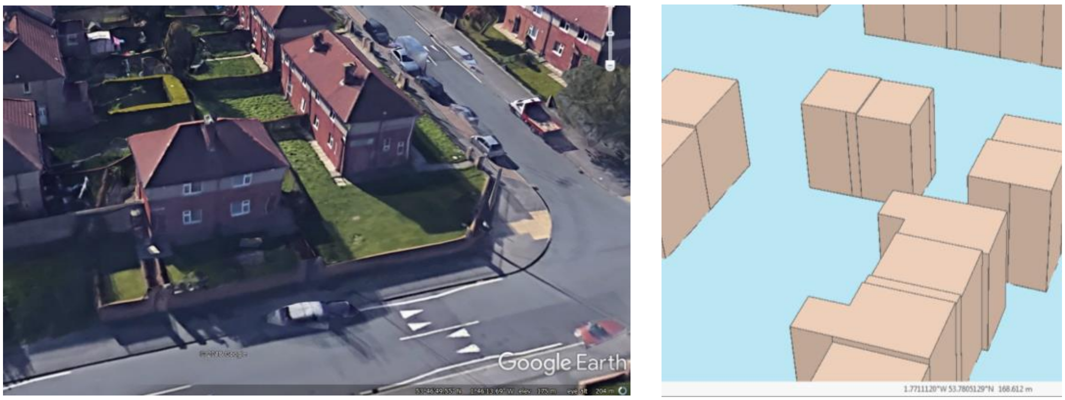

Figure 3. 3D imagery of the case study semi-detached building from Google Earth and the REBUILD 3D model.

A range of standard tools (e.g. Jewson on-line calculator https://www.jewson.co.uk/working-with-you/for-self-builders/preliminary-planning/calculators/brick-calculators/) for initially estimating the volume and numbers of bricks per sq. m external façade have been used to quantify the number of bricks per residential unit and then in total across the entire estate. Our analysis demonstrated that the case example building - an average semi-detached house (single) has about 7650 bricks in the external wall, with a current market value of £5730 assuming 75p per brick. We are currently validating these with on-site field studies and for a range of different building types including high and low rise concrete and steel framed residential and commercial buildings.

At the point of end of service life, most buildings and their structural products will typically be demolished using destructive techniques -much of the material being downcycled as aggregate/backfill or sent to landfill. Having assessed the material intensity of different buildings REBUILD is then looking to assess the potential to recover and re-use or remanufacture brick, steel and concrete product at a higher value than the current demolition systems. The aim of this task is to map value streams of current building construction demolition techniques, business models and end of life pathways for materials and products. The challenges of applying VSM to REBUILD include 1) the complexity and wide range of the products and materials and their condition 2) the lack of prior examples of costs of remanufacture of product 3) the range of uncertainties about recovery potential 4) absence of markets to derive reuse and resale values. Before we can do this however requires demonstration of whether it is technically possible to recover the most common construction products.

3. New techniques for the separation and reclaim of structural product

The relatively small literature on the recovery of bricks from concrete mortar has generally concluded that it is not feasible without damaging the bricks. REBUILD laboratory research has demonstrated the feasibility of reclaiming bricks with two methods, i.e. saw-cutting and punching. For the saw-cutting method, the diamond blade runs along the mortar layer to separate each course. For the punching method, the punch hits through the mortar joint to separate adjacent bricks. Figure 4(a) and 5(b) show reclaimed bricks after these two techniques. Reclaimed bricks were able to regain their original appearance and integrity. But avoiding breaking the bricks and cleaning the remaining mortar were the two major challenges. At this trial stage, cutting through one mortar joint of 215 mm long with saw-cutting method took about 20 s, whereas, punching 215 mm long, 102.5 mm wide and 10 mm thick mortar took about 6 s. Nevertheless, the saw-cutting method could salvage up to 97.8% (178/182) of bricks. Laboratory trials are being carried out on full-scale (4 m long and 2 m high) masonry walls built to reflect one part of existing construction, as shown in Figure 5. These walls will be deconstructed into large panels first and the bricks in the panels will be reclaimed using the above two approaches. For deconstructing the walls into large panels, the first method will mainly adopt the saw-cutting method. The wall will be cut vertically into panels. Then, the panels will be further separated into individual brick units. In the other method, the wall will be pulled down. Then the punching method will be used to reclaim the bricks.

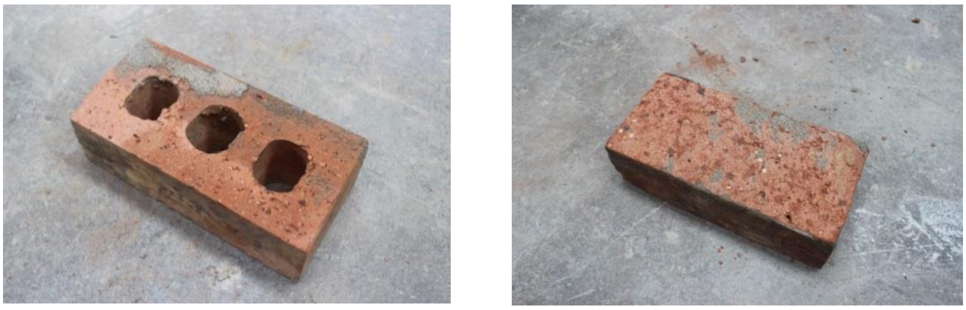

Figure 4 (a). Reclaimed bricks by saw-cutting method.

Figure 4 (b). Reclaimed bricks by punching method.

Figure 5. Full-scale masonry wall.

Another potential building product that can be obtained from saw-cutting method is brick slip. These brick slips can be manufactured from recovered bricks and have a retail value 3-5 higher than traditional bricks, thereby increasing their economic recovery potential. Brick slips of 10-20 mm have been demonstrated by saw-cutting (Figure 6). These brick slips can be used either individually or prefabricated into a panel with metal panel.

Figure 6. Brick slips obtained by saw-cutting.

A key concern about recovered structural products is whether they have a reduced performance and meet statutory standards. Compressive strength tests have been conducted on reclaimed bricks. As shown in Table 1. Results show that the reclaimed bricks have almost identical mechanical properties as new bricks. These results indicate that the reclaiming process has not degraded the mechanical properties of bricks.

Table 1. Preliminary performance data of new and reclaimed bricks by punching under uni-axial compressive strength tests.

Type No.	Perforated, 3 cores, Class B Engng Brick-65mm			Perforated, 5 cores, Sandown Red Facing Brick-65mm			Solid, Cheshire Common Brick-73mm		
	Density (kg/m^3)	σ_c (MPa)	STDEV	Density (kg/m^3)	σ_c (MPa)	STDEV	Density (kg/m^3)	σ_c (MPa)	STDEV
New	2138	63	3.9	2287	44	2.6	1957	30	2.6
Reclaimed	2108	60	5.1	2211	44	3.0	1936	30	3.5

Reclaiming steel members from composite steel-concrete structures is hampered by the difficulty of accessing shear connectors. REBUILD is currently testing a three-step process: (1) cut the floor slabs into strips using diamond saw cutting; (2) disconnect the steel/concrete composite beam from the frame; (3) cut the concrete attachment on top of the composite beam from the steel section. For this step, laser cutting is being explored. Laser cutting offers the advantage of precision and but a lack of direct access of the laser beam to shear connectors is the main challenge to be overcome.

4. Conclusion

The potential market for reclaimed, remanufactured and re-used product will be driven by many factors including rate of new build, building design and technical innovation. We are currently assessing future market potential to forecast the growth in building stocks (based on predicted need and forecasts) and secondly trends in building design and construction techniques (e.g. offsite fabrication, modular design) and product and manufacturing innovations (e.g. material choices, 3D printing) which will affect product choices and decisions. Other stages in the project involve comparison of the life-cycle assessment of reclaimed remanufactured products versus alternative ‘new’ virgin products.

The final stage of REBUILD will be to configure and model alternative system arrangements for capturing the value of re-used products and how this value might be distributed, and to evaluate outcomes and impacts against the base case system and how this might affect stakeholder decision choices in the future. There are four interrelated tasks and integrating all the stages above to assess potential scale of product re-use from current building stocks and its environmental benefit and value creation. To unlock re-use and value potential however will require significant changes in the configuration and interactions between different elements of the current building and construction system. 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[1,2,3] and Amsterdam City study[13]. REBUILD shares a similar vision to these proposals but will demonstrate how this can be achieved within a regional nexus for building construction products currently considered too difficult and hard to re-use. REBUILD is ambitious in undertaking modelling of the value creation of diverse, multiple EoSL building products into re-manufactured products and how this value will alter under different system arrangements, configurations and set ups. This work serves as the first stage in creating a longer term programme of research on developing a future circular building construction system.

5. References

[1] Ellen MacArthur Foundation 2015 Growth Within: A circular economy vision for a competitive Europe. Available from: http://www.ellenmacarthurfoundation.org/assets/downloads/publications/EllenMacArthurFoundation_Growth-Within_July15.pdf

[2] ECORYS 2014 *Resource efficiency in the Building sector*. *Final report* [Internet]. Available from: http://ec.europa.eu/environment/eussd/pdf/Resource efficiency in the building sector.pdf

[3] Stephan A and Athanassiadis A 2017 Quantifying and mapping embodied environmental requirements of urban building stocks. *Build Environ*. **114** 187–202

[4] Schebek L, Schnitzer B, Blesinger D, Köhn A, Miekley B, Linke HJ, Lohmann A, Motzko C and Seemann A 2017 Material stocks of the non-residential building sector: the case of the Rhine-Main area. *Resour Conserv Recycl.* **123** 24–36

[5] Oezdemir O, Krause K and Hafner A 2017 Creating a Resource Cadaster—A Case Study of a District in the Rhine-Ruhr Metropolitan Area. *Buildings*. **7**(2) 45

[6] Tanikawa H and Hashimoto S 2009 Urban stock over time: spatial material stock analysis using 4d-GIS. *Build Res Inf*. **37**(5–6) 483–502

[7] Mastrucci A, Marvuglia A, Popovici E, Leopold U and Benetto E 2017 Geospatial characterization of building material stocks for the life cycle assessment of end-of-life scenarios at the urban scale. *Resour Conserv Recycl*. **123** 54–66

Acknowledgments

We would like to thank the funding support of the UK Engineering and Physical Science Research Council (EPSRC) for REBUILD (2017-2020).