IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

Circularity in Selected EU Countries: The Case of Construction and Demolition Industry

To cite this article: N Dytianquin *et al* 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **855** 012017

IOP Conf. Series: Earth and Environmental Science **855** (2021) 012017 doi:10.1088/1755-1315/855/1/012017

Circularity in Selected EU Countries: The Case of Construction and Demolition Industry

N Dytianquin[1], J Gregersen-Hermans[2], N Kalogeras[34], J van Oorschot[5], M Ritzen[6]

Abstract. The construction and demolition industry (CDI) became a priority area for the EU circular economy as the industry has the largest waste stream by volume. Most of the CDI waste, however, ends up in incinerators for energy production or as downcycled content for road surfaces despite its enormous potential for recycling and reuse. This study focuses on the application of circularity in the CDI. We recognize that the construction industry provides a prominent decision context for studying circularity since many scrap materials resulting from demolished buildings and houses could be recycled, reused and refurbished in newly constructed edifices from foundation to rooftops. Adopting the fundamental circularity concepts, the study intends to compare how selected countries as early adopters of circularity in the EU apply distinct concepts of the circular economy in the CDI. The study investigates the manner circularity in CDI is achieved in the selected countries using determinants for project success in integrating the three dimensions of sustainability to identify and determine best practices. These determinants are: 1) stage of circularity as described in the waste hierarchy and circularity ladder, 2) building design principles, 3) life cycle stages specific to construction, and 4) availability and extent of policy or strategy on circularity in the EU countries where the selected projects are located. The EU countries covered are: the Netherlands, Belgium, Germany, France, and Denmark who are among the top 10 waste generators in Western Europe. The projects chosen are: (i) Superlocal project in the Netherlands; (ii) the Circular Retrofit Lab (CRL) project in Belgium; (iii) Open Air Library in Germany; (iv) Rehafutur Engineer's House project in France; and (v) Upcycle Studios in Denmark.

1. Introduction

The construction and demolition industry (CDI) became a priority area for the EU circular economy as the industry has the largest waste stream by volume contributing 374 million tons based on 2016 EU-wide data. This study focuses on the application of circularity in the CDI. We recognize that the construction industry provides a prominent decision context for studying circularity since many scrap materials resulting from demolished buildings and houses could be recycled, reused and refurbished in newly constructed edifices from foundation to rooftops. The objective of the study is to investigate how CDI-specific determinants affect project success in attaining sustainability by comparing selected EU countries (projects) in attaining and balancing environmental, economic and social sustainability performance in CDI. These determinants are: (1) circularity policy at the national, municipality or regional levels; (2) stages of circularity as described in the waste hierarchy or circularity ladder framework; (3) building design principles; and (4) the life cycle phases of the construction industry. In the end, the study intends to identify best practice and draw lessons for balancing the three sustainability dimensions and the different business models evolving from the different projects using these determinants.

2. The Context

The EU Action Plan on the Circular Economy (EU Commission, 2015) formalized the EU mandate for member states to transit towards a circular economy in line with the EU's commitment to reach the UN Sustainable Development Goals (SDGs) by 2030. A circular economy (CE) at the EU-level is envisioned to: (i) protect businesses against scarcity of resources and price volatility that accompanies it, hence generating innovative and sustainable competitive advantages; (ii) save energy and avoid

[1] *Center of Sustainable International Business, International Business School Maastricht, e-mail: norman.dytianquin@zuyd.nl*
[2] *Center of Sustainable International Business, International Business School Maastricht, e-mail: jeanine.hermans@zuyd.nl)*
[3] *Center of Sustainable International Business, International Business School Maastricht, e-mail: nikos.kalogeras@zuyd.nl)*
[4] *Commodity Risk Management Expertise Center Dept. of Marketing & Consumer Behaviour*
Wageningen University & Research, e-mail: nikos.kalogeras@zuyd.nl)
Center of Sustainable International Business, International Business School Maastricht, e-mail: nikos.kalogeras@zuyd.nl)
[5] Academy Built Environment, SURD Research Group, Zuyd University Heerlen, *email: john.vanoorschot@zuyd.nl*
[6] Academy Built Environment, SURD Research Group, Zuyd University Heerlen, *email: michiel.ritzen@zuyd.nl*

irreversible damages caused by resource usage that exceeds the planet's renewal capacity; and (iii) create business opportunities in more efficient ways of producing and consuming, thereby creating local jobs, fostering skills and promoting social cohesion and integration. The circular economy, in summary, cuts across many EU common policies and priority areas from energy, climate change and the environment, food safety and quality, farming and sustainable agriculture to social cohesion, research and innovation, and entrepreneurship and promotion of small and medium enterprises (SMEs).

Several sectors were targeted in the EU circular economy action plan. The priority sectors that were identified were plastics, food waste, critical raw materials, construction and demolition, and biomass and bio-based products. This paper will focus on the application of circularity in the CDI, which became a priority area as the industry according to Wahlström et al. (2020) has the largest waste stream by volume contributing 374 million tons based on 2016 EU-wide data (Eurostat, 2019). In 2018, this reached 36% of all waste in the EU as shown in Figure 1. Most of the CDI waste, however, ends up in incinerators for energy production or as downcycled content for road surfaces despite its enormous potential for recycling and reuse, hence of 'closing the loop'. Earlier, CDI was a target for the EU energy policy regarding its operational efficiency in energy usage.

The EU action plan on circularity requires translation into national action, requiring stakeholder involvement from member states, cities and municipalities, companies and citizens. The action plan for a circular CDI is linked to the revised Waste Framework Directive (WFD 2008/98/EC, amended 2018/851) where a mandatory target of 70 percent recovery rate was set by 2020. Recovery rates vary by member state based on Migliore, Talamo & Paganin (2020) as shown in Appendix Table 1, reaching 90 percent for all 28 members states in 2016. The countries chosen for this study were the Netherlands, Belgium, Germany, France and Denmark. Figure 2 shows that on a per capita basis, these countries were among the top 10 waste producers in Western Europe with the Netherlands ranking fourth (after Finland, Luxembourg and Sweden); Belgium, sixth; France, seventh; Germany, eighth; and Denmark, ninth.

3. Literature Review

The evaluation of selected projects in terms of their environmental, social and economic impacts will be conducted in terms of determinants and antecedents in addressing these three sustainability dimensions. The topics to be reviewed in this section will cover the stages of circularity, the building design principles, the life cycle of the construction industry and policy-making on circularity in the selected countries which form the dimensions for choice of projects in CDI used in the study. Literature review also covers the criteria or indicators used in environmental, economic and social impact assessments to be used in evaluating project success in achieving sustainability.

3.1 The Stages of Circularity

There is no universal definition of CE based on literature surveys of De Angelis (2018) and Sillanpää & Ncibi (2019) although a global definition of circularity awaits some consensus. The difficulty of finding a clear definition is attributed to the concept of the circular economy being intertwined with sustainable development, corporate social responsibility (CSR) and business models. While the former survey looks for common principles of CE found from originators in the various disciplines of economics[7]; industrial ecology[8], biomimicry[9], architecture[10], and management[11], the latter work decries the limited attention to the social dimension to complete the triptych of sustainable development (economy-environment-social) and CSR's 3 P's (people, planet, profit) found in existing definitions.

[7] See Boulding (1966), Mäler (1974), Tietenberg (1984), Pearce & Turner (1990), Daly (1992)
[8] See Frosch & Gallopoulos (1989), Allenby (1992), Bringezu (2003), Wells & Seitz (2005), Chertow (2007), Linton et al. (2007), Lifset & Boons (2012), Bloomsma & Brennan (2017)
[9] The study of innovative solutions in nature and natural processes. See Benyus (2002), Kennedy (2007), Marshall & Lozeva (2009), Habib (2011), Green et al. (2015), Das et al. (2015)
[10] See Stahel (1986), Lyle (1994), McDonough & Braungart (2002)
[11] See Lovins et al. (1999), Hawken et al. (2000), Pauli (2010)

Both above-mentioned surveys use the metaphors of spaceships and sailboats, dating back the conceptualization of CE to Kenneth Boulding's (1966) publication which allegorized a closed economy as a spaceship with limited finite resources subsisting on waste conversion. The sailboat analogy, in turn, refers to Ellen MacArthur for whom a foundation for circularity was created. She circumnavigated the world in 2004 in record time, alluding to her boat as her world, requiring minimum resources to make the boat lighter and faster, hence just relying on available supplies and avoiding unnecessary stops to restock. It was in 1990 though when the word CE was formally introduced by Peace & Turner (1990) in the second chapter of their book describing the path for economic growth within ecological limits. The early academic writings on CE resembled those of closed-loop supply chains described in industrial ecology although focusing more on technical and engineering rather than business perspectives.

De Angelis (2018) further explored the link between CE and business models where the latter were a crucial constituent. A circular business model is one that combines notions of *value proposition, value creation and delivery* and *value capture* within the Ellen MacArthur Foundation (EMF)'s ReSOLVE framework, which represent measures needed to innovate business models according to CE principles. The acronym stands for Regenerate, Share, Optimize, Loop, Virtualize and Exchange. Rizos et al. (2017) summarize multiple CE definitions and interpretations as found in Appendix Table 2. Evident from the surveys of the origins of CE is that the circular economy is conveniently juxtaposed against the alternative linear economy that is often characterized as a 'take-make-use-dispose' paradigm as shown in Figure 3. What is common among the different constructs of CE is the idea of '*closing the loop*' which means the disposal stage at the end feeds back into the production system to create circularity. Thus, the final state of waste disposal is linked to the concept of circularity as it is this waste that is looped back.

Grant, Trautrims & Wong (2017) developed a hierarchy of waste management that comprises the stages of circularity, namely: reduce, reuse, recycle, recover and dispose as shown in Figure 4. Reduce means using fewer resources. Reuse involves use of a product or some parts that can be shared, refurbished (restoring a product to good condition but not comparable to brand new), repaired (fixing a fault that made the product inoperable) or remanufactured (replacing worn non-functional product or component to 'like new' or 'better than new' condition, hence upcycling). Recycle refers to product recovery where waste is separated into materials that may be reprocessed or fitted into new products. Recover is creating energy from waste that cannot be reused or recycled and hence, incinerated. Disposal, in turn, is the final destination for waste as landfill, which may be problematic when materials are toxic or non-biodegradable. In this framework, waste prevention is preferable to waste disposal. Ghisellini et al. (2018) & Kirchherr et al. (2017) extend the hierarchy to comprise the 9Rs (Refuse, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover) which is a more comprehensive construct.

De Groene Zaak & Ethica (2015) amended this hierarchy and introduced a *circularity ladder* concept which probes into the environmental sustainability of different CE business models. A distinction is made between product life extension and sharing models and resource recovery business models where the former potentially reduces the amount of waste generated by slowing resource loops and funneling resource flows whereas the latter simply diverts existing waste towards material and energy recovery. Compared to the waste hierarchy model which ranks waste management options according to environmental impacts associated with the end of life phase, the circularity ladder takes into account the environmental impact of the entire product life-cycle. The circularity ladder is depicted in Figure 5. The EU defines CE using the circular stages approach as a "*production and consumption model which involves reusing, repairing, refurbishing, and recycling existing materials and products to keep materials within the economy wherever possible…waste will itself become a resource, consequently minimizing the actual amount of waste. It is generally opposed to a traditional, linear economy, which is based on a 'take-make-consume-throw away' pattern*" (EU parliamentary research, as quoted in Sillanpää & Ncibi, 2019, pp.8-9). Using this definition, the EU member states designed their circular strategies around the stages model as discussed later below.

3.2 Building Design Principles

Tebbatt Adams et al. (2017) note that the application of CE principles to CDI are heavily fixated on construction waste minimization and recycling, despite the existence of other circular strategies. Cheshire (2016), however, suggests that other stages of circularity can be applied in CDI by adopting approaches such as: building in layers, designing out waste, designing for adaptability, designing for disassembly or deconstruction, and selecting materials to allow a building to be more adaptable as its components can be reconfigured for repair or replacement as shown in Figure 6. These stages were identified as retain, refit, refurbish, reclaim/reuse, remanufacture and recycle/compost. The inner three circles depict that retaining existing buildings is the most resource-efficient option followed by refitting and refurbishing while the outermost circles pertain to building materials that could be reclaimed or remanufactured and only recycled or returned to nature as final end. The design principles associated with CE probes into the lifespans of the building components and possibilities of dismantling them for later reuse.

As described in Cheshire (2016), Mossberg (2018), and van Vliet (2018) the philosophy behind *building in layers* is partitioning building elements according to their different lifespans such that their independence allows different layers to be peeled off without damaging the adjoining layers. This is depicted in Figure 7 where a building structure is fragmented into 6S representing site, structure, skin (façade and roof), services, space plan and stuff (Brand, 1994), where the site and structure which is independent of the skin has the longest life span while the services are accessible layers that are replaceable when required, and the space plan and stuff are the short-lived components. *Designing out waste* principle employs lean design to explore waste reduction by reusing or recovering building components, producing off-site (i.e., pre-fabrication), materials optimization, waste efficient procurement and deconstruction, taking account of factors such as embodied carbon content and water use. *Designing for adaptability* involves reconfiguring buildings during their lifetimes by adapting their lay-out to changing markets from residence to retail to leisure and office spaces using multi-space concepts and flexed floor-to-ceiling height requirements. In *designing for disassembly,* parts of the building can be moved or transferred to another site by dismounting in case a site is no longer available as intended. This means that buildings and materials can be valuable assets independent from their site, thus prolonging their value and for extractable materials to be turned into ‘materials banks’. Finally, *selecting materials* distinguishes between technical and biological materials where the latter can easily be returned back to nature whereas the former is created using an industrial process and is harder to recycle at end of life.

Figure 8 depicts the benefits of circular built buildings versus linear economy buildings with reduced construction time and less wastage on site, increased rental yields from healthy interiors, higher residual values and longer life of material components, leading to more valuable assets. These benefits outweigh the costs of demolition and disposal of materials and depreciation and loss of rental yield in non-circular buildings.

3.3 Life Cycle Phases of Construction

Apart from the stages of circularity, one has to consider as well the stage of construction where circularity principles can be applied. Wahlström et al. (2020) identified the lifecycle in the built environment as: (i) *material production phase* – which refers to selection of building materials as having high recyclable or renewable or hazardous content, durability or life span, and the production processes of these materials having low environmental impacts (see Windapo & Ogunsanmi, 2013); (ii) *design phase* – which looks at resource use versus functionality of a building with deconstruction in view (i.e., easy to disassemble, durability, flexibility, upgradability, reparability and adaptability of structures; (iii) *construction phase* – where stocks of construction materials are recorded, avoiding material surpluses, creating a materials passport and selective sorting of construction waste; (iv) *use phase* – pertains to building maintenance and use intensity of buildings including flexible functionality for different users such as shared work or living spaces, and lifetime extension through retrofitting and rehabilitation of structures; and (v) *end of life phase* – which is the demolition or deconstruction phase involving removal and safe handling of hazardous materials, source sorting for material streams, and auditing of pre-demolition material.

3.4 Selected EU Member State Country (City/Regional) Strategies on Circularity

The available literature on country strategies on circularity mostly focus on city-wide and regional strategies in a specific country. Gravagnuolo, De Angelis & Iodice (2019) attribute this to the predicted rise in population that would reach 8.6 billion in 2030 according to the United Nations, accompanied by greater urbanization. As the EMF (2017) attributes cities to account for an average of 70% of greenhouse gas emissions, 75% of natural resource consumption and 50% of global waste production, city involvement in the transition to CE is pivotal for a country to attain its waste recovery targets. The EMF (2017, p. 7) defines a circular city as '*aim(ing) to eliminate the concept of waste, keep(ing) assets at their highest value at all times, and enabled by digital technology. A circular city seeks to generate prosperity, increase live-ability, and improve resilience, for the city and its citizens, while aiming to decouple the creation of value from the consumption of finite resources.*"

As such, the concept of *urban metabolism* is introduced where cities are likened to living organisms where energy and resources flow that allow it to function. Kennedy et al. (2010) define the concept of urban metabolism as the sum total of technological and socio-economic processes occurring in cities that result to growth, energy production and waste elimination. This is in line with the EMF & McKinsey (2012) conceptualization of CE as "an industrial system that is restorative or regenerative by intention or design". A more useful typology akin to urban metabolism was introduced by ESPON (2020) called the *urban circular collaborative economy* (UCCE) involving exchange of unused or underused resources as portrayed in Figure 9. The UCCE combines the triple bottom-line elements of sustainable development— people, planet and profits— into determining environmental, economic and social impacts in the CDI that will be addressed in a later section. The city-wide or region-wide circular strategies in the built environment moreover, are replicated in other cities and regions of the country, making them distinctively country-specific until another participant in CDI experiments with constructing techniques that pertain to another stage or another design principle or another construction life cycle phase in the circularity ladder.

In this paper, the country, regional and/or municipality-led strategies of the selected EU countries of the Netherlands, Belgium, France, Germany and Denmark are summarized in Appendix Table 3. The countries were chosen on the basis of the different stages and design principles of the circularity loop that were targeted to reduce waste and considering that these are among the top 10 waste generators in Western Europe. Based on the comparative table, the Netherlands and Denmark developed a well-defined country strategy to achieve a circular economy in the CDI sector. France developed a country circular economy strategy for all sectors in general where CDI is a subset. Belgium formulated a circular economy strategy for the CDI for the capital region Brussels. Finally, Germany developed a circular economy strategy in general but not specific for the CDI although a regional plan on CE in the construction industry exists.

3.5 Environmental, Economic and Social Impact Assessments

Building construction has a pivotal role to play in sustainable development as noted by Zabihi et al. (2012), Yilmaz et al. (2015), Zavadskas et al. (2018), and Zhang et al. (2014) requiring integration of technological, economic, social and environmental benefits. Following the triple bottom-line paradigm of sustainable development in the circular economy, the following section will compare the selected projects on the three dimensions of environmental, economic and social impacts using qualitative methodology of simple ranking based on the case project descriptions in the absence of more detailed environmental impact assessment, life cycle assessment, social impact assessment and economic feasibility studies. A case study approach was one methodology suggested by Best et al. (2018) in studying transitions to circular economies along with scenario-based modelling and statistics and indicators, which are not possible to do under this study given time constraints.

3.5.1 Environmental Impact

Singh et al. (2016) describe the common tools used to assess the environmental impact of projects, which are: environmental impact assessment (EIA), ecological footprint (EF) and life cycle assessment (LCA). Performed usually during the planning stage of a project, an EIA identifies and predicts the impact on the environment and outlines mitigation measures to eradicate negative effects of the project on the environment such as carbon or greenhouse gas (GHG) emissions, water use, energy demand, solid waste, exposure to hazardous and toxic materials and other forms of pollution. In Yijun et al. (2011) circular economy theory is applied to EIA. On the other hand, EF, based on the Global Footprint Network (see https://www.footprintnetwork.org/) was introduced in the 1990s to measure how much resources, especially from nature, are consumed and how much waste is generated, hence accounting for the demand for and supply of natural resources. On the demand side, EF aggregates all productive areas for which consumers, society or a given product compete, hence measuring the ecological assets required by users to produce the natural resources they consume and to absorb its waste, specifically carbon emissions. On the supply side, EF measures the bio-capacity or productivity of ecological assets to absorb the waste that an economy generates. The third tool LCA is an international standardized methodology for accounting for the environmental footprint of a product or service within the requirements of ISO 14040 and 14044, as cited by OECD (2019). LCA involves data collection on inputs (resources) and outputs (emissions and waste) that constitute inventory analysis, which are translated into indicators of environmental, health and resource availability impacts that lead to some quantification of the environmental load of products or services throughout their lifetime. In this regard, Ortiz et al. (2009) review research conducted on LCA in the construction or building sector. Meanwhile, Haupt & Hellweg (2019) developed a framework for measuring environmental sustainability in a circular economy that measures the environmental value retained by circular products through the different circularity stages.

3.5.2 Economic Impact

Rizos et al. (2017) describe the economic effects of CE as having general employment effects in the recycling business although caution should be placed on net employment as there are also jobs that will be displaced by CE especially in sectors involved in production of primary extractive materials. Other economic effects cited as in Hysa et al. (2020) are trade effects in terms of exports of new recycled materials coupled with reduction of imports of primary materials; value chain multiplier effects in terms of input purchases and delivery channels as well as cross-value chain cooperation; changes in consumption usage and demand patterns; higher value added and greater residual values at end of life of buildings; increase in investments in innovations and new technologies related to recycling and remanufacturing; and savings on maintenance costs of buildings. While most circular projects in the built environment are subsidized, the potential for self-financing is important for replication of similar CE projects, otherwise these become reliant on availability of subsidies.

3.5.3 Social Impact

Padilla-Rivera et al. (2020) surveyed how social aspects have been considered and incorporated in the circular economy and suggested thematic areas in terms of labor practices and decency of work, human rights, society and product responsibility. The social impact of the circular economy concerns mostly stakeholder participation as shown by Persson et al. (2004) and Bal et al. (2013) but social impact assessments suggest other indicators relating to income equality, cultural diversity, involuntary settlement, gender and race disparities; social cohesion and inclusion, and preservation of cultural heritage as outlined in IADB (2018). The social life cycle assessment (S- LCA) by UNEP (2009) also covers social and socio-economic aspects along the life cycle of products and services along extraction, processing, manufacturing, distribution, , use, reuse, maintenance, recycling and disposal stages that directly affects stakeholders positively or negatively but many of these indicators overlap with economic and environmental indicators such as local employment, supplier relationships, health and safety of consumers and workers. In this paper, these indicators were used in the economic impact instead of social.

4. Selected EU Projects for Comparison

The selection of EU projects were driven by the theoretical construct of determinants to project success in CDI presented in the literature review involving circularity stages, building design principles, life cycle stages of construction and availability of national strategies on circularity in the building environment. There was no selection criteria made for the type of building (whether residential or public or commercial) for as long as the project involves construction and demolition activities. Further, the more important consideration for project selection was availability of data in terms of project description, interim or final assessments as cited by official websites of the project sponsors, social media including architectural digests and magazines, or industry associations. Other selection bases were that the project must be located inside the five selected EU member states and represent as much as possible diverse elements of the determinants, e.g., different circularity stages, different building designs, different phases along the construction life cycle. The projects must also allow for expedient comparative analysis in line with the requirements of sustainable development.

The projects chosen are: (1) Superlocal project in the Netherlands (Figure 10); (2) the Circular Retrofit Lab (CRL) project in Belgium (Figure 11) ; (3) Open Air Library in Germany (Figure 12); (4) Rehafutur Engineer's House project in France (Figure 13); and (5) Upcycle Studios in Denmark (Figure 14). Appendix Table 4 compares the project descriptions. Appendix Table 5 compares the determinants for balancing the triptych of sustainability of selected projects on the basis of the determinants which are circularity stages, construction life cycle and designing principles and country strategies and policies on circularity. These determinants are rated from a scale from 1 to 3 with 3 being strong, 2 is moderate and 1 is weak as found in the project case descriptions.

The key points of this table are: (1) the Superlocal project of the Netherlands is distinct for dismounting a whole apartment studio hull and moving it to a new site which is a feature of designing for disassembly, as is the development of bricks that are stacked instead of cemented to facilitate disassembly at end of life for reuse; (2) the Retrofit Lab is prominent for designing for adaptability with reversible solutions being brainstormed by stakeholders including architecture students, contractors and product manufacturers; (3) the Open-Air Library project in Germany will be remembered as a community project that was involved in the design using donated beer crates and reused façade of a historic warehouse as construction materials as well as reclaiming unused abandoned industrial site for the project; (4) the Rehafutur Engineer's House in France exemplifies the selection of materials as it experiments on use of natural or biological resources for insulation while preserving cultural heritage; and (5) the Upcycle Studios in Denmark showcases the use of upcycled materials from construction debris, careful segregation of toxic from non-toxic elements and designing for adaptability where functionality of space is flexed between housing and business configurations.

5. Methodology for Comparing Environmental, Economic and Social Impacts

To compare the selected EU projects on the three dimensions of sustainability, a qualitative approach of multi-criteria decision analysis was used where criteria for each sustainability dimension on environmental, social and economic impacts were ranked by importance and then projects were scored based on each criteria used for assessing impacts of the three dimensions. The criteria used for economic, environment and social dimensions were chosen based on indicators cited in impact assessments discussed under Literature Review Section 3.5 of the paper. The literature review which established the determinants of project success was the initial step of the methodology which led to the choice of projects and also described elements of environmental, economic and social impact assessments and identified relevant indicators that were used for evaluating sustainability performance of the selected projects.

In multi-criteria decision making (MDCM) analysis, Odu (2019) outlines several weighting methods broken down into subjective, objective and integrated methods. In this paper, the subjective method of direct rating or ranking was chosen for convenience and expediency as the other methods require more sophisticated statistical techniques, hence, more data requirements. The importance of the criteria in each sustainability dimension (environment, social and economic) were ranked from 1 to 3 where 3 is the highest, depending on whether the criteria is a necessary and sufficient condition to produce the required sustainability effect. A necessary condition must be present for an event to occur while sufficiency establishes conditions that will produce the event. A necessary condition must be present but it alone does not provide sufficient cause for the event to occur. According to Dul (2015), a necessary condition allows an outcome to exist whereas a sufficient condition ensures and produces the outcome. The author uses the analogy of a high score on the Graduate Record Examination (GRE) test for a student to enter graduate school (the outcome) where an adequate score is necessary for the outcome but not sufficient as other admission requirements like a good motivation letter, TOEFL score, recommendation letter, evidence of student performance and grades, etc. are required although a low GRE score would certainly not lead to admission independent of how the student performs on the other requirements. A sustainability criteria is a 3 if it is both necessary and sufficient to produce the sustainability effect, a 2 if it is sufficient but not necessary, and a 1 if it is necessary but not sufficient.

All indicators of each sustainability dimension are likewise scored from 1 to 5 with 5 indicating the highest if it relates specifically to the main construct of circularity as applied in the CDI. A Likert scale from 1 to 5 will be used where the higher the rating, the more the project addresses the sustainability/circularity yardstick or indicator of the sustainability dimension. The scale allows some range of scoring that is not too close than if only 3 scores were used. A score of 5 means that the project carries this indicator as a dominant project objective or intention, a 4 means that the indicator is not dominant but the project intends to address the issue in project implementation; a 3 means the indicator exists in the project but it is not clear as to whether it was intentionally designed or is just a side effect or whether this was indeed achieved even if intended in the absence of final impact assessments; a 2 means that the indicator is just a side effect of the project but was not originally designed nor intended; and a 1 means that the indicator was not addressed at all by the project nor is it a project objective. The scores are then multiplied by the rank of the indicator for each dimension and then summed up to get the total score for the project for that sustainability dimension. Then the ranks of each project on all dimensions are averaged implying equal weights for each dimension of environment, economic and social. The lower the calculated average for rank, the more balanced the project is in attaining the three goals of sustainability and circularity, hence representing best practice. The environmental, economic and social impacts of the projects were compiled by the authors from the sources listed in Appendix Table 6.

5.1 Environmental Impact

In this paper, a combination of indicators from all three tools of EIA, EF and LCA relevant to circularity in CDI will be employed. The indicators for environmental impact are: 1) *reduction of GHG emissions*; 2) *savings on water use*; 3) *savings on energy consumption*; 4) *embodied pollution*; 5) *solid waste reduction*; 6) *product life cycle extension*; 7) *use of biotic materials*; 8) *reduction of exposure to human toxicity*; and 9) *land use*. Appendix Table 7 provides a description of these indicators. The indicators ranked by importance to environmental impact are: 3 for reduction of GHG emissions, water use, energy use, embodied pollution, solid waste reduction; and 2 for use of bio-based materials, land use, product life cycle extension and human toxicity as these are sufficient to achieve the outcome but not necessary conditions. The ratings of the selected projects based on these indicators for the environmental dimension are shown in Appendix Table 8. The Rehafutur project in France scored the highest on environmental impact followed by the Dutch Superlocal Project, the Danish Upcycle Studios, and the Belgian Circular Retrofit Lab, with very close scores. The German Open Air Library ended up with the lowest score. All projects scored equally on solid waste reduction and product life cycle extension which are the main indicators of the waste disposal directive applied to CDI. The projects varied in their scores on reduction of greenhouse gas emissions and energy savings with the highest scores for the Danish and French projects where these two environmental indicators where specifically targeted. Also both projects included human toxicity of building materials into account. The French and Dutch projects scored higher than the Danish project because of the use of bio-based materials as dominant feature along with land use considering that the project was built on UNESCO heritage site for Rehafutur and in the case of Superlocal, land threatened by demographic transition. Land use also boosted the score of the German project which converted abandoned industrial site with fallow land to a green public or community space. So based on environmental impact, the projects are ranked from 1 to 5 with 1 being the best as follows: 1 Rehafutur House of France; 2 Superlocal project of the Netherlands; 3 Upcycle Studios of Denmark; 4 Circular Retrofit Lab of Belgium; and 5 Open Air Library of Germany.

5.2 Economic Impact

The economic impact of the projects will be similarly scored and evaluated as in the environmental dimension. As many of the projects do not have ex post evaluation studies, the following indicators based on ex ante case descriptions will be used for assessing their economic impact along with available mid-term impact reviews and press releases: 1) *employment generation*; 2) *trade effects*; 3*) business creation and multiplier effects on the value chain*; 4) *financial self-sufficiency*; 5) *consumption patterns*; 6) *savings on maintenance costs*; 7) *higher residual values*; 8) *increase in innovation and new technologies and associated investments*; and 9) *fiscal effects*. These economic indicators are described or defined in Appendix Table 9. Appendix Table 10 compares the economic impact of the selected EU projects using these indicators. By importance, the indicators for economic dimension were ranked from 1 to 3 with 3 indicating the highest as the indicator is necessary and sufficient to produce the sustainability outcome. Employment generation, business creation and value chain multiplier effects, financial self-sufficiency, consumption patterns, and increase in innovation and new technologies were ranked the most important at 3; followed by trade and fiscal effects, savings on maintenance costs, and higher residual values ranked at 2 by importance. For economic impact, the projects ranked as follows: 1 Upcycle Studios of Denmark; 2 Rehafutur House of France; 3 the Circular Retrofit Lab of Belgium; 4 Superlocal project of the Netherlands; and 5 Open Air Library of Germany. The projects scored equally or fractionally the same in the indicators for higher residual values and business creation and value chain multiplier effects, and in innovation effort and associated investments in new technologies except for the German library project. The Danish project scored high because of the fiscal effect with no amount of subsidy used for financing, having been designed as a commercial project whereas the Dutch, Belgian and French projects were funded by the EU while the German project was partly financed by the federal state although most of the funding were raised from public donations. The employment effects varied with the Danish project intentionally using upcycled materials to be sourced locally to provide local employment whereas the Dutch, Belgian and French projects created jobs during project implementation and potentially in the future with the application of the business models. Trade effects also varied with conscious decisions to reduce reliance on imports for the Danish, Belgian and French projects compared to the Dutch project which entailed importation of machinery from China for the development of the detachable bricks.

5.3 Social Impact

In this study, absence of data precluded assessment of other indicators commonly found in social impact assessments such as gender and race equality, cultural diversity, or human rights violations. For the comparison of the selected EU projects, the following indicators for the social dimension are used: 1) *Stakeholder participation*; 2) *Community engagement*; 3) *Preservation of cultural heritage*; 4) *Development of social capital*; 5) *Regional inequality*; 6) *Formation of human capital*; 7) *Demographic transition and change*; and 8) *Social cohesion.* Appendix Table 11 provides a description of these social indicators. The social indicators ranked by importance are as follows: 3 for stakeholder participation, community engagement, development of social capital, regional inequality, formation of human capital, and social cohesion. The remaining two indicators on preservation of cultural heritage and demographic transition and change are ranked a 2 by importance as they can produce social outcomes but are not requisite conditions. The results of the assessment of social impacts of the projects are tabulated in Appendix Table 12. The German Open Air Library ranks the highest with a 1 as it excelled in all the social impact indicators, being a social project from the start. This is followed by 2 Rehafutur House in France;3 the Superlocal project in the Netherlands; 4 Circular Retrofit Lab and 5 the Upcycle Studios. While both projects have elements of cultural preservation and demographic transition and change, the French project edged out the Dutch project in terms of issues of regional inequality considering the geographical significance of the project site. Meanwhile, the Danish project was a brainchild of the architectural company and did not involve much stakeholder participation except with the product manufacturers.

Based on the rankings on the three dimensions of environmental, economic and social impacts, Table 1 summarizes the projects to obtain an average rank.

Table 1. Summary of Ranks on Environmental, Economic and Social Impacts of Selected EU Projects

Project	Environmental Impact	Economic Impact	Social Impact	Average Rank
Superlocal Project, NL	2	4	3	3
Circular Retrofit Lab, BE	4	3	4	3.7
Open Air Library, DE	5	5	1	3.7
Rehafutur House, FR	1	2	2	1.7
Upcycle Studios, DK	3	1	5	3

The results show that the Rehafutur House in France achieved a neat balance, hence, best practice of environmental, economic and social dimensions of sustainable and circular construction. This was followed by both the Danish Upcycle Studios and Dutch Superlocal projects which only varied in their rankings for social and economic impacts where the former was stronger on economic but weak on social and conversely, the latter was stronger on social and weaker on economic effects. The Circular Retrofit Lab of Belgium and the German Open Air Library tied in last place although the Belgian project was more balanced in addressing the three dimensions compared to the German project which only scored strongly on social impact.

6 Findings and Conclusion

The CDI sector generates the most waste among all economic sectors and has been the target of sustainability and circularity efforts of the EU. While the overall aim is to reduce waste, the paper has shown that the success of a project on balancing sustainability goals of environment, economic and social objectives are determined by the stages of circularity the project operates in, the building design principles it applies, the phase of the construction life cycle where it is focused and the overall policy framework that can be national, municipal/city-wide or regional that guides the project conception.

Depending on the stage of circularity, the higher the rung a project targets in the waste hierarchy or circularity ladder from merely reuse or recycle to refurbish and remanufacture, the more economic benefits accrue, specifically business creation and value chain multiplier effects, greater residual values, increase in innovation effort and new technologies along with associated investments, and possible trade effects by reduced imports of primary materials and potential rise in exports of circular building materials. These augments the employment effects that already exists at lower rungs of the ladder. Meanwhile the environmental effects are enhanced the higher a project goes through the waste hierarchy or even the circularity ladder. More than simply reducing solid waste and greenhouse gas emissions or saving water and energy, more environmental benefits accrue with product life cycle extension and use of natural or bio-based materials.

The building design principles discussed in the paper also influence the triple bottom line. Building in layers, building for adaptability and building for disassembly have the most potentials as shown by the projects to attain more economic, environmental and social objectives. In the Danish and Belgian projects, designing for adaptability/disassembly or what in the Belgian case is called reversible building solutions create possibilities for the sharing economy business model where different reconfigurations of a building create flexibility for office and living spaces, fostering not only income potentials for entrepreneurs but also formation of social capital. A key first step though is selecting materials for the built environment and evaluating their embodied pollution in addition to toxicity levels on human health, which was evident in majority of the projects, thus enabling a system of materials passport.

In the construction life cycle, the design phases and use phases are critical in framing the building design principles discussed above while the use phase looks at business model applications like the sharing economy and reversible functionalities as shown in the Danish and Belgian projects, respectively, where more economic and social benefits accrue. In the material production, construction and end of life stages of construction, more environmental impacts are achieved as waste reduction and embodied pollution of materials are performed more in these stages.

The cross country comparison of projects show that projects that involve use of biotic resources in the environmental indicators (i.e., the Rehafutur House in France, Superlocal project in the Netherlands and CRL project in Belgium) edged out the other projects that do not. Land use is another feather in the environmental cap as shown in the French, Dutch and Belgian projects but also in the German project where abandoned fallow land was reclaimed. Checking for the toxicity of building materials is also integral to environmental impact which boosted the score of the Danish project as many demolished materials were constructed in the 1950s to 1970s when lead and asbestos were commonplace building fixtures. Embedded or embodied pollution in materials should also be considered and not just the visible reductions in energy and greenhouse gas emissions that circular projects offer as evident in the French, Dutch and Belgian pilots.

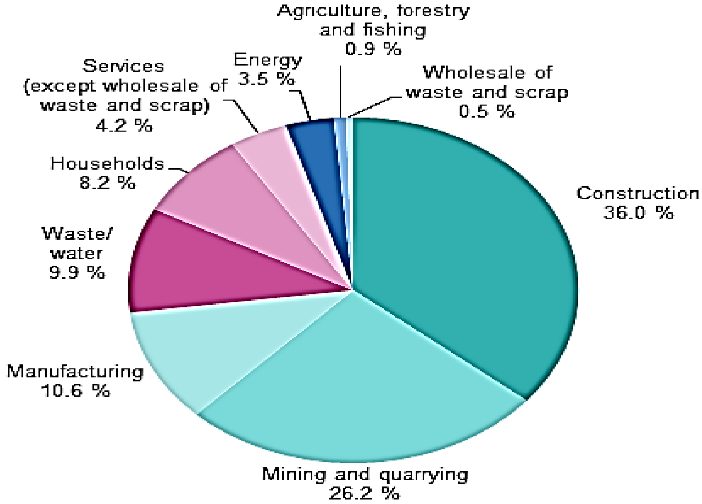
In the economic realm, financial self-sufficiency of the projects is critical for circular projects to thrive as availability of subsidies limit replication of similar initiatives. The Upcycle Studios in Denmark showcase the importance of market solutions in attracting consumer acceptance when offering circular building materials that are equivalently aesthetic and price-competitive as conventional alternatives.. The German project in a way underscores the momentum that the private sector (social or community-led) cooperation can exert on circular initiatives which later on in the project cycle drew supplemental federal support to fill in the financial gap needed for the project. While subsidies help in triggering pilot circular prototypes as displayed by the Dutch, French and Belgian projects, more self-sustaining funding will be required for these circular projects to thrive. Even in the absence of the self-financing solution that the market offers, the Danish landfill tax system to finance recycling technologies would achieve the same effect as government revenues collected from landfilling will be diverted to finance circular projects in CDI and hence be self-continuing. Multiplier effects from commercialization and scaling of innovation and newly discovered technologies on the value chain such as those from eco-materials used for insulation in Rehafutur, the stackable bricks of Superlocal, the reversible wall panels of the Retrofit Lab, and the upcycled wood, glass and concrete of Upcycle Studios amplify the job creation effects on the economies of the sampled countries.

The social aspect which is often the ignored pillar of the sustainability triptych should transcend just mere stakeholder participation but a deeper community engagement and ownership of the project as validated by the German Open Air Library where residents not only donated the beer crates and books but took over running the management and maintenance of the project. The downside to this private communal endeavor is the ‘tragedy of the commons’ that public property are prone to, with incidences of vandalism inflicted on the library. However, as economic theory suggests, Coasean bargaining solutions as opposed to Pigouvian state solutions may prevail as attested to by residents assuming the maintenance responsibility. Many of the projects exploited the opportunities for developing social capital through co-ownership and formation of clusters and networks of users, suppliers and producers of circular building materials as shown in the Dutch, Belgian and French projects, as well as fostering social cohesion among residents of the demolished buildings of Superlocal or the artisans and farmers of Rehafutur for processing the eco-materials. The element of a sharing economy or business model also bolsters the social impact as shown by the flexible residential/workspace townhouses of Upcycle Studios or the reversible functionalities of building space that CRL in Belgium endorses.

The projects selected for this comparative study comprised countries that reflect country-wide, city-wide or region-wide strategies of circularity with only the Netherlands and Denmark articulating a national circular strategy in CDI. France composed a national strategy on CE but more encompassing several sectors including CDI. Belgium adopted a circular strategy for the construction industry but was not national but focused on the capital region. Finally, Germany has a regional circular strategy but not specific for construction. This lack of political impetus shows why the German project lagged behind the other projects and was more a grassroots attempt, hence more dominantly displaying its social enterprise nature. The point here being made is that for the circular mentality to take root in society, political ascendancy is needed and is an antecedent to steer stakeholders to this mindset.

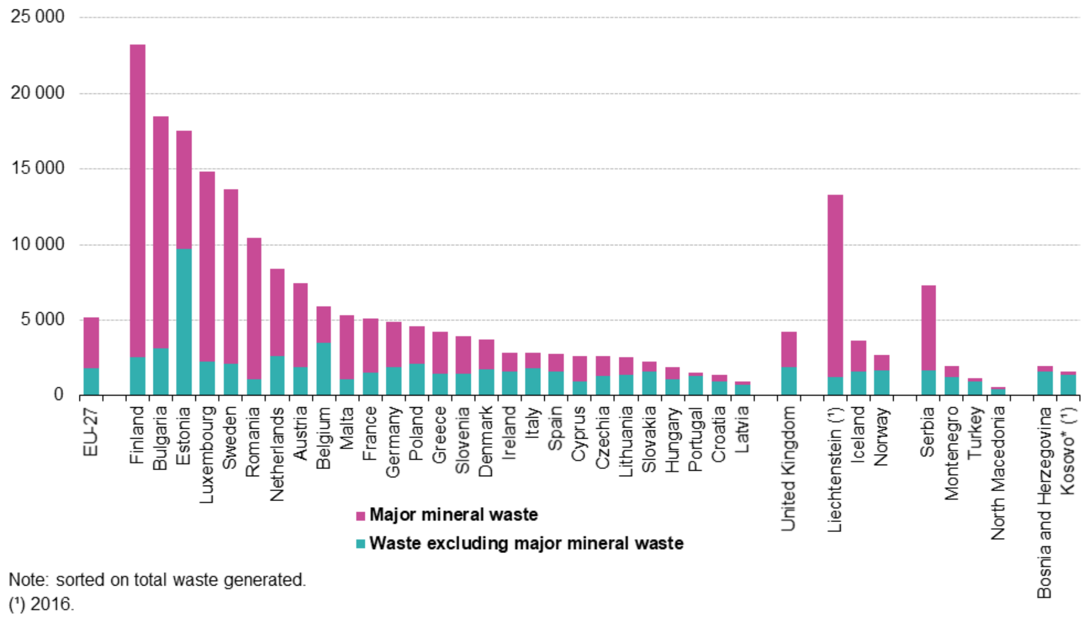
The basic limitations of the study is the *ex-ante* nature of the analysis, relying only on project or case descriptions and in some cases mid-term reviews. There are also partial overlaps in the determinants such as between circularity stages and life cycle stages that could possibly lead to double counting or over- and under-evaluation of some projects. The scoring and ranking system may also be subjective although the findings would not have been significantly altered unless the multi-criteria decision making analysis were more developed mathematically or scientifically. The choice of projects also do not speak volumes about the national strategy as a better project could have boosted the ranks or the scores of a particular country. To achieve a better comparison among EU experiences on circularity in CDI, several projects like 3 to 4 projects and not just one prototype project of that country would be a better gauge. There is also need for further study on multi-criteria decision analysis in the context of circularity like the use of objective or integrated methodologies to properly weigh the different criteria on environmental, social and economic impacts. Another area for future study is to include more EU/European countries (i.e., Finland, Spain, Italy, Sweden, Austria, UK, Switzerland, Norway) and the Eastern European countries (Slovenia, Hungary, Czech Republic, Poland) which are the largest waste generators and which have themselves defined circular strategies in CDI at the state, regional or metropolitan level. Finally, a more global comparison of experiences in circularity in CDI with Asian countries (e.g., Japan and Korea), countries on the American continent (e.g., Canada, Mexico, USA), Africa (South Africa) and Oceania (Australia) may unlock significant insights.

Figure 1. Waste Generation by Economic Activity and Households, EU-27, 2018



Source: Eurostat (online data code: env_wasgen)

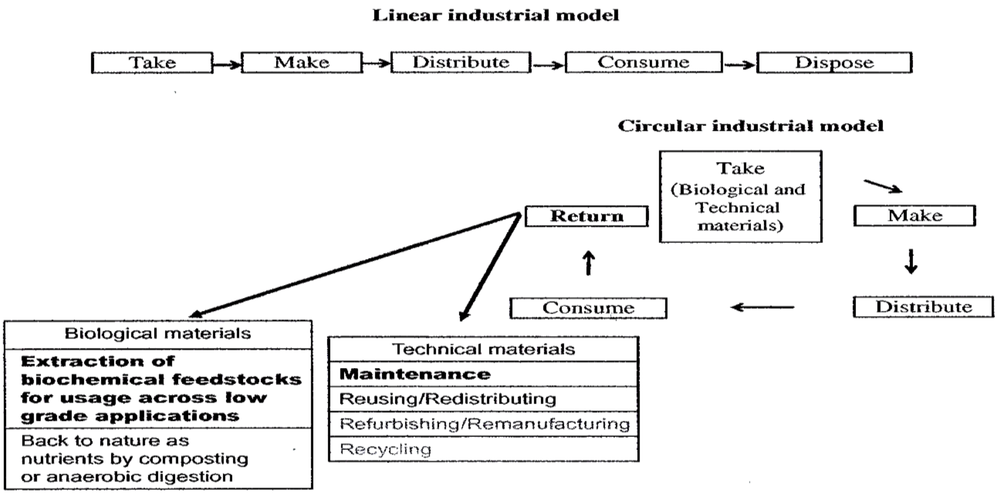
Figure 2. Per Capita Waste Generation in the EU-27 (in kg)



Note: sorted on total waste generated.
(¹) 2016.
** This designation is without prejudice to positions on status, and is in line with UNSCR 1244/1999 and the ICJ Opinion on the Kosovo declaration of independence.*

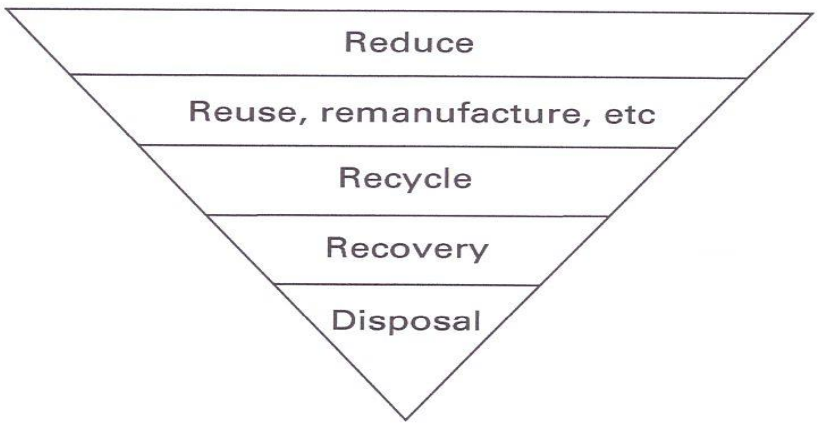
Source: Eurostat (online data code: env_wasgen)

Figure 3. Circular vs. Linear Economy



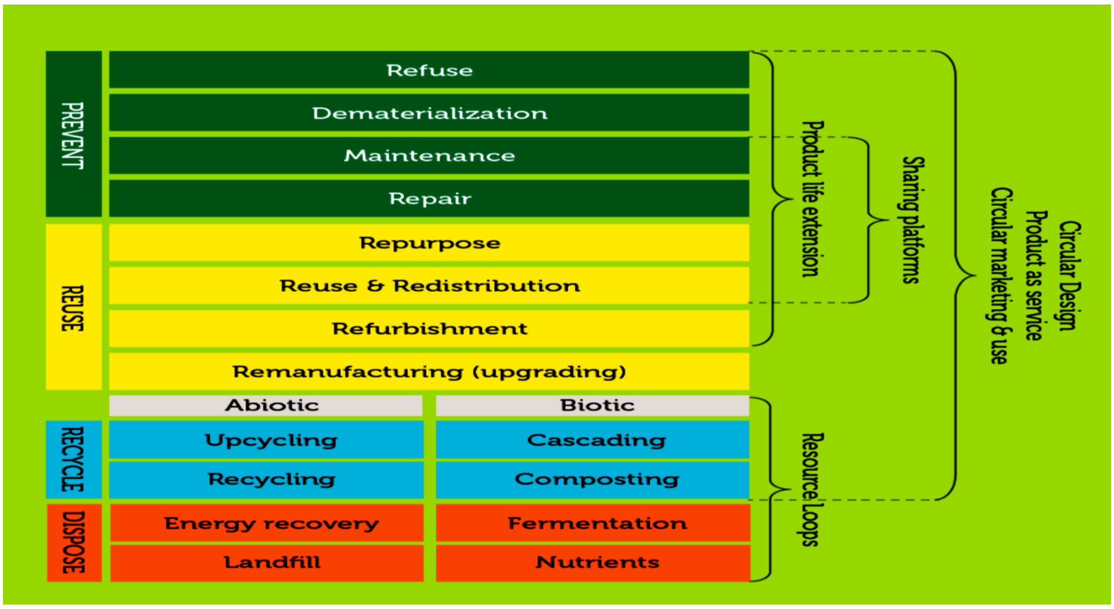
Source: De Angelis (2018), p.21.

Figure 4. Hierarchy of Waste Management



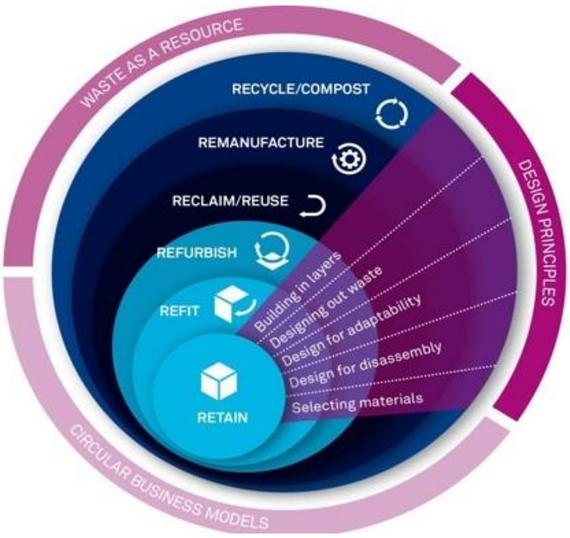
Source: Grant, Trautrims & Wong (2017), p. 183.

Figure 5. Circularity Ladder Concept



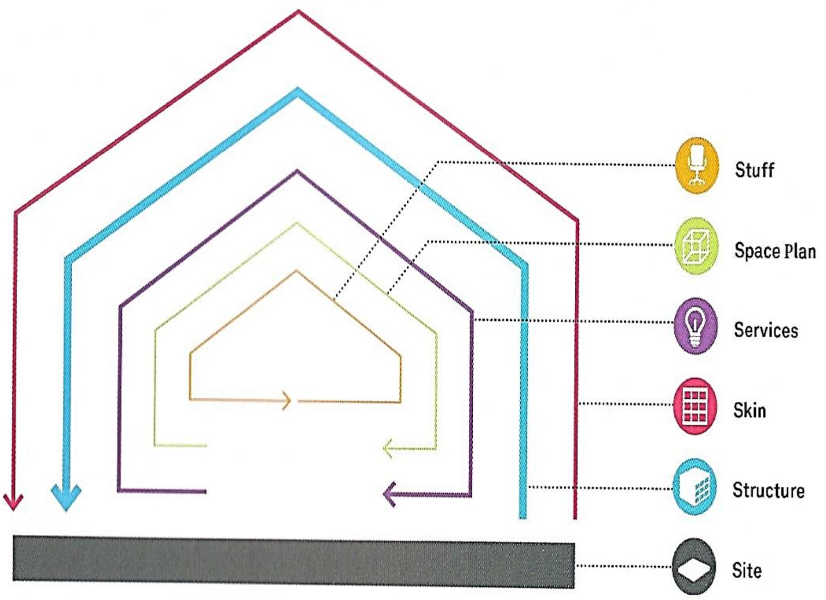
Source: De Groene Zaak & Ethica (2015)

Figure 6. The circular economy stages in the building environment



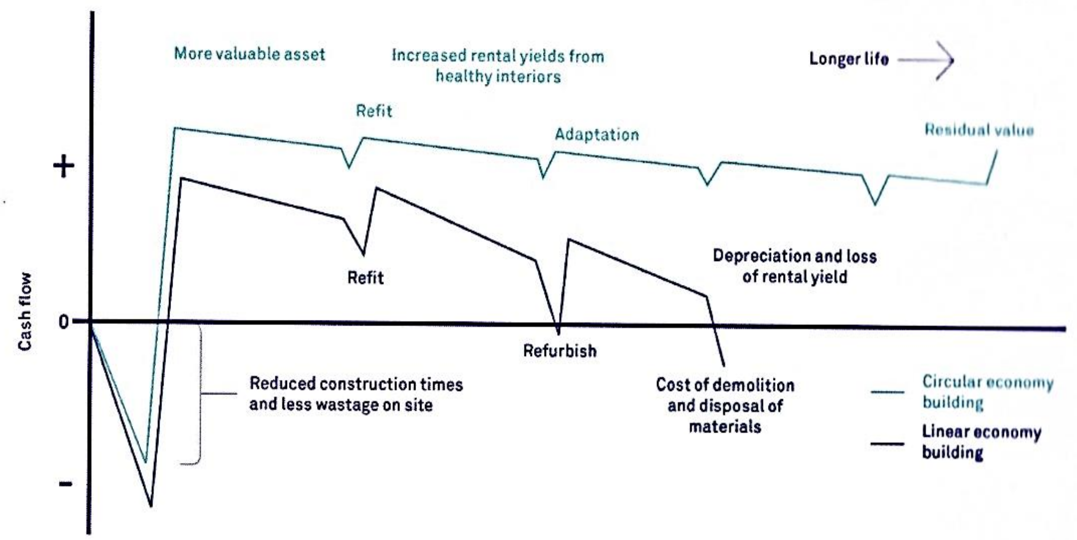
Source: Cheshire (2016)

Figure 7. Building in Layers



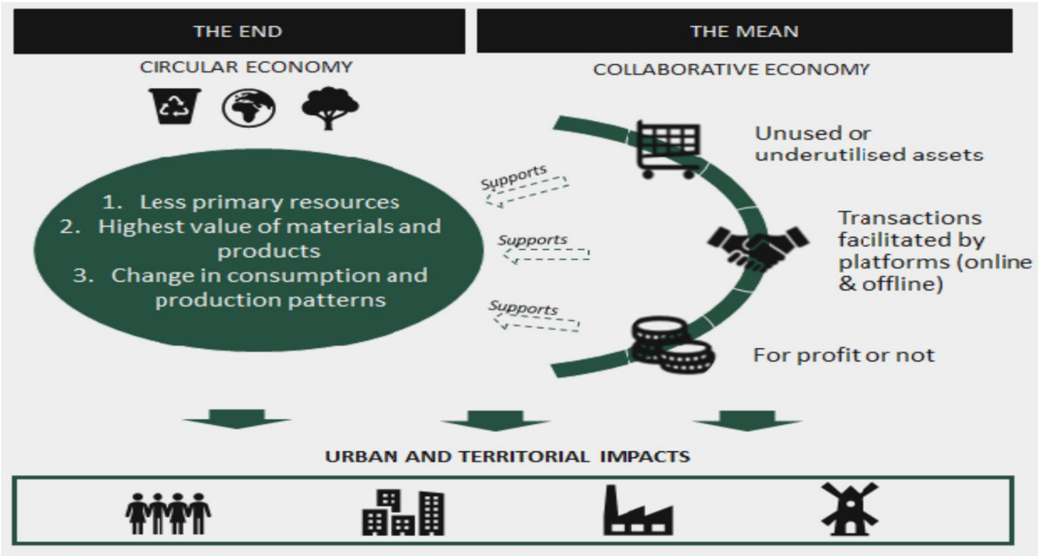
Source: Brand (1994)

Figure 8. Benefits of Circular Economy Buildings



Source: Cheshire (2016)

Figure 9. Concept of Urban Circular Collaborative Economy



Source: Valdani, Vicari & Associati (VVA) Economics and Policy as cited in ESPON (2020), p. 8.

IOP Conf. Series: Earth and Environmental Science **855** (2021) 012017 doi:10.1088/1755-1315/855/1/012017

Appendix Table 1. Recovery Rates of Construction and Demolition Waste in the EU (%)

Geo\time	2010	2012	2014	2016
EU (28 countries)	79	86	89	90
Euro area (19 countries)	:	:	:	:
Belgium	17	18	32	95
Bulgaria	62	:	:	90
Czechia	91	91	90	92
Denmark	:	91	92	90
Germany	95	94	:	:
Estonia	96	96	98	97
Ireland	97	100	100	96
Greece	0	0	0	:
Spain	65	84	70	79
France	66	66	71	72
Croatia	2	51	69	76
Italy	97	97	97	98
Cyprus	0	60	38	57
Latvia	:	:	92	98
Lithuania	73	88	92	97
Luxembourg	98	99	98	100
Hungary	61	75	86	99
Malta	16	100	100	100
Netherlands	100	100	100	100
Austria	92	92	94	88
Poland	93	92	96	91
Portugal	:	:	:	97
Romania	47	67	65	85
Slovenia	94	92	98	98
Slovakia	:	:	54	54
Finland	5	12	83	87
Sweden	78	81	55	61
United Kingdom	96	96	96	96
Iceland	75	100	86	99
Liechtenstein	:	:	:	:

Data from Eurostat, dataset (cei_wm040)

Appendix Table 2. Definitions and Interpretations of the Circular Economy

Source	Definition/interpretation
Sauvé et al. (2016)	Circular economy refers to the "production and consumption of goods through closed loop material flows that internalize environmental externalities linked to virgin resource extraction and the generation of waste (including pollution)".
Preston (2012)	"Circular economy is an approach that would transform the function of resources in the economy. Waste from factories would become a valuable input to another process – and products could be repaired, reused or upgraded instead of thrown away".
EEA (2014)	Circular economy "refers mainly to physical and material resource aspects of the economy – it focuses on recycling, limiting and re-using the physical inputs to the economy, and using waste as a resource leading to reduced primary resource consumption".
Mitchell (2015)	A circular economy is an alternative to a traditional linear economy (make, use, dispose) in which we keep resources in use for as long as possible, extracting the maximum value from them whilst in use, then recovering and reusing products and materials.
Heck (2006)	The utilisation of sustainable energy is crucial in a circular economy. The transition to a circular economy would require addressing the challenge of establishing a sustainable energy supply as well as decisive action in several other areas such as agriculture, water, soil and biodiversity.
Su et al. (2013)	The focus of the circular economy gradually extends beyond issues related to material management and covers other aspects, such as energy efficiency and conservation, land management, soil protection and water.
Bastein et al. (2013)	The circular economy transition "is an essential condition for a resilient industrial system that facilitates new kinds of economic activity, strengthens competitiveness and generates employment".
EEA (2016)	"A circular economy provides opportunities to create well-being, growth and jobs, while reducing environmental pressures. The concept can, in principle, be applied to all kinds of natural resources, including biotic and abiotic materials, water and land".
Ghisellini et al. (2016)	The radical reshaping of all processes across the life cycle of products conducted by innovative actors has the potential to not only achieve material or energy recovery but also to improve the entire living and economic model.
ADEME (2014)	The objective of the circular economy is to reduce the environmental impact of resource consumption and improve social well-being.
Ellen MacArthur Foundation (2013a; 2013b; 2015a)	Circular economy is "an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models". The overall objective is to "enable effective flows of materials, energy, labour and information so that natural and social capital can be rebuilt".
European Commission (2015a)	The circular economy is an economy "where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimised". The transition to a more circular economy would make "an essential contribution to the EU's efforts to develop a sustainable, low-carbon, resource-efficient and competitive economy".

Source: Rizos, Tuokko & Behrens (2017), p.6.

Appendix Table 3. Country (City-Municipality and/or Regional) Strategies on Circularity in the CDI Sector

Country	Strategy Document	Goal	Strategy/ Approach
Netherlands	Holland Circular Hotspot (2018); Breen et al. (2018); Pötting et al (2018); Schut et al. (2015)	• Make Dutch economy fully circular by 2050, • Reduce use of primary raw materials by 50% • Halving CO2 emission in construction industry by 2030 • Realizing high grade (or higher grade) recycling in all construction submarkets (civil engineering & utility construction, (C&U), ground water & road construction (GWR) • Construction of 1 million energy neutral houses in circular way in period of 10 years per De Bouwagenda • Develop knowledge, experience & tools for people in whole construction chain • Research into stimulating socio-innovation • Develop uniform circularity measuring method	• Encourage use of granulated/recycled concrete mixed with new • Apply circular criteria on public land used for housing development projects • Training for large contractors on circular procurement and construction • Optimal use of materials for all phases in the construction cycle • Use many infinite sources as possible with more and higher grade reuse at end of life phase • Make use of finite sources as efficiently as possible • Pioneer research and execute practical projects from experiment to demonstration to market introduction of new products and services for circular construction • All public tenders will be circular by 2030 • Mandatory materials passport by looking at value added of all materials and resources used in buildings • Government subsidy and financial support at individual business level for circular business and revenue models • Circular construction as comprehensive part of education in 2021 involving architectural training and circular commissioning training programs
Belgium	Fontaine & Dewulf (2018); Fontaine & Dewulf (2019); Breen et al. (2018)	• Circular design, building maintenance, reuse and remanufacturing of construction waste in the territory • Design buildings that allow them to adapt to new uses while limiting environmental impact, promote maintenance of material resources, build from recovered elements • Integrate circularity in territory programming • Stimulate/support requests of clients • Stimulate/accompany the offer with professionals • Develop a sector of re-employment materials • Prepare/create a favorable logistics framework • Prepare/create a favorable regulatory framework	• Transitioning businesses to more circular use of materials and subsidized collaborative work spaces (i.e., Greenbizz program) • Pilot projects for reversible construction • Business park created for CE companies • Co-creation workshops with stakeholders • Adopted "Be circular" to become resource efficient, maximize local resources to boost entrepreneurship and create employment opportunities • Support new retail businesses and start-ups/ existing businesses to adopt CE principles

France	Ministry of Ecological and Solidarity Transition (2018); Breen et al. (2018)	• Make waste collection in built environment more effective by combatting use of landfill and enable good sorting of construction materials so these can be recycled • Move to assessment/ inventory process for reuse and recovery of waste from renovation and demolition sites	• Make a building stock bank for future construction materials • Material recovery from exchange, repair, reuse, and recycling • Waste reduction • Networking of and synergies among actors • Raise awareness and train contractors on CE
Germany	The Circular Economy in Southern Germany (2019); Breen et al. (2018); Lah (2016)	• Raising resource efficiency in production and consumption • Reduction of using non-renewable resources in construction and replacement by re-growable raw materials • Extending the life span of buildings and reconstruction using passivhaus (energy efficient) standards	• Increased application of recyclate materials in construction instead of natural resources at no additional costs • Quality insurance of recyclate materials • Information campaign promoting usage of recyclate materials
Denmark	Deloitte (2015); Ministry of Environment and Food and Ministry of Industry, Business and Financial Affairs (2018); Breen et al. (2018)	• The recycling of construction and demolition waste (CDW) does not cause contamination of environment and maintains high recycling rate • Identifying, separating and safe handling of problematic substances in buildings before demolition • Improve quality of CDW using new technologies for specific waste streams aiming for high grade recycling (upcycling) • Focus on quality recycling of CDW	• Develop new technological solutions for waste management by recycling and embracing CE principles where new technologies aim for high-grade recycling for specific waste streams (concrete, bricks, wind turbine blades, impregnated wood, district heating pipes, tar paper, etc.) • Final recycling and upcycling of resources • Screening by developers to assess whether buildings or structures contain polychlorinated biphenyls (PCBs) • Sorting of CDW into 10 waste fractions (natural stone, non-glazed tiles, concrete, mixtures of the first 3, iron and metal, gypsum, rock-wool, soil, asphalt and mixture of concrete and asphalt_ • Stakeholder involvement in construction and renovation of buildings and structures (producers of construction products, contractors and architects) • Use of landfill tax with lower rates for recyclable materials to reduce amounts to be landfilled and finance development of recycling technologies

Source: Compilation of authors from sources cited in column 2 of the table.

Appendix Table 4
Selected EU Projects Case Descriptions

EU Projects	Project Case Descriptions
Superlocal, Netherlands Figure 10. Superlocal Project, Netherlands  Source: www.superlocal.eu	The Superlocal project in the Netherlands entails the demolition of 10-storey apartment blocks into components ranging from complete apartments to concrete aggregates for use in building new houses (superlocal.eu) and construction of 100 new homes in a district facing population decline and threat of vacant occupancy. The project used three construction techniques: 1) removal of an entire studio unit and reusing the hull as shell for new houses; 2) remanufacturing concrete bricks that can be stacked on top of each other without cementing them but using steel tension cables or rods to form a concrete wall, thus facilitating disassembly at end-of-life for reuse; and 3) retrieving concrete rubble from demolition to be upcycled into new circular concrete that reduces use of new cement, water and plasticizer usage. The project was funded by a €4.8 million EU subsidy under the Urban Innovative Actions program and is a collaborative effort with 12 associations that range from surrounding municipalities, universities, construction companies, utilities provider, and homeowner's association to experiment on new building techniques in the circular construction of homes. This project combines retain, reuse, and refit stages in circularity with elements of designing for disassembly and designing for adaptability using Cheshire's (2016) framework. The Superlocal project in the construction lifecycle is oriented towards the material production, design, construction and end of life phases.
Circular Retrofit Lab, Belgium] Figure 11. Circular Retrofit Lab, Belgium  Source: www.bamb2020.eu	The Circular Retrofit Lab (CRL) project in Belgium is a pilot project of the Buildings as Material Banks (BAMB) initiative, involving renovation and transformation of eight student houses that were built using prefabricated concrete support modules which could be arranged in spatial ways leading to urban cluster configurations through reversible solutions (bamb2020.eu/topics/pilot-cases-in-bamb/retrofit-lab/). Renovation involves internal, external and spatial transformation of concrete structural modules. The Retrofit Lab is a pilot project owned by the Vrije Universiteit Brussel (VUB) for circular reconstruction that engages co-creation process with stakeholders (architecture students, contractors and construction material suppliers) along the redesign, rebuild, reuse, and dismantling stages of on design and test solutions with hands-on workshops for students and to test integration of materials passport. Reversible solutions for circularity. The team in charge of the project organized roundtables with industry stakeholders to debate internal partition walls and facades using modular, pre-fabricated and kit-of-part design approach to foster flexibility in assembly, manufacturing efficiency and scalability in implementation. New and reversible functionality of partition walls to living room separation was explored together with product manufacturers. The project employs refit, refurbish, remanufacture principles of Cheshire (2016) with strong design for adaptability and building in layers applications. The Retrofit Lab could be positioned in the material production, design, construction and use phases of the life cycle.
Open Air Library, Germany Figure 12. Open-Air Library, Germany  Source: www.archdaily.com/39417/open-air-library-karo-architekten	The Open Air Library in Germany is a community endeavor that reclaimed land on abandoned industrial site using beer crates as building material and donations of books and other materials from residents (archdaily.com/39417/open-air-library-karo-architekten). The library was constructed in 2005 in an abandoned fallow industrial site in Magdeburg, East Germany. Started as a public initiative with supplemental funding from the federal government, the library used beer crates lent by local residents as building material. The residents filled the shelves of the library with books they donated which now houses a collection of 30,000 as of the latest count. The shelves are never closed and anyone can just take a book without registration provided they are returned or replaced with another book. The outdoor space was designed with local residents with a stage for communal functions such as theater plays for the elementary school, concert gigs for youth bands and other cultural events. Besides the social aspect, the architecture holds historic significance as it re-used the facade of the old Horten warehouse of the city of Hamm which was demolished in 2007. The project exemplifies the reclaim and reuse stage of circularity and applies designing as waste principle. In terms of the construction lifecycle, the Open Air Library involves the design, construction and use phases.
Rehafutur Engineer's House, France	The French project Rehafutur Engineer's House is unique in that renewable eco-materials such as flax fiber, wood fiber, hemp bricks, sheep wool, recycled textile and the like were used as insulation materials [Derbal, Lucas, Brachelet, Defer & Antczak (2016); CE100 (2016)]. The

Figure 13. Rehafutur Engineer’s House, France  Source: www.cd2e.com	project also involves preservation of cultural heritage as it renovated a typical mining house into offices in the Loos-en-Gohelle region in Northern France which is a UNESCO-listed historical site. This is one of the projects under the EU-sponsored CAPEM (Cycle Assessment Procedure for Eco-Impacts of Materials) consisting of improving the building thermal insulation. Because of the historical value, the external façade could not be touched so that retro-fitting could only be done in the interiors. Reuse of existing materials were applied by moving two marble fireplaces as ornamental pieces in public rooms, by relaying 62 square meters of hundred-year-old spruce floorboards after careful dismantling to install the new floor insulation, by reusing 18 square meters of multi-colored cement tiles, and by repaving the parking spaces and access paths with 350 square meters of rubble. The project applies the retain, refit and refurbish phases of Cheshire (2016) with selection of materials as the major design principle. In the construction lifecycle, the project involves material production, design, and construction stages.
Upcycle Stuidos, Denmark Figure 14. Upcycle Studios, Denmark  Source: www.lendager.com	Finally, the Upcycle Studios in Denmark consists of twenty terraced houses that were constructed using upcycled waste materials consisting of glass, wood and concrete refuse (urbannext.net/upcycled-studios/). Based on the concept of raw urban context where houses blend with surroundings while economy business model as principles of new housing, where ownership is cast aside in favor of access to resources. This is facilitated by the use of the houses at all hours of the day not just by the owners but by creative freelancers and self-employed entrepreneurs while serving as one dwelling promoting sustainable living, the Upcycle Studios uses symbiosis, resource efficiency and the shared for large families as houses can be split into two separate apartments. The owners can earn extra income by renting out one apartment either permanently a la Airbnb, or temporarily while waiting for their household memberships to enlarge at a time when only few rooms are used. The Upcycle Studios, built by the Lendager Group, is located in the Ørestad Syd district of Denmark, requiring balancing of housing and business elements. Similar to the Rehafutur house in France, the Upcycle Studios blends new building with history by reusing walls, residual wood, crushed concrete and windows from abandoned buildings and construction waste that are non-toxic certified. About 75 percent of the windows originate from abandoned buildings in North Jutland, Denmark; 1,400 tons of upcycled concrete are forged from durable concrete waste from the construction of the Copenhagen Metro; and the wood and floors are manufactured from off-cuts of Dinesen which is Denmark’s leading manufacturer of plank floors. The Upcycle Studios combine refit-refurbish, reuse, remanufacture stages of circularity and applies the designing principles of selecting materials, building in layers, and designing for adaptability. In the construction life cycle, the project manifests aspects of material production, design, construction, and use phases.

IOP Conf. Series: Earth and Environmental Science **855** (2021) 012017 doi:10.1088/1755-1315/855/1/012017

Appendix Table 5
Comparison of Selected Projects on Basis of Circularity Stages, Construction Life Cycle and Design Principles

	Superlocal Netherlands	*Retrofit Lab* Belgium	*Rehafutur House* France	*Open Air Library* Germany	*Upcycle Studios* Denmark
Circularity Stages					
• Retain	3	3	3	2	2
• Refit	3	3	3	3	3
• Refurbish (Upcycle)	2	3	2	2	3
• Reclaim/Reuse	3	3	3	3	3
• Remanufacture	3	3	3	1	3
• Recycle/Dispose (Downcycle)	3	2	3	2	3
Construction Life Cycle					
• Material production	3	3	3	1	3
• Design	3	3	3	3	3
• Construction	3	3	3	3	3
• Use	2	3	3	3	3
• End of life	3	3	2	1	3
Design Principles					
• Build in layers	3	3	3	3	3
• Design out waste	3	3	3	3	3
• Design for adaptability	2	3	2	2	3
• Design for disassembly	3	2	2	1	2
• Material selection	2	2	3	2	3

Source: Authors

Appendix Table 6
Sources for Project Descriptions

- Netherlands:
  - Superlocal Play Publicatie (n.d.); Superlocal Indexation (n.d.); Burenboek (A)BCD (n.d.) downloadable from www.superlocal.eu
  - Fernandez, A. (2020). *Superplocal Flash Lecture*, Zuyd University of Applied Sciences
  - Ritzen et al. (2019)

- Belgium:
  - Paduart et al. (2018)
  - D12. Feasibility Report,
  - D13 Protyping + Feedback report,
  - D14 4 Pilots Built + Feedback Report downloadable from https://www.bamb2020.eu/topics/pilot-cases-in-bamb/retrofit-lab/

- Germany:
  - https://www.archtopia.com/karo-architekten-open-air-library/
  - https://inspiration.detail.de/open-air-library-in-magdeburg-103470.html
  - https://designlike.com/open-air-library-in-magdeburg-germany/
  - https://inhabitat.com/stunning-open-air-library-pops-up-in-east-germany/
  - https://creatingvibrantcommunities.com/shared/open-air-library-magdeburg-germany/
  - https://miesarch.com/work/2769
  - https://www.dezeen.com/2009/10/28/open-air-library-by-karo/
  - https://www.archdaily.com/39417/open-air-library-karo-architekten
- France:
  - CE100 (2015)
  - Gravagnuolo et al. (2019)
  - Derbal et al. (2017)
- Denmark:
  - https://lendager.com/en/architecture/upcycle-studios-en/
  - https://urbannext.net/upcycled-studios/
  - https://arcspace.com/feature/upcycle-studios/
  - https://www.dezeen.com/2019/04/16/upcycle-studios-townhouses-lendager-group-copenhagen-recycled-materials/
  - https://architizer.com/projects/upcycle-studios/
  - https://issuu.com/lendagertcw/docs/achangemakersguidetothefuture_2.udg

Appendix Table 7
Description of Environmental Indicators

Indicator	Description
Reduction of GHG emissions	refers to CO_2 emissions from energy consumed in building material production as well as release of volatile organic compounds such as nitrogen oxides and sulphur dioxides in the manufacture and transport of construction materials that lead to ozone depletion
Savings on water use	pertains to reduction in water use in construction activity but also developing building products that enable building occupants to recycle or use alternative water sources such as rainwater runoff
Savings on energy consumption	relates to use of energy saving materials in the design and construction of buildings, improving building insulation and sealing performance, and enhancing the efficiency of heating, cooling, ventilation and lighting systems to reduce energy consumption
Embodied pollution	concerns the extent of energy, carbon and water used in the extraction, production, transport and use of construction materials, implying higher ecological consequences
Solid waste reduction	entails the extent that unwanted products from demolition, pre-construction, on-site construction and post construction are managed by sorting, reducing, reusing and recycling of waste materials including sorting before use as landfill
Product life cycle extension	relates to selection of materials with recycled content, high durability and resilience from shocks and high recycling or reuse potential in the design and pre-construction phase; building performance that minimizes need for maintenance and replacement; and maximizing recovery of materials at end of life considering as well ease of deconstruction or disassembly
Use of biotic materials	concerns the use of conventional bio-based materials made from plant and animal materials that are biodegradable and emerging bio-renewable materials that are extracted by industrial processes or produced from materials with biological origins but can be regrown
Reduction of exposure to human toxicity	involves segregation and safe disposal of hazardous and toxic construction waste upon demolition, replacement of existing toxic building materials such as asbestos-based materials, radioactive materials, lead plumbing, materials that release toxic fumes during a fire, and emit volatile organic compounds from paints and varnishes and impregnating agents (see Pacheco-Torgal et al., 2011)
Land use	Relates to land occupied by construction assets as well as embodied land use in non-renewable and renewable raw materials and energy over the building's value chain which affect soil sealing (when agricultural or other non-developed land is built upon), soil compaction (high loads caused by construction that reduces soil absorptive capacity), change of land use (ecological land which is built up causing biodiversity loss, soil degradation, and changes in hydrology) (see Häkkinen et al.,2013).

IOP Conf. Series: Earth and Environmental Science **855** (2021) 012017 doi:10.1088/1755-1315/855/1/012017

Appendix Table 8. Environmental Impact of Selected EU Projects

Indicators for Environmental Sustainability	Rank of Importance	**Superlocal, NL**	Score	**Circular Retrofit Lab, BE**	Score	**Open Air Library, DE**	Score	**Rehafutur House, FR**	Score	**Upcycle Studios, DK**	Score
• Reduction of GHG Emissions	3	Planned use of equipment (cranes, loaders) and labor to lower CO_2 emissions plus on-site construction to minimize transportation	4	Construction practices and plants are used to reduce emissions. Building materials used are prefabricated offsite to minimize onsite construction and reduce emission.	3	Designed as open air by residents to reduce emissions	3	Avoided use of 17 semi-trailers to carry debris to landfill and monitoring of CO_2 emissions during use phase of the building	5	The upcycled materials used to build the residential buildings help minimize emissions. Upcycle Studios reduces the total CO_2 emissions considerably over the life of the building. Upcycle Studios potentially reduces the total CO2 emissions over 50 years by about 60 percent	5
• Savings on Water Use	3	Less water used in technique 3 on upcycled concrete & bricks without wet connection. Worked with WML to develop closed water cycle using rainwater collected and purified to drinking water	5	Use of grey water or rain water in construction and operation of the building. Reversible Building solutions considers sustainable use of water	3		1		1		1
• Savings on Energy Consumption	3	Lower diesel and energy costs of equipment by planning distance travelling from demolition to construction site	4	Construction practices and plants are used to reduce energy	3	The project with limited funds kept construction costs low and avoided the energy consumption of air-conditioning, by designing it as open air.	4	Reduction in heating demand to 34 kWh/m^2 from 104 kWh/m^2 which is maximum in region	5	Upcycle Studios saves 15 metric tons of CO_2 annually per dwelling using renewable heating through solar power combined with geothermal energy. With rooftop	5

										solar panels the houses are potentially self-sufficient	
• Embodied energy and pollution	3	The investigated pilot dwelling consists of 3.35E02 GJ embodied energy, of which 65% is embodied in re-used materials, and 4.62E01 tons of embodied CO2, of which 90% is embodied in re-used materials (Ritzen et al., 2019)	5	Sustainability of supply, durability, embodied carbon and embodied water were considered when specifying materials	5	Cut down on crates of pressed tree pulp by using shared resources such as book donations and beer crates	3	Hygrothermal behaviour (repeated wetting, drying, freezing and thawing of the fabric of a building leading to mold growth, condensation and loss of thermal performance), of the insulation materials were analyzed and quantified. Each façade is monitored to measure the thermal resistance of the insulation materials on-site (including the roof). Comfort parameters are also monitored; room temperature, relative air humidity and carbon dioxide levels.	5	Biodiversity of the neighborhood increases with the roof gardens; Each of Upcycle Studio's building components are analyzed in isolation, scrutinizing its whole-life energy performance against a strict set of parameters	5
• Solid Waste Reduction	3	Project recycled concrete and reused entire apartment hulls which were supplanted on construction site to build stand-alone	5	Building elements can be maintained, upgraded or replaced without creating excessive waste; identification of where on-site	5	Assemblage of 1,000 empty beer cartons donated by residents as building material	5	350m^3 of rubble stored at rear of house was reused to level parking spaces and access paths	5	The wood for floors, walls and facades are produced from offcuts and surplus materials from Dinesen – these materials could have	5

		houses to minimize waste. Materials of demolition were segregated per material for reuse.		waste arises; use of materials with high recycled content						ended up as landfill or incineration plant.	
• Product life cycle extension	2	Technique 2 developed bricks that are not glued but stacked on steel cables Whole apartment hulls that were extracted and moved to construction site extended their product cycles.	5	Design ensures that building is flexible in use and adaptable to changes in use over its life span, allows building materials to be easily disassembled and can be reused and recycled at end of life. Life cycle of materials used estimated at: Fibre-cement façade panels (outside finishing) (100 years) Wooden battens (15-60 years) Waterproof layer (30-60 years) Insulation between wooden substructure (30-50 years) Vapour barrier (sealing tape) (10 years)	5	Reuse of modernist façade of old department store Horten warehouse of city of Hamm without any structural change due to its being properly maintained	5	2 marble fireplaces were moved to become ornamental features in public room; 62m^2 of spruce floor boards were dismantled and relayed after installing insulation; 18m2 of multicolored cement tiles were reused as features	5	About 75 percent of the windows come from abandoned buildings in North Jutland, Denmark. And 1400 tons of upcycle concrete are casted from very durable concrete waste from the construction of Copenhagen Metro.	5
• Use of biotic materials	2	The ground-level houses are being built	3	Use of fiber boards as wall materials	5		1	Use of 8 bio-based materials for	5		1

		based on three construction principles: 1. Materials come from their own area; Those materials were recently released at the demolition of the adjacent flat and/or 2. Materials are bio-based; These raw materials grow in one natural way back and/or 3. It must be dismountable. But to what bio-based materials were used is not known.		being lightweight and impact resistant and mineral wool as insulators				interior insulation – both vegetal (i.e., wood fiber, flax fiber, hemp bricks, expanded cork) and animal-based (sheep wool) and recycled materials (cellulose, recycled textile and recycled glass)			
• Reduction of Exposure to Human Toxicity	2		1	Wall materials meet acoustical and fire safety requirements	2		1	Comfort and health parameters being monitored such as indoor air quality, relative air humidity, and CO_2 levels as well as hygrothermal properties of eco-materials	5	Waste materials used in Upcycle Studios are upcycled to nontoxic and certified materials. All hazardous and toxic waste from debris are sorted out from demolished buildings	5
• Land use	2	Thinning out housing stock because of declining population and increase green shell within fabric of the city	4	The current building standards and the respect of the heritage value of the site had to be taken into consideration.	4	Involved reuse of abandoned industrial site with fallow land and conversion to green public space	5	Preservation of mining houses in the site which was declared a UNESCO heritage site so external façade	5	Upcycle Studios has street spaces on either side and therefore not the same clear front/back situation as the rest of the district, balancing high and low, shadow and sun, housing and business. The site is	4

IOP Conf. Series: Earth and Environmental Science **855** (2021) 012017 doi:10.1088/1755-1315/855/1/012017

										designed after shared economy principle balancing commonality and individuality with series of flexible spaces. Roof gardens add value to physical space.	
Overall Score			**95**		**89**		**72**		**103**		**93**

Source: Authors compilations from sources listed on Appendix Table 4

Appendix Table 9
Description of Economic Indicators

Indicator	Description
Employment generation	concerns potential to create new jobs and skills related to any of the circularity stages
Trade effects	relates to trade creating effects by way of imports and exports and potential to raise net exports by reducing imports of extractive and energy-intensive primary materials and export of recycled building materials
Business creation and multiplier effects on the value chain	pertains to new businesses created such as small and medium enterprises revolving around new building materials that result from any of the circularity stages and multiplier rounds of buying and selling on suppliers and users of these materials
Financial self-sufficiency	refers to extent the project is scalable and can be financed sustainably from operating profits
Consumption patterns	entails changes in consumer usage and buyer acceptance of building materials that are reused, recycled or refurbished
Savings on maintenance costs	involves reduction of building maintenance and operational costs due to savings on energy and water use
Higher residual values	concerns extension of product life cycles of building materials that raise residual values of the building or the materials themselves
Increase in innovation and new technologies and associated investments	relates to innovation effort and investment potential of new technologies and innovations arising from any of the circularity stages in the built environment
Fiscal effects	pertains to potential for not adversely affecting the budget position by reducing reliance on government or EU subsidies and potential for revised and progressive taxation systems to finance investment costs of the projects

IOP Conf. Series: Earth and Environmental Science **855** (2021) 012017 doi:10.1088/1755-1315/855/1/012017

Appendix Table 10. Economic Impact of Selected EU Projects

Indicators for Economic Feasibility	Rank of Importance	**Superlocal, NL**	Score	**Circular Retrofit Lab, BE**	Score	**Open Air Library, DE**	Score	**Rehafutur House, FR**	Score	**Upcycle Studios, DK**	Score
• Employment generation	3	Employment generated limited to demolition of buildings and construction of the houses	3	The project involves training architecture students about reversible solutions in circular economy which will potentially enhance future employment in the sector. Project also involves local actors such as local architects, contractors, producers and suppliers in project development and implementation, hence contributing to local employment.	3	The project is located in an abandoned industrial site in a district with high unemployment and vacancy rates of 80 percent but employment effects are not known, although houses surrounding the site have been renovated.	2	The developers found that in reusing materials, the majority of the budget goes towards labor costs rather than in the purchase of new, virgin materials – which is a positive for a region in need of employment.	4	Upcycled building materials are locally sourced, creating local jobs	5
• Trade effects	2	Importation of machinery from China for molding the brick mortars	3	Project designed against backdrop of Belgium being an importer of building materials and need to reduce this reliance on outside suppliers	4		1	The region is classified as fuel poor so the project will reduce fuel imports	5	The products are harvested and processed locally so no imports involved although there is potential for exports of upcycled materials	5
• Business creation and value chain multiplier effects	3	Potential business created for brick technique if commercialized; houses made are bought by local housing corporation who leases them out	4	Reversible building solutions for e.g. wall partitions, can be developed in the future with a larger application in mind, namely as a building systems that can be interchanged over the	5	A reading café and stage was added among residents to host public plays, youth concerts and other communal gatherings	4	Value creation and value chain effects of the eco-materials used as insulation. Coordination of different tradespeople to achieve specific	5	Designed townhouses as series of flexible spaces that can be used as offices, rental accommodation, workshops and other user-defined activities, Collaboration with wood manufacturer	5

				total university campus.				training on the worksite with all the teams was undertaken on this issue. Multiplier effects on 70,000 mining houses in the area		Dinesen for surplus and off cuts of wood. Lendager Group has developed upcycled materials designed for implementation on industrial scale	
• Financial self-sufficiency	3	Potential self-sufficiency from rental income from completed houses for the housing corporation and commercialization of mortar brick technique	4	Potential self-financing from use of available materials and commercialization of insulation techniques used in partition walls that can easily be dismounted.	3	The project relied primarily on donations by the community of 1,000 beer crates and books. The community took over management and maintenance of the library	4	The Rehafutur House was converted into office spaces which would generate rental income for the landlord	4	Commercial project, built on market conditions and designed for scale. Also, the landfill tax system of Danish government was restructured to finance reuse and recycling of waste. Financed by real estate developers.	5
• Consumption patterns	3	Possible change in consumer reaction to recycled building materials	2	The living lab acts as a demonstrator of how the existing modules' transformation potential can be enhanced. The project applies kit of parts modular building design related to prefabricated components where suppliers were invited to provide take back and end-of-life scenario for products. There is a reception desk and information center to show the used techniques. It will raise awareness and	5		1	Tradespeople used to demolishing floorboards in other projects and this project changed their mentality	4	Finding multiple alternative uses for innovative materials and utilizing efficiency dynamics and architectural aesthetics to increase the affordability and viability of these new products for consumers	5

				foster circular thinking within the future generation of local construction stakeholders.							
• Savings on maintenance costs	2	Closed water loop system will reduce maintenance costs	4	Project will improve the quality and comfort of the buildings, since they can be adapted and maintained more easily, without the need for destructive transformation works. The project improves maintenance savings by designing for assembly and disassembly. Selecting durable materials is important to lengthen the lifespan of the building elements and because the materials and building elements must withstand being reused, which includes the wear-and-tear of frequent transport and intensive use of construction products	5	Being designed as public space and open air, the project cut down on maintenance costs although later, there were signs of vandalism but residents took care of library as if it were a public toy.	3	The project was designed to make the building efficient during the use phase so that it has less environmental impact but is also less expensive to run. The house used to burn off 1,000 liters of fuel each year; after renovation, the insulation is such that the heating demand is very low at 34 kWh/m2 a year	5	Upcycle Studios are exclusively sustainable housing with minimal or no operating costs. The mission of the project was to construct the first residential area built by upcycled and local waste materials without compromising on aesthetics, quality or price. Upcycle Studios saves 15 tons of CO2 annually per unit using renewable heating using solar power combined with geothermal energy. Shared economy principles potentially reduces maintenance costs of users.	5
• Higher residual values	2	Higher residual values for mortar detachable bricks and houses that were developed from whole demolished studios	5	The financial impact will be evaluated of transformability in building valuation and throughout the total building life cycle. In this respect, the team together with the	5	The community reused the façade of the warehouse which was properly maintained from the 1960s without any structural change during	5	Energy efficiency of eco-materials used together with thermal monitoring endures higher residual values. The project intended to keep	5	Upcycled building materials were designed to be sustainable both from an environmental perspective, an operation perspective, an indoor climate	5

				industry partners implemented efficient operational solutions, such as the use of dry, robust and reversible technical solutions and the use of materials able to endure multiple reuses without being damaged.		construction except for recoloring of aluminum modules		high heritage value of the building (floorboard, fireplaces, tiles)		perspective, a biodiversity perspective, raising their residual values.	
• Increase in investments in innovation and new technologies	3	Innovation and new technology developed in the techniques 2 and 3 involving mortar bricks and upcycled concrete rubble	5	For investors, the future flexibility of buildings may create new business opportunities, as project creates more spatial and functional opportunities. The project tested on two cases of buildings as infrastructure and buildings as investments. Depending on their expected rate of change in the floor plan, three different types of walls were defined, analyzed, constructed and transformed: walls with (1) a high rate of change, (2) a high degree of flexibility for the integration of technical infrastructure and 3) a low rate of change. The CRL pilot project applied a step-	5		1	A recycled material called *metisse* was used for the insulation. This regional material is made out of old clothes (mainly cotton). Lot of innovation went into testing thermal capacity of the eco-materials.	5	Materials were processed so they both appear as beautiful and sustainable in quality and function as well as aesthetically compared to traditional building materials	5

				by-step innovation strategy based on products available on the market. This strategy thus incrementally improves products that are already technically and commercially viable.							
• Fiscal effects	2	Funding from EU subsidy	2	Funding from EU subsidy	2	Relied on public donations but partly funded by federal government to raise required money for construction	4	Funding from EU subsidy	2	No reliance on subsidies but commercially financed	5
Overall Score			**82**		**95**		**62**		**100**		**115**

Source: Source: Authors compilations from sources listed on Appendix Table 4

IOP Conf. Series: Earth and Environmental Science **855** (2021) 012017 doi:10.1088/1755-1315/855/1/012017

Appendix Table 11
Description of Social Indicators

Indicator	Description
Stakeholder participation	refers to the extent of consultation, workshops, meeting, and participation of different stakeholder groups affected by circular buildings
Community engagement	relates to commitment and actual engagement and ownership of affected communities in the construction and upkeep of the project
Preservation of cultural heritage	involves reconnecting, reminding, preserving cultural values, historical memories and traditions of the project including architectural landmarks
Development of social capital	concerns promotion of networks among people who live and work in particular society to enable it to function effectively
Regional inequality	entails extent the project addresses regional disparities in income, wealth and human development opportunities
Formation of human capital	relates to the extent the project enhances human capital by way of education, upskilling, literacy, and health
Demographic transition and change	refers to the extent the project responds to demographic changes such as declining and ageing population, outmigration, and urbanization
Social cohesion	concerns the promotion of local communities, sense of community spirt and belongingness.

Appendix Table 12. Social Impact of Selected EU Projects

Indicators for Economic Feasibility	Rank of Importance	**Superlocal, NL**	Score	**Circular Retrofit Lab, BE**	Score	**Open Air Library, DE**	Score	**Rehafutur House, FR**	Score	**Upcycle Studios, DK**	Score
• Stakeholder participation	3	In behalf of the Urban Innovation Action application for the project, no less than twelve partners are intensively cooperating: housing association HEEMwonen, the municipality of Kerkrade, IBA Parkstad, City Region of Parkstad Limburg, demolition firm Dusseldorp Infra, Sloop en Milieutechniek B.V.,VolkerWessels Construction and Real Estate Development South (VW VolkerWessels Construction and Real Estate Development South (VW), Waterboard Company Limburg (WBL), Limburg Drinking Water Company (WML), the municipalities of Landgraaf and Brunssum, Zuyd	5	For the **Circular Retrofit Lab**, a steering group was set up to check at any time if the initial aims are being respected during the development of the CRL solutions, and to evaluate the feasibility of the planning and budget. The group consists of the building owner (VUB), the TRANSFORM research team (VUB), the architect (Kaderstudio), IBGE (as the Work Package 4 leader), the general construction coordinator (Groep Van Roey) and the engineering office (MK engineering). Groep van Roey, a general building provider. Furthermore, a group of stakeholders, including industrial partners, has been put together for this	5	The project was planned right from the beginning as a social sculpture. The design and the functions were planned in a very close and open participation process. During the participation process several citizens demanded to construct the facade out of recycling material	5	The management team were very collaborative when it came to working towards circularity, especially since there was a desire to increase skills amongst building professionals to influence future projects. With this demonstration site, the cluster Ekwation engage in partnerships with regional enterprises, laboratories, schools, universities and education centers, stakeholders and policy-makers in order to offer them a complete tool to exhibit, test and understand the process of renovating the ancient housing stock in the	5		1

IOP Conf. Series: Earth and Environmental Science **855** (2021) 012017 doi:10.1088/1755-1315/855/1/012017

		University of Applied Sciences and Association of Demolition Contractors (VERAS). The knowledge the partners attain during the implementation of the SCE project is open-source, the acquired skills are therefore available for use in other international projects.		specific Pilot Project, enabling the stakeholders to work together on the development of innovative dynamic and circular solutions				region (especially mining housing). CAPEM brought together the expertise of 11 partner organisations to improve the production, distribution and use of eco-materials.			
• Community engagement	3	Residents and neighbors can contribute ideas about the future of the neighborhood through a residents' panel. Residents and students were consulted for ideas about the project.	5	Industrial stakeholders, like manufacturers, were involved from the design phase, but also during the progress of the works. This allowed co-developing the systems and making intermediate improvements. Three working groups were formed: external systems, internal systems and service. The university organized several round tables with industry stakeholders where design solutions were debated and improved, as well as hands-on workshops	5	The library began as an assemblage of 1,000 empty beer cartons pulled together by residents. The shelves of the temporary library were filled by the residents with book donations. With limited resources, the residents have brought into being a building that is innovative in both form and function and which, thanks to their involvement in the project, precisely responds to their demands. The citizen participation that is revitalizing the social fabric does not end	5	The construction workers were very proud to work on the project, with continuous visits and communication around the building site. Those who set the insulation materials were used to eco-materials but enjoyed working with the flax fiber enough that they have made themselves a tool to cut it.	4		1

				with students where solutions were tested.		with conceiving a building since, now the professionals who acted as advisers have gone, the residents have taken over its management.					
• Preservation of cultural heritage	2	After almost 50 years in high-rise blocks, it is time for an evaluation to see if the apartment blocks served their purpose well (structurally, architecturally, socially), their value during their lifespan, partly from the residents' view. In order to explore these issues, a book of neighbors is currently being compiled together with the last remaining residents. This book of neighbors gives a more detailed illustration of the matrix 'past- present- future' versus 'individual- community- location' of the residents and the buildings. The project also envisions to create links to the	5	The development of the transformable façades encountered major challenges. The current building standards and the respect of the heritage value of the site had to be taken into consideration. A case was made to keep part of these student housing units for their architectural specificity using Willy Van Der Meeren concept of prefabricated concrete modules were installed in the 1970's to cope with the increasing demand for student housing on site. The flexibility of this modular system developed in Switzerland allowed a random layout and generated a sequence of qualitative green urban spaces.	4	Remembrance, history and narratives provided the background for the "re-occupation" of the abandoned expanse. An old empty shop was used as base for a temporary library and camp for a building workshop. The architectural highlight of the project is the re-use of the modernist facade of the old HORTEN warehouse of the City of Hamm [built in 1966], which has been knocked down in 2007. The warehouses of the entrepreneur Horten which have been built in numerous German cities represent *sustainability of*	5	Given the building's significant heritage value, it was important for the team to reuse as much as possible whilst ensuring the longevity of the site – so circularity was a strong element from early on. Interior insulation compulsory as the building is on the UNESCO list of world heritage sites. Due to its heritage value, the renovation of this building could not affect the external façade, meaning that retrofitting could only involve interiors,	5	By reusing the walls from the abandoned dwellings as new facade elements, the project not only saves CO_2 and virgin materials, but also gets a new building with history and character with 75 percent of the windows coming from abandoned buildings in North Jutland, Denmark and 1400 tons of upcycle concrete casted from very durable concrete waste from the construction of Copenhagen Metro.	3

		mining past of the area.				*signs* of the postwar period					
• Development of social capital	3	In a declining population, residents are a unique form of capital. The residents have strong ties with the area. Many have lived here their whole lives. Cohesion is vital to a district, particularly one with a declining population. The current residents are being mobilized to preserve and develop the qualities present in the area. The project s want to recycle their knowledge of and vision on the area and, if possible, keep residents in the area.	4	In order to build this demonstrator lab, VUB and IBGE are working together with pioneers in the building sector, like product developers, entrepreneurs and enterprises that support this circular demonstrator lab. Their support consists of integrating existing (dynamic) solutions in the lab, joint development of new building solutions, funding through material donations or material leasing, etc. The Circular Retrofit Lab has developed partnerships with a large group of industrial partners. In a first phase, a temporary lab allowed exploring different building solutions, mainly wall assemblies, that will be used in the final demonstrator lab	5	The grassy plaza features a reading cafe and a stage that hosts elementary school theater plays, public readings, concerts-gigs of local youth bands and other cultural events.	5	Potential networks created between trades people and material suppliers on insulation properties of eco-materials used. The project creates opportunities to connect farmers living in the communes around the mining town and light industry artisans and textile makers on use of eco-fibers for insulation	5	Upcycle Studios is designed as a new model for shared living, which seeks to find a balance between commonality and individuality, as 'the community thrives best if there is space for the individual.' This taps into various aspects of the 'sharing economy', by prioritizing access over ownership and providing generous spaces for shared living and private accommodation. The result is a series of flexible spaces that can be used as offices, rental accommodation, workshops or a multitude of other user-defined activities, with each townhouse able to be divided and shared in different ways. Much like their approach to material use, Lendager Group emphasize the economic incentive of this 'sharing', with its potential benefit for	5

										both ‘owner and consumer’.	
• Regional inequality	3		1		1	The southeast of Magdeburg belongs to these urban areas in Eastern Germany which are characterized by shrinkage, abandoned industrial plants and fallow land. A post-industrial city landscape with high unemployment and figures of vacancy up to 80%. Like many other suburbs of East Germany, the Salbke district is deeply immersed in a state of physical and social decadence. Unemployment figures are high and public facilities are scarce.	5	The Rehafutur Engineer’s house project responds to the challenge that France faces in renovating existing building stock to high energy efficiency standards. Rehafutur aims to offer solutions for the renovation of the typical mining housing in the region which have specific high energy requirements as the region is affected by fuel poverty. Demonstrating circular solutions at Rehafutur has a huge multiplier effect as there are approximately 70,000 mining houses still occupied in Northern France.	5		1
• Formation of human capital (education and health)	3	The playbook of the project presents many collaborations with students from elementary, high	5	The project will show how an existing structure can get more potential for the future in order to be easily	5	The residents which take care themselves for a reading-café as well as for the Open-Air-Library call it a	5	Training sessions were held on the work site on airtightness	5	Waste materials used in Upcycle Studios are upcycled to nontoxic and certified materials	5

		school, university and technical schools in eliciting designs for the project including asoects related to circularity and sustainability, finance, architecture and technical specifications of materials used for the project.		transformed into different functions (e.g. a dissemination space, a co-working space, an eco-guesthouse in the middle of the campus). The CRL will demonstrate how this change can be anticipated by supporting other functions every 6 months on the first floor level. On the ground level a dissemination space will be situated in which the results of the BAMB project will be shown to a large audience, sustainable lectures can be given, the technical solutions developed with the industrial stakeholders can be observed, etc. During Summer School, these solutions were tested by a group of enthusiastic students.		"library of confidence": There is no registration needed and there is no control. A book can be taken whenever wanted, but should be returned voluntarily or replaced with another one. The shelves are never closed - the library is opened for 24 hours a day. This contributes to increasing literacy and education of residents.		with all trades people to make this intricate system work, so collaboration was key to the success to the project.			
• Demographic transition and change	2	The project is based in a sustainable shrinkage area in Stadsregio Parkstad	5		1	In the old center closed-down businesses abound along with	5	The very rural village changed into a town, with	5	Three million people will have completed their move from rural to urban areas. The	5

		Limburg in the South of the Netherlands. In the next 30 years, the Parkstad Limburg region's population will shrink by 27% due to population ageing and young people moving to urban agglomeration cities such as Amsterdam and Rotterdam. This implies less housing accommodation will be demanded in the following decades. High-rise apartment buildings, which were mainly built in the 1960s when housing shortage was a primary issue, no longer satisfy requirements and inhabitants' needs. Three vacant high-rise apartment buildings in the project-area in the city of Kerkrade contain valuable materials, qualities and former social structures. Demolition of these buildings will irreversibly impair these values. The				unoccupied housing, vacant lots and abandoned factories that populate the post-industrial landscape. One of the vacant lots was the triangular space defined by the intersection of the main street with Blumenberger Strasse, which remained vacant after the old district library was demolished.		many foreign workers, especially from Poland, swelling the workforce. A former mining site (*Écopole*) has been preserved and now hosts many cultural, economic and environmental activities which are the symbol of new developments for the commune. In recent years, population left the mining towns seeking work elsewhere, about 1000 homes have been demolished in the recent past. The mines of the Nord-Pas de Calais region have become the 38th French site on the list of UNESCO World Heritage. As of 2008, Loos-en-Gohelle was a town whose economy was dominated by light industry, textiles and workshops for		increased demand for housing means that an estimated 60 percent of the new urban areas needed in 2030 have not yet been built. The entrepreneurial spirit has increased in recent years in the metropolitan area. For more and more people, the day is not clean cut into distinct categories as it used to be and the dream of the good life has become more about living and working with a flexible schedule rather than the well-known "9-17". Concepts such as flexibility, symbiosis, exchange and resource efficiency are high on the agenda for many Danes, which goes to show that alternative ways of thinking of life and social structure are emerging.	

		objective of the project is to circularly reuse these values within the project area while boosting the local economy and creating a high-quality and desirable urban environment. The former social structures will be recovered by actively stimulating former inhabitants to take residence in the area again. The project serves as a best example for approximately 1250 similar housing accommodations in the Parkstad Limburg region.						artisans and professionals, but it also still retained a strong rural connection with thirty farms within the commune. The Rehafutur project converts one of the mining houses into office spaces.			
• Social cohesion	3	Some neighbors lived next to each other for years. They had good social contacts. If the flats were demolished, those qualities would be lost. With demolition, not only the tangible value, such as the building and materials, but also invisible values, such as social structures between	4	The project provides opportunities for actors in the supply chain for co-creation / co-making processes. The client, design team, suppliers and builders can help build this trust. This, however, requires time and willingness to adapt the procurement process. The CRL involved contractors,	4	Open to the public twenty-four hours a day, the library is managed by the residents themselves who, without any checks or monitoring, freely borrow and return books. Although, as if testifying to the harsh surroundings, the new library has been vandalized on	5	Coordination of different tradespeople to achieve specific training on the worksite with all the teams was undertaken on this issue.	4	The Upcycle Studios is designed socially by fostering neighborly relations and increasing sharing economy potentials – all of which adds a value to the physical space. The core focus for the development of Upcycle Studios is based on the Sharing Economy. Communities are developing around the	3

		residents and the ideas about life in and around the flats, disappears. The wish is therefore to maintain the qualities of the existing flats when building new homes and to use materials. In line with circularity principles, former inhabitants will be invited back into the area. These potential tenants will be strongly involved in the co-design, operation and monitoring of the new collaborative economy services and facilities (such as a shared mobility platform and a social services center) within the area.		manufacturers, designers, and researchers upstream, in an intensive collaborative design process with very good circular results. Once the construction has started, more and more manufacturers and construction contractors from small to big companies became interested in the “reuse” potential of materials.		occasion, it is a fully functioning concern.				concept of sharing resources, which has the benefit of providing economic gain for both owner and consumer.	
Overall Score			**92**		**85**		**110**		**104**		**64**

Source: Authors compilations from sources listed on Appendix Table 4

REFERENCES

Allenby BR 1992 Achieving sustainable development through industrial ecology. *International Environmental Affairs* **4** (1) pp. 56-68.

Bal M, Bryde D, Fearon, D and Ochieng E 2013 Stakeholder Engagement: Achieving sustainability in the Construction Sector *Sustainability* 2013 **6**, pp. 695-710 doi:10.3390/su5020695.

Bayern Innovativ 2019 *The circular economy in Southern Germany* Market Study Final report Retrieved on 10 December 2020 from www.nederlandwereldwijd.nl

Benyus J 2002 *Biomimicry: innovation inspired by natu*re (2nd ed.) New York: Harper Perennial.

Best A, Duin L and Chelminska M 2018 *Macroeconomic and Societal Impacts of Mainstreaming the Circular Economy* Retrieved on 15 December 2020 from http://circular-impacts.eu/deliverables.

Bloomsma F and Brennan G 2017 The emergence of circular economy: a new framing around prolonging resource productivity *Journal of Industrial Ecology* https:// doi.org/10.1111/jiec. 12603.

Boulding K 1966 The economics of the coming spaceship earth. In Jarett H ed., *Environmental quality in a growing economy* pp. 3-14 Baltimore, Md Resources for the Future/Johns Hopkins University Press.

Brand S 1994 *How buildings learn – what happens after they're built* London: Phoenix, p.13.

Breen C and Vangsbo P 2018 Municipality-led circular economy case studies EIT Climate-KIC, Retrieved on 5 December 2020 from https://circulareconomy.europa.eu/platform/en/knowledge/municipality-led-circular-economy-case-studies

Bringezu S 2003 Industrial ecology and material flow analysis In Bourg D and Erkman S eds. *Perspectives on industrial ecology* Sheffield, UK: Greenleaf.

CE100 2015 *Circularity in the Built Environment Case Studies: A compilation of case studies from CE100*, April

Chertow M 2000 Industrial symbiosis: Literature and taxonomy *Annual Review of Energy and Environment*, **25**(1), pp. 313-37

Cheshire D 2016 *Building Revolutions: Applying the Circular Economy to the Built Environment*. Riba Publishing ISBN 10: 1859466451.

Daly HE 1992 Allocation, distribution and scale: towards an economics that is efficient, just and sustainable *Ecological Economics* **6**, pp. 185-93.

Das S, Bhowmick M., Chattopadhyay, SK and Basak S. 2015 Application of biomimicry in textiles. *Current Science* **109**: pp. 893-901

De Angelis R 2018 *Business Models in the Circular Economy*. Palgrave Macmillan. ISBN 978-3-319-75126-9.

Deloitte 2015 *Construction and Demolition Waste Management in Denmark*. September, Retrieved on 10 December 2020 from https://ec.europa.eu/environment/waste/studies/deliverables/CDW_Denmark_Factsheet_Final.pdf

De Groene Zaak and Ethica 2015 *Boosting Circular Design for a Circular Economy* Joint Report funded by EU Climate KIC Pioneers into Practice Programs.

Derbal R, Lucas, A, Brachelet F, Defer D and Antczak E 2017 Rehafutur Insitu instrumentation for a comprehensive building analysis *Energy Procedia* **139**, pp.301-06 Elsevier.

Dul J 2015 Necessary condition analysis : Logic and methodology of "necessary but not sufficient" causality. Organizational Research Methods **19** (1), pp. 10-52.

EMF and McKinsey 2012 Towards the circular economy Economic and business rationale for an accelerated transition, Retrieved 8 December 2020, from https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf

EMF 2017 *Cities in the circular economy: An initial exploration*, Retrieved on 5 December 2020 from https://www.ellenmacarthurfoundation.org/publications/cities-in-the-circular-economy-aninitial-exploration

ESPON 2020 Stocktaking and assessment of typologies of Urban Circular Collaborative Economy initiatives *ESPON SHARING Final Report* 01/04/2020.

EU Commission 2015 *Closing the loop: An EU Action plan for the circular economy* Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions COM(2015) 614 final Brussels, 2/12/2015

Fernandez A 2020 *Superlocal: concrete recycling techniques developed in the project* Flash lecture given in the Rescue Minor Sustainability Course at Zuyd University of Applied Sciences, 5 October 2020.

Fontaine F and Dewulf B eds. 2018 *Feuille de Route des Acteurs de la Construction a Bruxelles vers une Economie Circulaire*, Retrieved on 10 December 2020 from https://www.circulareconomy.brussels/decouvrez-la-feuille-de-route-des-acteurs-de-la-construction-vers-une-economie-circulaire/

Fontaine F and Dewulf B eds. 2018 *The Construction Sector in Brussels: Findings and Perspectives towards a Circular Economy*, Retrieved on 10 December 2020 from https://www.circulareconomy.brussels/wp-content/uploads/2017/05/be_prec_construction_sector_EN.pdf.

Frosch R and Gallopoulos N 1989 Strategies for Manufacturing. *Scientific American* **261**, pp. 94-102.

Ghisellini P, Ripa M. and Ulgiati S. 2018 Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector: A literature review. *Journal of Cleaner Production* **178**, Elsevier, pp. 618-43.

Grant D, Trautrims A. and Wong CY 2017 *Sustainable Logistics and Supply Chain Management* (2nd Ed.) London: Kogan Page Ltd. ISBN 9780749478278.

Gravagnuolo A, De Angelis R and Iodice S 2019 Circular economy strategies in the Historic Built Environment: Cultural heritage adaptive reuse *Proc. of the STS Conference*, Graz, 2019, pp 121-44.

Green DW, Lee JM and Jung HS 2015 Marine structural biomaterials in medical biomimicry *Tissue Engineering Part B Reviews* **21** (5), pp.438-50.

Habib MK 2011 Biomimetics: innovations and robotics *International Journal of Mechatronics and Manufacturing Systems* **4** (2), pp. 113-34.

Häkkinen T, Helin T, Antuña C, Supper S, Schiopu N and Nibel S 2013 Land use as an aspect of sustainable building. *International Journal of Sustainable Land Use and Urban Planning* **1** (1): pp.21-41.

Haupt M and Hellweg S 2019 Measuring the environmental sustainability of a circular economy *Environmental and Sustainability Indicators* **1-2** 10005, September Science Direct

Hawken P, Lovins A and Lovins L 2000 *Natural capitalism; The next industrial revolution* London: Earthscan

Holland Circular Hotspot 2018 *Circular Construction Economy Transition Agenda 2018*, Retrieved on 15 December 2020 from https://hollandcircularhotspot.nl/wp-content/uploads/2019/09/Circular-Construction-Economy.pdf.

Hysa E, Kruja A, Ur Rehman N and Laurenti R 2020 Circular economy innovation and environmental sustainability impact on economic growth: An integrated model for sustainable development *Sustainability 2020*, **12**, 4831, doi:10.3390/su12124831

Inter-American Development Bank (IADB) 2018 *Social impact assessment: integrating social issues in development projects*, IDB Series on Environmental and Social Risk and Opportunity.

Kennedy C, Pincetl S and Bunje P 2007 The study of urban metabolism and its applications to urban planning and design *Environmental Pollution* xxx, pp. 1-9, doi:10.1016/j.envpol.2010.10.022

Kennedy S 2007 Biomimicry.bimimetics: general principles and practical examples *The Science Creative Quarterly*, Retrieved on 10 December 2020 from https://www.scq.ubc.ca/biomimicrybimimetics-general-principles-and-practical-examples/

Kirchherr J, Reike D and Hekkert M 2017 Conceptualizing the circular economy: An analysis of 114 definitions *Resources, Conservation & Recycling* **127**, pp. 221-32. Elsevier.

Lah O 2016 Circular Economy Policies and Strategies of Germany. In Anbumozhi V and Kim J eds., *Towards a Circular Economy: Corporate Management and Policy Pathways* ERIA Research Project Report, 2014-44, Jakarta: ERIA, pp.59-74.

Lifset R and Boons F 2012 Industrial ecology: Business management in a material world. In Bansal P and Hoffman A eds.*The Oxford handbook of business and natural environment*, pp. 311-26. Oxford University Press.

Linton J, Klassen R and Jayaramman V 2007 Sustainable supply chains; An introduction *Journal of Operations Management* **25**, pp 1075-82.

Lovins A, Lovins I and Hawken P 1999 A road map for natural capitalism *Harvard Business Review* **77** (May-June), pp. 145-58.

Lyle JT 1994 *Regenerative design for sustainable development* New York: John Wiley & Sons

Mäler KG 1974 *Environmental economics: a theoretical inquiry* Baltimore: Johns Hopkins University Press.

Marshall A and Lozeva S 2009 Questioning the theory and practice of biomimicry *International Journal of Design & Nature & Ecodynamics* **4**(1), pp.1-10.

McDonough W and Braungart M 2002 *Cradle to cradle: Remaking the way we make things* New York: North Point Press

Migliore M, Talamo C and Paganin G 2020 *Strategies for Circular Economy and Cross-sectoral Exchanges for Sustainable Building Products* Springer Tracts in Civil Engineering ISBN 978-3-030-30317-4.

Ministry of Ecological and Solidarity Transition 2018 *Circular economy Roadmap for France: 50 measures for a 100% circular economy*, Retrieved on 12 December 2020 from https://www.ecologique-solidaire-gouv.fr/sites/default/files/FREC%20anglais.pdf.

Ministry of Environment and Food and Ministry of Industry, Business and Financial Affairs 2018 *Strategy for Circular Economy* Danish Government, Retrieved on 22 December 2020 from https://circulareconomy.europa.eu/platform/sites/default/files/eng_mfvm_cirkulaer_oekonomi_as5_uk_final_web.pdf

Mossberg M 2018 *Evaluation of Circular Economy design principles by material Flow Analysis*. Chalmers University of Technology Masteral Thesis. Gothenburg, Sweden.

Odu, G.O. 2019 Weighting methods for multi-criteria decision making technique. *Journal of Applied Sciences and Environmental Management* **23** (8), pp. 1449-1457, August.

OECD 2019 *Building Models for the Circular Economy: Opportunities and Challenges for Policy* OECD Publishing, Paris, https://doi.org/10.1787/g2g9dd62-en.

Ortiz O, Castells F and Sonnemann G 2009 Sustainability in the construction industry: A review of recent developments based on LCA *Construction and Building Materials* **23**, pp. 28-39 Science Direct.

Pacheco-Torgal F and Jalali S 2011 Toxicity of building materials *International Journal of Sustainable Engineering* iFirst article, pp. 1-7 Taylor & Francis Group.

Padilla-Rivera A, Russo-Garrido S and Merveille N 2020 Addressing the social aspects of a circular economy: a systematic literature review *Sustainability 2020*, **12**, 7912, pp. 1-17.

Paduart A, Elsen S and De Temmerman N 2018 *Circular Retrofit Lab; A Brussels' renovation experiment on how to redesign existing buildings into circular buildings* Powerpoint presented at the WASCON Conference 6 June 2018.

Pauli G 2010 *The blue economy: 10 years, 100 innovations, 100 million jobs* Taos, NM: Paradigm Publications.

Pearce DW and Turner KT 1990 *Economics of natural resources and the environment* Baltimore: Johns Hopkins University Press.

Persson U and Olander S 2004 Methods to estimate stakeholder views of sustainability for construction projects *The 21st Conference on Passive and Low Energy Architecture* **19-22** September 2004 Eindhoven, Netherlands.

Pötting J and Hanemaaijer A eds. 2018 *Circular economy: what we want to know and can measure. Framework and baseline assessment for monitoring the progress of the circular economy in the Netherlands* Policy Report PBL Netherlands Environmental Assessment Agency.

Ritzen M, van Oorschot J, Cammans M, Segers M, Wieland T, Scheer P, Creugers B, Abujidi N 2019 Circular (de)construction in the Superlocal project *IOP Conference Series: Earth and Environmental Science* 225. doi:10.1088/1755-1315/225/1/012048

Rizos V, Tuokko K and Behrens A 2017 The circular economy: A review of definitions, processes and impact *Center for European Policy Studies (CEPS) Research Report* No. 2017/8, April 2017.

Schut E, Crielaard M and Mesman M 2015 *Circular economy in the Dutch construction sector* Final Report. Rijkswaterstaat Ministry of Infrastructure and the Environment and the National Institute of Public Health and the Environment (RIVM).

Sillanpää M and Ncibi C 2019 *The Circular Economy: Case Studies about the Transition to the Linear Economy* London: Elsevier/Academic Press. ISBN 978-0-12-815267-6.

Singh A, Sharma B, Gaurav N and Singh N 2016 Environmental impact assessment as a tool to achieve the sustainable development *IMPACT International Journal of Research in Applied, Natural and Social Sciences,* Vol. **4**, Issue 8, pp. 143-56.

Stahel WR 1986 Product life as a variable: the notion of utilization. *Science and Public Policy* **13** (4), pp.185-93.

Tebbatt Adams K, Osmani M, Thorpe T and Thornbach J 2017 Circular economy in construction: current awareness, challenges and enablers *Proc.of the Institution of Civil Engineers Paper 1600011*.

Tietenberg T 1984 *Environmental and natural resource economics* Illinois, Scott: Foresman & Company.

United Nations Environment Program (UNEP) 2009 *Guidelines for social life cycle assessments of product*s ISBN: 978-92-807-3021-0

Van Vliet MM 2018 *Disassembling the steps towards Building Circularity: Reinventing the Building Disassembly assessment method in the Building Circularity indicator* Eindhoven University of Technology Masteral Thesis.

Wahlström M, Bergmans J, Teittinen T, Bacher J, Smeets A and Paduart A 2020 Construction and Demolition Waste: challenges and opportunities in a circular economy *Eionet Report –* ETC/WMGE 2020/1 European Environmental Agency, European Topic Center on Waste and Materials in a Green Economy.

Wells P and Seitz M 2005 Business models and closed loop chains: A typology *Supply Chain Management: An International Journal* **10**, pp. 249-51.

Windapo A and Ogunsanmi O 2013 Construction sector views of sustainable building materials *Proc. of the Institution of Civil Engineers Paper* 1300011 ICE Publishing.

Yijun J, Ying H and Xuhong S 2011 Applying circular economy theory in Environmental Impact Assessment *2010 International Conference on Biology, Environment and Chemistry* IPCBEE 1, Singapore: IACSIT Press

Yilmaz M and Bakis A 2015 Sustainability in Construction Sector *Procedia – Social and Behavioral Sciences* **195**, pp. 2253-62 Science Direct.

Zabihi H, Habib F and Mirsaeedie L 2012 Sustainability in building and construction: Revising definitions and concepts *International Journal of Emerging Sciences* **2**(4), pp.570-78.

Zavadskas EK, Saparauskas J and Antucheviciene J 2018 Sustainability in Construction Engineering. *Sustainability* 2018 **10**, 2236, doi:10.3390/su10072236.

Zhang X, Wu Y, Shen L and Skitmore M 2014 A prototype system dynamic model for assessing the sustainability of construction projects *International Journal of Project Management* **32**, pp.66-76 Science Direct.