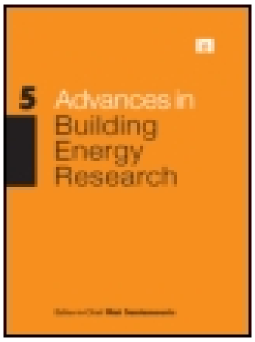

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Novel construction and demolition waste (CDW) treatment and uses to maximize reuse and recycling

Mark James Whittaker[a], Konstantinos Grigoriadis[a], Marios Soutsos[a], Wei Sha[a], Andrea Klinge[b], Sara Paganoni[b], Maria Casado[c], Linus Brander[d], Marjan Mousavi[d], Michael Scullin[e], Ruben Correia[f], Tommaso Zerbi[g], Giovanni Staiano[h], Irene Merli[i], Ilaria Ingrosso[j], Agnese Attanasio[j] and Alessandro Largo[j]

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ABSTRACT

The EU Waste Framework Directive 2008/98/EC states that all member states should take all necessary measures in order to achieve at least 70% re-use, recycling or other recovery of non-hazardous Construction and Demolition Waste (CDW) by 2020. In response, the Horizon 2020 RE^4 project consortium (REuse and REcycling of CDW materials and structures in energy efficient pREfabricated elements for building REfurbishment and construction) consisting of 12 research and industrial partners across Europe, plus a research partner from Taiwan, was set up. For its success, the approach of the Project was manifold, developing sorting technologies to first improve the quality of CDW-derived aggregate. Simultaneously, CDW streams were assessed for quality and novel applications developed for aggregate, timber and plastic waste in a variety of products including structural and non-structural elements. With all products considered, innovative building concepts have been designed in a bid to improve future reuse and recycling of the products by promoting prefabricated construction methods and modular design to ease future recycling and increase value of the construction industry. The developed technologies and products have been put to the test in different test sites in building a two-storey house containing at least 65% of CDW.

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CDW-derived materials; prefabricated structures; recovery; recycling; reuse

Introduction

Construction and Demolition Waste (CDW) constitutes the largest waste stream in the European Union (EU), accounting for more than 350 million tonnes/year excluding excavated soil and dredging spoil (European Commission, 2017). It consists of a heterogeneous mix of concrete, mortar, bricks, tiles, mineral aggregate, bitumen, ferrous, plastic, wood

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and organic lightweight particles (European Commission, 2018). Current building practices do not allow for ease of disassembly. After removing all building fixtures and fittings, a process known as soft stripping, the skeleton is effectively demolished and the CDW generated is disposed in landfills (Sassi, 2019). In addition, most recovered CDW is confined to low-value applications, e.g. pipe bedding or subbase and base course in road pavement construction, despite the fact that some of its constituents have a high resource value.

To improve the recycling rate of CDW in Member States (MS), the EU Waste Framework Directive 2008/98/EC (European Commission, 2008) was introduced in 2008. According to it, all MS should take all necessary measures in order to achieve at least 70% by weight re-use, recycling or other recovery of non-hazardous CDW by 2020. In addition, towards the end of 2015, the European Commission adopted a new Circular Economy Action Plan entitled 'Closing the loop – An EU action plan for the Circular Economy' (European Commission, 2015). The plan aims to give a new boost to jobs, growth and investment and to develop a sustainable, low carbon, resource efficient and competitive economy. The legislative proposals adopted within the document focus on changes in production and consumption behaviour through reuse and recycling, as well as waste management for reducing the amount of waste sent to landfills. This in turn, will close the loop of product lifecyles while supporting the circular economy in each step of the value chain. Additional measures are proposed to aid implementation, promote economic incentives and improve extended producer responsibility schemes (Dodick & Kauffman, 2017). The plan contains 54 actions which amongst other things include the following:

- Develop product requirements related to durability, repairability and recyclability under the Ecodesign Directive 2009/125/EC (European Commission, 2009).
- Clarify rules on by-products to facilitate industrial symbiosis where by-products from one industry become resources for another.
- Include guidance in Best Available Techniques Reference Documents (BREFs) (European Commission, 2010) for waste management and resource efficiency.
- Produce a new energy labelling system for products, with new durability requirements.
- Produce a study on planned obsolescence.
- Take action on Green Public Procurement by incorporating criteria on circular economy.
- Produce a study on repair information provisions under the Ecodesign Directive 2009/125/EC (European Commission, 2009).
- Revise waste legislation.
- Identify best practices in waste collection systems.
- Develop EU wide quality standards for secondary raw materials.
- Develop pre-demolition assessment guidelines for the construction sector.
- Develop a voluntary industry-wide recycling protocol for CDW.
- Develop core indicators for the assessment of the lifecycle environmental performance of a building as well as inceptives for their use.
- Support innovation and investment through 'Industry 2020 and the Circular Economy' initiative under Horizon 2020 Framework Programme for Research and Innovation.
- Develop a monitoring framework for circular economy.

In March 2019, the European Commission adopted a comprehensive report entitled 'On the Implementation of the Circular Economy Action Plan' (European Commission, 2019).

According to the above report, all 54 actions of the Circular Economy Action Plan have been delivered, even if work on some of them will continue beyond 2019.

Based on the above, the development of reliable strategies and innovative technologies is required in order to:

- Increase the percentage of CDW-derived materials in new residential construction.
- Increase the technical and economic value of CDW-derived materials.
- Minimize future CDW coming from the next generation of buildings.
- Increase building energy efficiency.

Prefabricated elements (structural and non-structural) which incorporate large amounts of CDW-derived materials can have a significant effect towards achieving the above objectives. This paper aims to provide an outline of the efforts of the RE^4 project consortium (RE4, 2019), one of six cluster projects funded by the Horizon 2020 Framework Programme in developing prefabricated building components which incorporate at least 65% by weight of CDW-derived materials while describing the challenges that have been faced along the way.

Reuse and recycling of CDW in structural elements

Recycled aggregates in concrete

Raw CDW first needs to be treated in order to become suitable for use as recycled aggregate. This involves removing unwanted fractions such as lightweight particles (plastic and wood particles), clay and soil, ferrous metals, rubber and gypsum. Once CDW recycled aggregate is obtained, it can be used in the manufacture of structural concrete. After treatment, CDW sourced recycled aggregate is made up of various constituents, included mineral aggregates partially covered in cement, mortar, bricks and tiles, and in lesser amounts glass, metals, and bitumen (Figure 1).

Currently, EN 206:2013 + A1:2016 (EN 206, 2013) and EN 12620:2013 (EN 12620, 2013) limit the amount of coarse natural aggregate that can be replaced by recycled aggregate in the production of structural concrete up to a level of 50%, depending on exposure

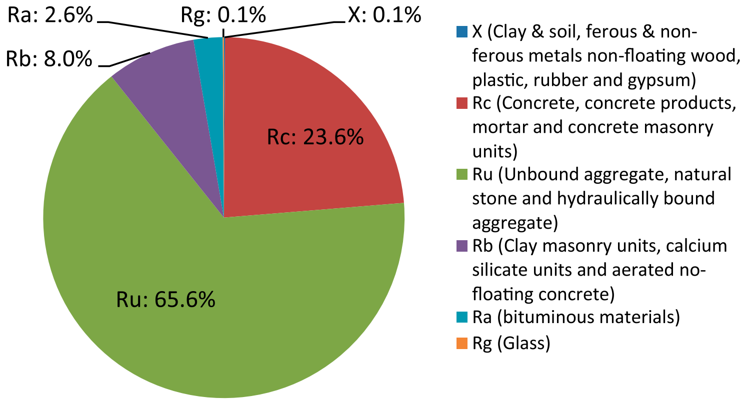


Figure 1. Typical composition of 8–16 mm processed recycled aggregate coming from a recycling plant near Marseille, France.

conditions. This is done to limit loss of workability, compressive strength, modulus of elasticity and long-term durability of concrete. Typically, recycled fine aggregates are not permitted in the manufacture of new structural concrete.

Timber

Structural timber sections hold great potential to be reused and recycled as a structural element, provided they satisfy the general requirements set out in EN 14081-1:2016 (EN14081-1, 2016) and EN 14080:2013 (EN 14080, 2013) for structural timber and glulam, respectively.

Timber holds great recycling potential due to the scale at which timber or wood can be recycled. If structural timber cannot be reused as a structural element on its own, it can be converted to glulam, or further treated for non-structural elements, including panels, weatherboard, and chip or fibre-based products (Figure 2).

As a precondition, recycled timber sections must be free from wood preservatives, fungal or insect infestation and serious damage. Visual, on-site inspection is sufficient to determine fungal or insect infestation and hence potential damage. In addition, it enables identification of the wood species, its nature and moisture content. The raw density can be estimated through literature data, in case no information about the location of growth of the CDW timber is available. Salvaged sections must then be cleaned from impurities such as metal fittings, paint, etc. in order to be assessed with regards to dimensions and location of cracks, branches and slope of grain. Visual inspection can be complemented with laboratory studies to determine the presence of contaminants. Depending on the site and laboratory investigations, the timber section can be either trimmed to remove the damaged sections and reused as whole sections, treated to prepare glulam or reused as weatherboards.

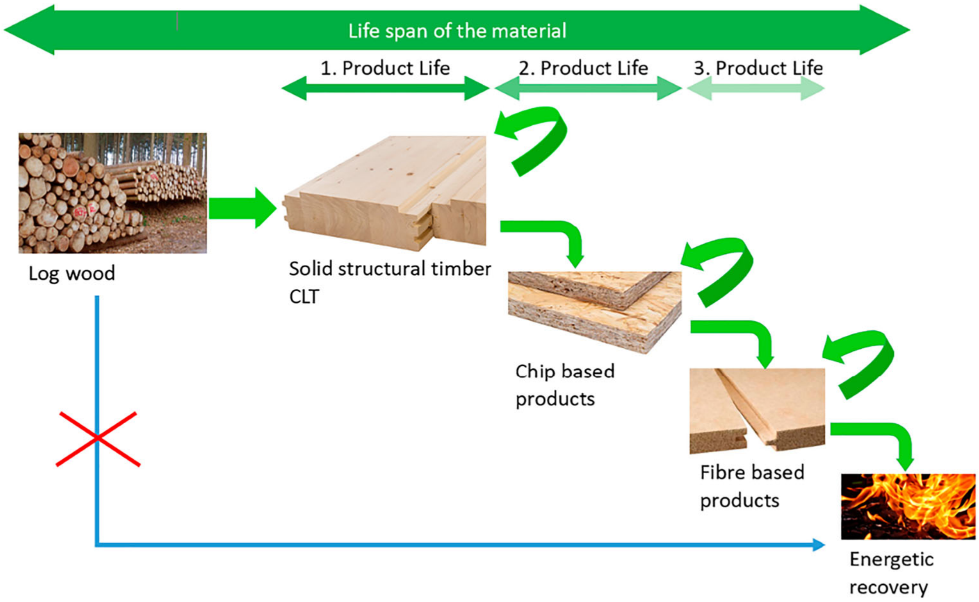


Figure 2. Life span and recycling of timber and wood products.

Reuse and recycling of CDW in non-structural elements

Beyond the structural performance of the designed elements containing recycled aggregates, the lightweight fraction contained in CDW can be used to prepare recycled insulation materials. In this project, the lightweight fraction was differentiated as rigid plastics particles, mixed wood/plastics scraps, or wood fibres.

Incidentally, the use of recycled aggregates in concrete can already exhibit improved thermal performance (Diez, Munoz, Lopez, & Polanco, 2013; Kim, Jeon, & Kim, 2003). Bravo and Evangelista (2017) prepared concretes replacing either just the fine or just the coarse aggregate fraction, in increments, with recycled aggregates (RA). The control concrete, made with virgin aggregates exhibited a thermal conductivity of 2.08 W/mK, just over the limit stated in Eurocode 2 for a specimen at 20 °C; substituting virgin aggregates with recycled aggregates lowered the thermal conductivity to a minimum value of 1.2 W/mK. However, the use of low-density lightweight aggregates can further reduce that value, e.g. plastics and wood fibres.

Plastics and wood typically make up the lightweight fraction of CDW. Rather than being disposed, they can be potentially reused for insulation purposes. Plastic particles have previously been used as aggregates in concrete composites. Akçaözoğlu, Akçaözoğlu, and Atiş (2013) produced concretes containing 60% of waste plastic with a thermal conductivity of 0.39 W/mK; in contrast, sand has a thermal conductivity of approximately 2 W/mK.

Other low-density aggregates and particles can be, and have been, used to produce thermally efficient concretes (Abidi, Nait-Ali, Joliff, & Favotto, 2015; Herki & Khatib, 2017; Jedidi, Benjeddou, & Soussi, 2015; Kekavovic, Kukaras, Ceh, & Karaman, 2014). Kekavovic et al. (2014) studied the performance of lightweight concrete containing ground expanded polystyrene (EPS). They produced concrete incorporating waste EPS with densities as low as 350 kg/m^3 with a corresponding thermal conductivity coefficient of 0.074 W/mK. However, strength was sacrificed to achieve these thermal efficiencies, with tested mix designs reaching strengths of only 7.5 MPa after 28 days of curing.

Similarly, perlite and vermiculite can be used as lightweight aggregates in concrete (Abidi et al., 2015; Jedidi et al., 2015). Abidi et al. (2015) found that the thermal conductivity more than halved in systems containing approximately 80% of perlite or vermiculite again at the expense of strength. It should be noted that perlite and vermiculite can be used as insulating materials in their own right.

With respect to potentially recycle wood fibres, Sekino and Kawamura (2004) prepared binderless panels containing wood shavings, intended to be used in wooden frames. The panels were prepared with densities varying from 80 to 120 kg/m^3. Depending on the density of the panel and the size of the wood shavings used, panels with thermal conductivities as low as 0.06 W/mK were achieved.

REuse, REcycling, PREfabrication, REfurbishment – RE^4

RE^4 aims to improve the recycling rate of CDW by investigating various ways through which CDW can be incorporated into prefabricated building elements, both structural and non-structural. The following sections aim to highlight the methodology adopted by the project partners to address the requirements of the Waste Framework Directive (2008) and Circular Economy Action Plan (2015).

Changing construction practices to facilitate and improve recyclability rates

A case for prefabrication

Prefabricated concrete differs from in-situ concrete as the former is first cast in the premises of precast concrete factories and then delivered to site. This has many added benefits, including better quality control, less waste, improved health and safety, increased speed of manufacturing and reduced cost (Wong, Hao, & Ho, 2003). Furthermore, precast concrete allows for the building of standardized products, but also bespoke elements to answer the needs of any client.

Modular design

In parallel to the development of CDW containing building elements, the prefabricated elements are designed to be reused as whole functional units. To achieve this, the designed buildings within the scope of RE^4 are to be modular, where each 'module' (beam, column, slab, façade panel, etc.) can be removed and reused later in its design life. This presents a series of challenges including:

- Ensuring all elements comply with existing building regulations.
- Using available mechanical connections to facilitate assembly and disassembly.
- Limiting the number of different elements to a reasonable number to enable future use.
- Limiting element size for standard lorry transport, saving time and cost.
- Life span, ease of repair, maintenance or replacement.
- Traceability i.e. specifying information into Building Information Modelling (BIM).

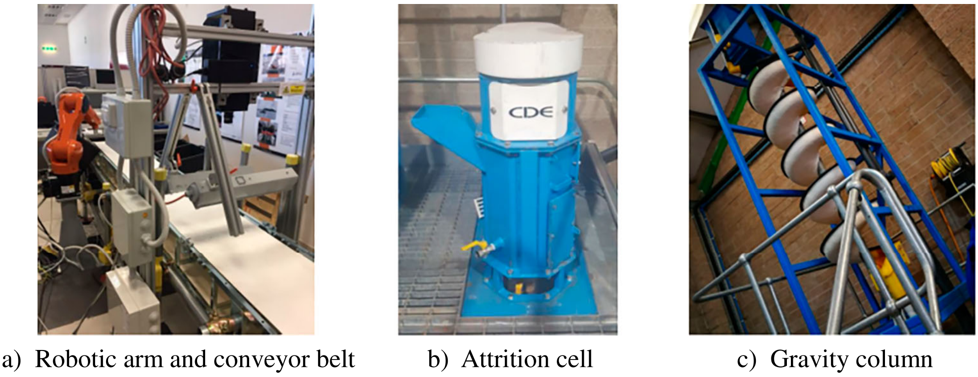
All elements were deemed suitable for modular design with the exception of foundations, as their performance relies on soil conditions.

Increasing the recycling rate of CDW sourced recycled aggregate

Improving the quality of CDW aggregates

Not all recycled aggregate (RA) constituents behave the same and it was identified in the project that the mineral aggregates, albeit sullied with paste, together with mortar and concrete particles were the more performant aggregates. Consequently, in order to improve the quality of RA, and in turn increase the recycling rate of RA in concrete, the more defective particles ought to be removed (e.g. bricks, tiles, glass & bitumen).

In a bid to increase recycling rate, the RE^4 consortium sought testing novel technologies to improve the quality of recycled aggregates (Figure 3(a–c)). For coarse aggregates (≥8 mm), an automated mechanism has been devised to remove the remaining 'unwanted' particles. These particles are determined on a real time basis using advanced electronic and optical systems based on the infrared reflectance signature of different types of CDW. The sensing unit determines the reflectance of the particles in different wavelengths (1000–1700 nm i.e. near infrared) to differentiate the unwanted particle which is then removed using a 6 degrees of freedom robotic arm. The physical handling of the CDW fragments is achieved by a vacuum generator based on the Venturi effect, thus giving a high flexibility to the system in terms of shape and size of the parts to be separated. The pieces are picked from a moving conveyor belt and then placed in different bins,



a) Robotic arm and conveyor belt b) Attrition cell c) Gravity column

Figure 3. Examples of new technologies used for improving CDW-derived mineral fractions.

according to the material classes. Currently, the system is still being calibrated and will be tested soon to determine the effectiveness of recycling. Once complete, the improved recycled aggregates can be tested in concretes.

What to do with the ceramic fraction?

Bricks and tiles can hold a more practical use than just being an aggregate, and can be used either as a supplementary cementitious material (Heikal, Zohdy, & Abdelkreem, 2013; Naceri & Hamina, 2009; Schackow, Stringari, Senff, Correia, & Segadaes, 2015) or as a precursor to manufacture an alkali-activated binder (Komnitsas, Zaharaki, Vlachou, Bartzas, & Galetakis, 2015; Reig et al., 2013; Robayo-Salazar, Rivera, & Mejia de Gutierrez, 2017).

Naceri and Hamina's (2009) results showed that blending brick waste with cement can effectively reduce the grinding time and specific weight of a blend and increase setting time. Strength was increased for blends containing up to 10% by weight of brick waste, albeit with prolonged curing (90 days). Heikal et al. (2013) measured an increase in strength in self-compacting concrete containing ground clay brick prepared with a polycarboxylate based superplasticizer. Interestingly, concretes prepared without an admixture showed a reduction in strength.

Reig et al. (2013) prepared pastes and mortars using red brick waste only activated with sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), cured at 65°C. By varying the composition of the activating solution, the authors prepared mortars achieving strengths of up to 50 MPa after just 7 days of curing. Komnitsas et al. (2015) similarly looked at alkali-activated brick and tile and concrete waste. They varied curing temperature and NaOH molarity, keeping the sodium silicate amount constant. Performance depended on the precursor used (either brick, tile or concrete), temperature and NaOH concentration. Brick- and tile-based precursors reached the higher strengths, in excess of 40 MPa with the 'right' activator composition and temperature condition.

RE^4 sought to reuse ceramic waste first as a precursor for alkali-activated binders. The ground powder comprised of both red brick and tile waste. It was then activated using a mixture of sodium oxide (Na_2O) and Na_2SiO_3 varying their proportion. The Na_2O content M + was fixed as a percentage of the precursor by mass. The Na_2SiO_3 content was expressed as ratio of Na_2O/SiO_2, known as the alkali modulus AM, and varied from 0.5 to $+\infty$ (no added sodium silicate). The water/binder (w/b) content was fixed at 0.37. Depending on the chemistry of the activating solution, 50 mm mortar cubes cured for 28 days at 70°C reached strengths of up to 30 MPa.

Ceramics were also reused as floor or wall tiles. This was achieved by blending the ground ceramic fraction in resin and allowed to harden in moulds. The grading of the ceramic powder and the resin to ceramic fraction ratio were investigated to achieve the desired strength and workability properties. Optimal performance, obtained with lab-scale production line, was achieved when blending 3 parts of resin to 7 parts of ground ceramic by mass. A flexural strength of 19.7 MPa according to EN 14617-2:2016 (EN 14617-2, 2016) and a compressive strength of 54.4 MPa according to EN 14671-15:2005 (EN 14671-15, 2005) were obtained for these reconstituted tiles.

Recycling and use of CDW in structural elements

Concrete

Concrete is perhaps the focal material due to the breadth of structural and non-structural elements that can be designed within the scope of the project. The project's approach was to design various concrete types and strength grades from which various elements could be made (beams, columns, slabs, blocks, façades, stairs, etc.). The type of concretes designed are detailed in Table 1 and include 3 types of concrete mixes – vibrated (VC), self-compacted (SCC) and semi-dry (SD) – suitable for the needs of the relevant partners within the project. After carrying out trial mixes, the designed concretes reached the target strength and workability targets set by the manufacturers within the project. Virgin aggregate replacement varied from 70% to 100% depending on the source of the recycled aggregate and the type of concrete produced.

Timber

Provided a timber section is free of damage, as previously explained, the section may be reused with minimal treatment, e.g. cleaning and cutting ideally to standardized sizes in order to be classified according to DIN 4074-1:2012 (DIN4074-1, 2012). This in turn, leads to the respective strength class according to EN 338:2016 (EN338, 2016). Such procedure enables the effective reuse and recycling of waste wood with minimal loss in performance for reuse as structural elements (Cavalli, Cibecchini, Tongi, & Sousa, 2016). Reclaimed timber can also be further treated to manufacture glulam. Depending on the final strength grade, the nature of the element and its conservation, several strategies can be adopted to reuse the wood, including:

- Complete reuse of the element with minimal processing (Figure 4(a)).
- Reprocessing into standardized cross sections.
- Reprocessing into lamellas for glulam fabrication (Figure 4(b)).

Table 1. Different types of concrete incorporating high levels of CDW-derived aggregate.

Product	Strength class	Consistency class	RA content (%)	Intended use
VC	C25/30	S2/S3	100	Structural
	C32/40	S3		
SCC	C40/50	640–770 mm based on slump flow test	40–80	Structural
SD	7.3 MPa	N/A	70	Building blocks

Within RE^4, reclaimed timber was tested to be used as either whole sections as received from site or as glulam. In the case of glulam timber beams, timber strength grade GL24 was targeted, meaning the timber beams reached a target flexural strength of 24 MPa. If the elements were deemed not to be suitable for use as structural elements, the timber could potentially still be reused to prepare non-structural elements, for example to be recycled as panels (complete with insulation containing CDW recycled wood chip for example) or cladding. Because of the varied forms timber can take and the potential for a cascading use, the recycling rate of all wood and timber products remains very high (Figure 2).

Developing insulating elements made from CDW

Lightweight particles for the preparation of insulating elements

Typical lightweight CDW particles used in the project were made of rigid plastics particles, mixed wood/plastics scraps and wood fibres. RE^4 attempted to utilize these fractions in the development of insulation materials having low density and low thermal conductivity. Specifically, lightweight CDW particles were used to develop low density concretes and insulation panels. Table 2 highlights the target properties for the development of lightweight Portland Cement (PC) concrete and optimized mixes meeting those targets. Depending on the source, rigid plastics particles or mixed wood/plastics scraps could replace up to 70% and 50% of the natural aggregate fraction, respectively.

For insulation panels containing rigid plastics, the plastic particles were embedded in polyurethane foam, already a popular cavity insulation material. The ratio of aggregate to binder was varied to create panels of different density values, from 5% plastic up to 50% plastic by volume. The panels performed best at 5% plastic content, keeping the density and thermal coefficient low.

a) Reclaimed timber sections b) Glulam from reclaimed timber

Figure 4. Converting reclaimed timber section into glulam.

Table 2. Requirement set for lightweight concretes for panels made with rigid plastics particles and mixed wood/plastics scraps.

Requirements	Targeted performance	Rigid plastics	Wood/plastics
Consistency class	S4	S4/S5	S5
Density (kg/m^3) @ 28 days	800–1400	1260	1250
Compressive strength (MPa) @ 28 days	4.5–24.0	7.5	4.5
Thermal conductivity (W/mK) @ 28 days	0.16–1.00	0.31	0.29

Figure 5. Insulation panel made from wood fibres.

Wood fibres (≤4 mm in size) and rigid plastics were also used to prepare insulating panels, moulded into shape. The production process of the panels differed depending on the material used. For wood fibres panels, the wood was first soaked in water for 72 h. Thereafter, the wood was compacted into moulds and kept under pressure, at 15 bar and 120°C or 160°C from 3.5 to 30 h. Finally, the panels were dried. To improve their fire resistance, prior to making the panels, the wood was mineralized by forcing a MgO solution into it under pressure (8 bar). Wood panels were found to be least dense when the curing period was the longest. Optimized wood fibres panels achieved a density of 215 kg/m^3 and thermal conductivity of 0.07 W/mK. An example panel can be seen in Figure 5.

Pilot trials

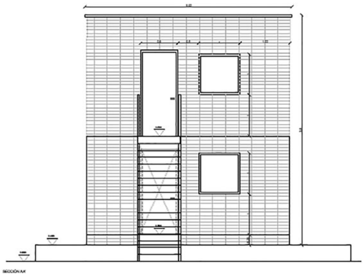
The ultimate test will come during the pilot trials. Several sites have been identified between the partners, including one in Northern Ireland, one in Spain and another in Italy. Table 3 details some of the elements designed to be tested in a two-storey building with the dimensions shown. With regard to concrete products, the estimated recycling rate varies from 40% to 90%, depending on the elements. With regards to timber elements, the recycling rate can be as effective as 100%.

At this point in the project, the design and production of the elements (load-bearing and non-load-bearing) and components has been completed. Currently, construction of demonstration buildings in Northern Ireland and Spain as well as refurbishment of a building in Italy are taking place. Once construction and refurbishment are completed, all three buildings will be monitored in terms of energy efficiency and compared with conventional ones.

Figures 6 and 7 show examples of elements designed in RE^4. In the first instance, a precast concrete beam (Figure 6) is shown containing 100% recycled aggregates. The beam has been cast to carry out a 4-point bending test. Cube specimens were also cast from the same batch, and reached 61 MPa in strength after 28 days of curing.

Figure 7 shows how a single timber element (Figure 7(a)) can be treated to produce a series of by-products, including off-cuts, standard timber sections, and saw dust (Figure 7 (b)). These by-products can be reused for making cladding and insulating panels as shown

Table 3. Types of elements (load-bearing and non-load-bearing) and components of a two-storey building to be tested.

Type of element/component	Side elevation of two-storey demo building
Reinforced concrete beams, columns, slabs & stairs Sandwich panels (load-bearing[1] & non-load-bearing[2]) Semi-dry mix concrete building blocks Timber façades Timber based inner partitions Wood fibre insulation panels Rigid plastic insulation panels Concrete roof tiles (made using extrusion)	

[1] Load-bearing sandwich panels consist of two layers of steel reinforced SCC (C40/50) and a PE-PIR insulation board.

[2] Non-load-bearing sandwich panels consist of one layer of steel reinforced SCC (C40/50), one PE-PIR insulation board and one layer of textile reinforced high performance concrete.

in Figure 7(c). The frame is further fastened with wood fibre boards, studs and battens while the exterior cladding will be made from recycled weatherboards (not shown).

Life Cycle Sustainability assessment (LCSA)

Types of elements/components evaluated using LCSA

Life Cycle Sustainability Assessment (LCSA) in the form of Environmental-Life Cycle Assessment (E-LCA) and Life Cycle Costing (LCC) is currently being performed in order to evaluate the environmental impact and cost together with associated savings of a number of RE^4 developed products. More specifically, 6 different types of RE^4 elements/components are investigated. Each element/component is compared against a reference state-of-the-art conventional element/component. Both conventional and RE^4 elements have been designed taking into account the different energy requirements of the 3 demonstration sites which are determined by Southern Europe (S-EU) and Northern Europe (N-EU) climatic conditions. The RE^4 elements/components to be evaluated include the following:

- Sandwich load-bearing panel (designed for N-EU climatic conditions)
- Sandwich non-load-bearing panel (designed for S-EU climatic conditions)

Figure 6. Precast concrete beam cast for upscaled testing.

a) Timber element

b) Timber by-products

c) Timber façade panels

Figure 7. Façade panel made using by-products obtained during processing of an old timber element.

- Timber non-load-bearing façade panel (designed for S-EU climatic conditions)
- Timber non-load-bearing façade panel (designed for N-EU climatic conditions)
- Timber-based internal partition wall
- Ventilated façade to be used in refurbishment projects (designed for S-EU climatic conditions)

Example of LCSA performed on sandwich load-bearing panel

Type of element

The element analysed in this example is a sandwich load-bearing panel designed for N-EU climatic conditions. Analysis is performed in accordance with EN 15804:2012 + A1:2013 (EN15804, 2013).

System boundaries

For the purpose of this analysis, conventional sandwich load-bearing panels are assumed to have a service life of 50 years at the end of which, they reach their end of life. When conventional panels reach their end of life, they are demolished using standard demolition methods and disposed into a landfill. RE^4 sandwich load-bearing panels are also assumed to have a service life of 50 years. However, like most of RE^4 products, they have been designed for easy disassembly and reuse. When RE^4 panels reach the end of their service life, they are selectively demolished or disassembled and then reused for making a new product, which in turn, is assumed to have a service life of 50 years. At the end of the reuse phase (i.e. after 50 years), the product which was made based on the original RE^4 panel is demolished and disposed into a landfill. As such, RE^4 panels are assumed to have a total service life of 100 years and hence reach their end of life at 100 years.

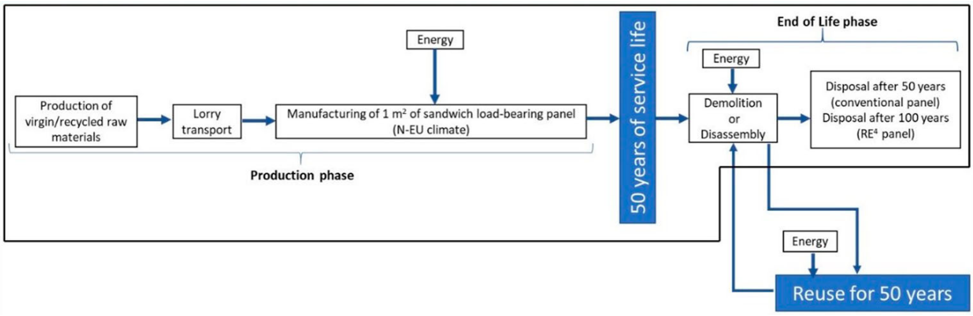


Figure 8. System boundaries considered for the E-LCA and LCC of sandwich load-bearing panels.

Figure 8 shows the material/energy flows and processes included in the system boundaries which are considered for E-LCA and LCC of both conventional and RE^4 panels exposed to N-EU climatic conditions. Virgin/recycled raw materials shown in Figure 8 represent the amount required to manufacture 1 m^2 of the panel. The energy required for making the new product during the reuse phase is also taken into account in the analysis. The black lines show the system boundary considered for the conventional panel, whereas the red lines show the boundary system adopted for the RE^4 panel.

Functional unit

The functional unit used for the analysis is 1 m^2 of panel of uniform thermal performance (U-value). U-value for both types of panel exposed to N-EU climatic conditions is assumed to be 0.21 W/m^2. A schematic diagram of both types of panel is shown in Figure 9.

Environmental impacts

For the purpose of this analysis, the following environmental impacts were considered: Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Ozone Creation Potential (POCP) and Embodied Energy (EE).

E-LCA results

E-LCA results showed that the main contributor to the total environmental impact for both conventional and RE^4 sandwich panels is the production phase. More specifically, the production phase accounted for 75% to 95% to each of the above six environmental impacts when it comes to the conventional panel. In the case of RE^4 panel, the production phase contributed between 76% and 99% to each of the above six environmental impacts. However, production of the RE^4 panel generated significantly less amount of environmental impacts compared to conventional panel as shown in Figure 10. Similarly, the end of life phase of RE^4 panel generated significantly less amount of environmental impacts compared to conventional panel (Figure 11).

LCC results

As already mentioned, the service life of a conventional panel is 50 years, whereas that of a RE^4 panel is 100 years. Hence, in order to be able to compare the LCC results between the

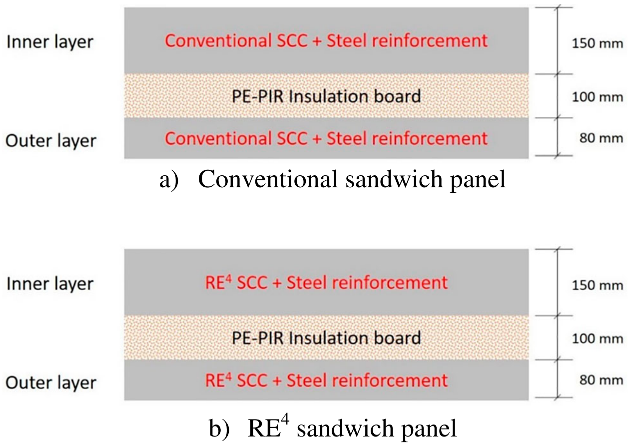


Figure 9. Schematic diagram of conventional and RE^4 sandwich load-bearing panels designed for N-EU climatic conditions.

two types of panel, the LCC of a conventional panel manufactured in 50 years and disposed in 100 years from now, was determined. Figure 12 shows the comparison between the LCC results of the conventional and RE^4 element assuming 3% discount rate.

As shown in Figure 12, RE^4 panel is more cost effective compared to the conventional panel throughout its entire service life. The total Net Present Value (NPV) of the RE^4 panel is 24% less of that of the conventional panel.

Conclusions

RE^4 project has tackled the concept of reusing and recycling CDW back into the built environment. This was done by developing prefabricated structural and non-structural elements and building components which incorporate at least 65% of CDW-derived

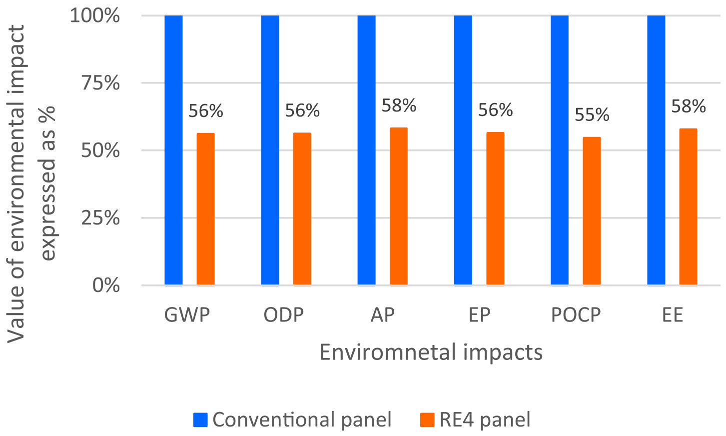


Figure 10. Comparison of environmental impacts between conventional and RE^4 panel during production phase.

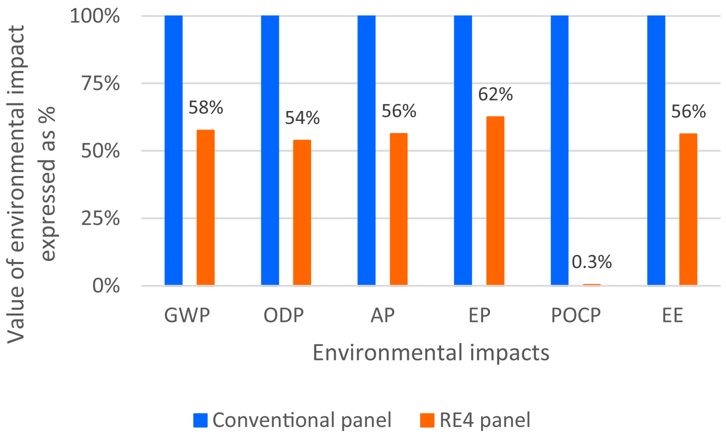


Figure 11. Comparison of environmental impacts between conventional and RE^4 panel during end of life phase.

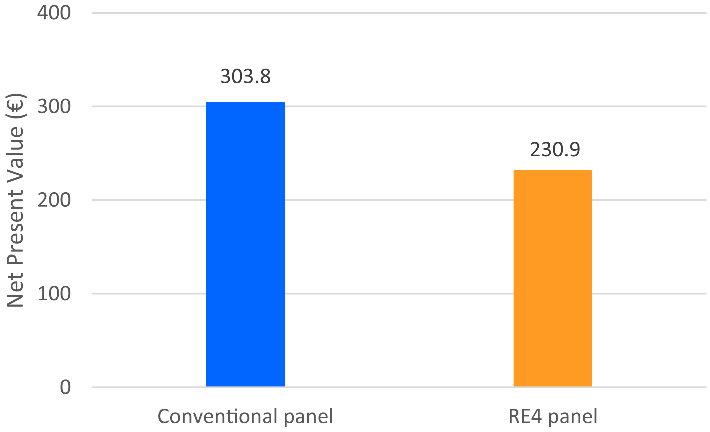


Figure 12. LCC comparison between conventional and RE^4 panel.

materials such as recycled aggregate, large pieces of timber and lightweight particles (i.e. wood flakes and mixed wood/plastics particles). In addition, modular design of the developed elements and components was employed together with the use of reversible connections for ensuring ease of reuse and recycling at the end of their service life. The above target was achieved by adopting an extensive testing regime to ensure that CDW-derived materials comply with existing national building codes and European structural design norms regarding their physical, chemical, mechanical and durability properties. In addition, new technologies were developed for improving the treatment process of raw CDW and hence the quality of CDW-derived materials. Finally, valorization of certain CDW fractions i.e. ceramics (bricks and tiles) was achieved through their use in the development of (a) floor/wall tiles by moulding and (b) alkali-activated mortars for structural and non-structural applications. Next, full-scale elements and components were made and are currently evaluated by building two-storey demonstration residential buildings in Spain and Northern Ireland as well as installing a new façade system to an existing building in Italy. Finally, environmental and cost impact together with associated savings are currently being evaluated using Environmental Life Cycle Analysis (E-LCA) and Life Cycle Cost (LCC) assessments. If successful, then existing standards and methods of practice can be challenged to facilitate the uptake of CDW in construction.

Disclosure statement

No potential conflict of interest was reported by the authors.

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