Economic assessment of circular patterns and business models for reuse and recycling of construction and demolition waste

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Patrizia Ghisellini, Sergio Ulgiati
Parthenope University of Naples, Department of Sciences and Technologies, Naples, Italy

3.1 Introduction

The transition to the circular economy (CE) and sustainable development is posing new challenges to the construction and demolition waste (C&DW) sector for the purpose of guiding it to balance better the goals of socioeconomic development with the ones of better environmental protection involving a reduction of resource materials' exploitation and waste production (Rau and Oberhuber, 2019; Adams et al., 2017).

The strategical framework of the CE focuses on some building blocks depicted in Fig. 3.1 which aims to manage better the use of finite stocks of natural resources and optimize resource productivity by retaining as long as possible the value of products, components, and materials in use in both technical and biological cycles (Ellen MacArthur Foundation, 2017). The final goal is to improve the effectiveness of the economic system by revealing and designing out negative externalities (Ellen MacArthur Foundation, 2017) related to the use of natural resources, emissions release, and waste generation.

The implementation of the CE entails the adoption of more sustainable practices in the whole life cycle of products or systems (e.g., C&D projects related to buildings or infrastructures) (Ghisellini et al., 2018, b), the boundaries of analysis of which are based on the concept of "cradle to cradle" (Braungart et al., 2008).[a] This approach focuses on resource materials (in particular technical materials) that flow continuously in a system as products and their components are designed and optimized for a cycle of disassembly and reuse (Moreno et al., 2016; Ellen MacArthur Foundation, 2012).

From a life-cycle thinking perspective it implies to consider the environmental and socioeconomic impacts (Hossain and Ng, 2019; Hossain et al., 2017; Di Maria et al., 2018) related to all the processes from the extraction of resources, manufacturing, maintenance and repair, reuse and recycling of waste materials from a product *and using these materials again and again for producing new products* (Dieterle et al., 2018) (Fig. 3.2).

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[a] Braungart et al. (2008) distinguish between "cradle-to-grave" flows of materials and cyclical "cradle-to-cradle" flows. In that they mark a difference in resource flow patterns that characterize linear and circular models (Bocken et al., 2016).

Advances in Construction and Demolition Waste Recycling. https://doi.org/10.1016/B978-0-12-819055-5.00003-6

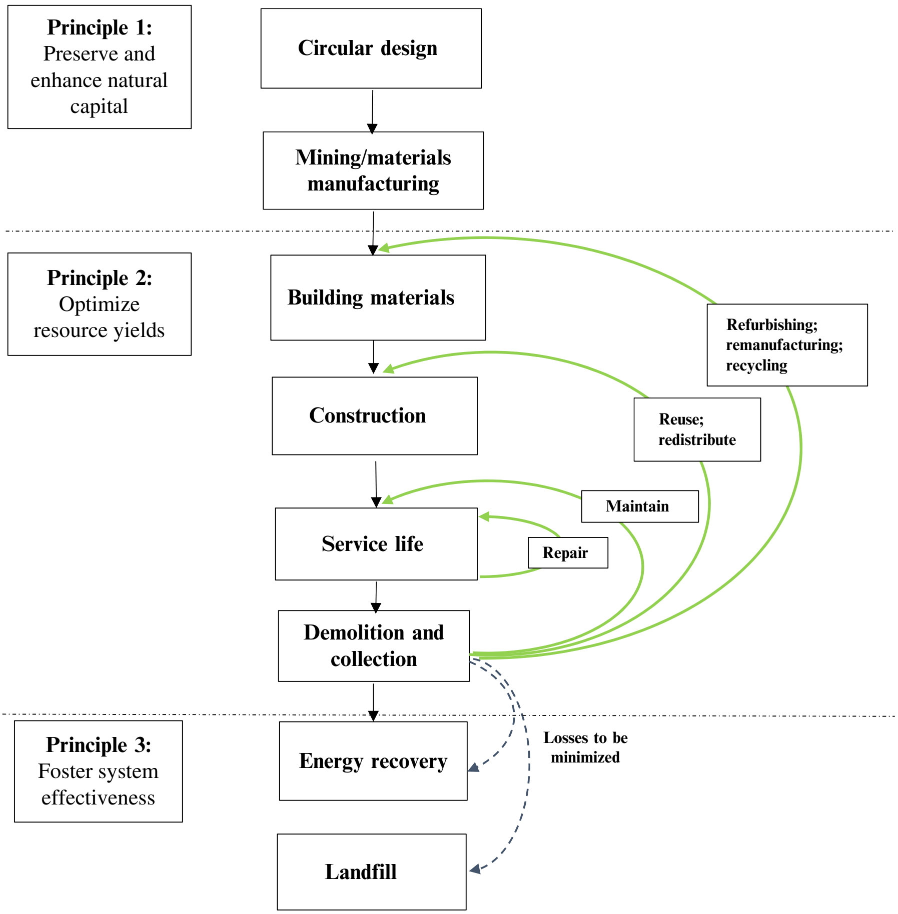

Fig. 3.1 Basic principles for managing the adoption of the CE in the technical cycle of construction value chain.
Modified from World Economic Forum, 2016.

For example, in the construction sector the concept of buildings as "material banks" has been developing (European Union, 2019), highlighting the importance that each material should be designed for recoverability as well as its identity is stored in a database (Rau and Oberhuber, 2019). In that the constructor or the owner should establish an intimate relationship with the building, its component materials, and be responsible for their destiny. This hopefully should act as an antidote to move beyond our "throw-away society" (Castellani et al., 2015; Stahel, 2013).

Recycling of C&DW is one of the available and relevant practices within the circular patterns and business models and in the wider framework of sustainable construction measures that favor prevention over mitigation of the environmental impacts of the C&D industry. Recycling as a mitigation measure bears positive and negative impacts (Silva et al., 2017) and the inclusion in CE framework is important to maximize the quality of the recycling process and preserve the integrity of material recycling (Den Hollander

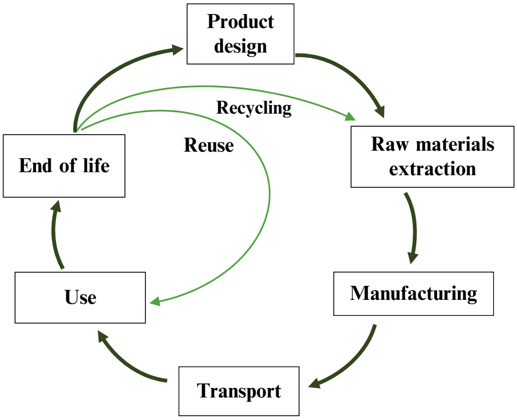

Fig. 3.2 Life cycle stages of a product according to the cradle-to-cradle approach. In a cradle-to-cradle life cycle assessment (LCA), all life cycle stages are taken into account in the calculation of the environmental impacts starting from raw materials extraction, manufacturing, maintenance and repair, waste disposal, and recycling. The inclusion of this last stage differentiates the cradle-to-cradle LCA from the cradle to grave LCA that ends to waste disposal stage (Cao, 2017; La Rosa, 2016).

et al., 2017). In that the CE requires favoring a particular form of recycling, the so-called "upcycling" versus the actual most practiced "downcycling" (Dieterle et al., 2018).

In this initial stage of transition toward the CE that is characterized by uncertainty of the outcomes (Lahti et al., 2018), the assessment of the sustainability of circular patterns and business models for reuse/recycling of C&DW provides a useful framework for supporting decision-making at both private and political levels.

This chapter deals with the economic impacts of circular patterns and business models for reuse and recycling of C&DW and presents an overview of the most recent results coming from the available economic and financial studies that evaluate the economic performances of recycled products from C&DW. The assessment will be supported by data on the reuse/recycling of C&DW at the global level, on the products that can be derived from C&DW and the main barriers that such products as well as the general implementation of circular patterns for the management of C&DW are experiencing.

The study aims to complement the available international literature, which mainly addresses the environmental performances of secondary products from C&DW by means of the life-cycle assessment approach (Vilches et al., 2017; Vieira et al., 2016; Bowea and Powell, 2016; Lu and Yuan, 2011), with the final purpose to contribute to promote further research on these topics.

3.2 Global recovery of C&DW

3.2.1 *Current reuse/recycling of C&DW*

At the global level, the recycling rates of C&DW are rather differentiated within and among the several geographical areas: North and South America, Europe, Africa,

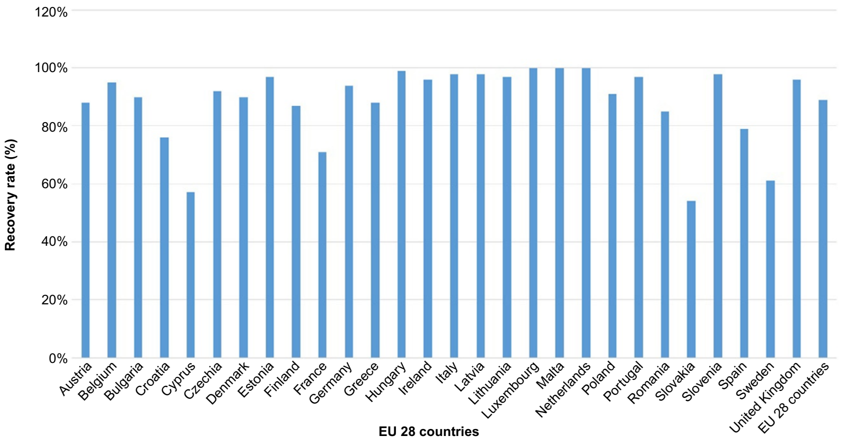

Fig. 3.3 Recovery rate of C&DW in European Countries (28 countries).
Data from EUROSTAT, 2016. Recovery rate of construction and demolition waste. Available at: https://ec.europa.eu/eurostat/databrowser/view/cei_wm040/default/table?lang=en (Accessed 27 August 2019).

Asia, and Oceania (Aktar and Sarmah, 2018). Fig. 3.3 shows the recovery rate for each country of European Union (28 countries). The recovery rate is the ratio of C&DW which is prepared for reuse, recycling, or subject to material recovery, including backfilling operations, divided by the C&DW treated as defined in Regulation (EC) N. 2150/2002 on waste statistics. The indicator refers to the waste category "Mineral waste from construction and demolition" (EWC-Stat 12.1) and takes into account only nonhazardous waste (EUROSTAT, 2016).

In Asia, Japan and South Korea are the leading countries recycling more than 90% of its C&DW (Aktar and Sarmah, 2018), whereas in the Americas, United States seems the best performer as it recycles more than 70% of its C&DW. More or less the same recycling rates are achieved in Australia for C&DW coming from masonry that are the major fraction of C&DW in that country (Aktar and Sarmah, 2018). Overall, the recycling rate of Australia is equal to 55% (Wijayasundara et al., 2016).

In emerging countries, the available national data for India and Brazil (Aktar and Sarmah, 2018) and China (Jin et al., 2017) show that they recycle only a small amount of C&DW as the bulk of them is disposed of in landfills (Aktar and Sarmah, 2018). However, again the performances are very differentiated as, for example, in China the national average recycling rate is 5%, whereas the cities of Shanghai and Shenzhen recycled 20% and 16% of their C&DW in 2014 (Huang et al., 2018; Duan and Li, 2016). Finally, Fig. 3.4 compares the total production of aggregates at the global level with the production of recycled aggregates and highlights that the latter still has a marginal role in the total production of aggregates and is mainly concentrated in a few countries such as Germany and United Kingdom.

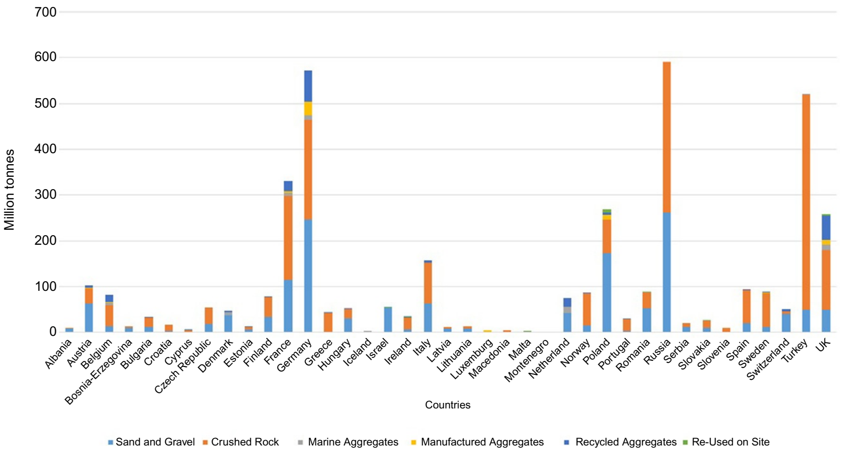

Fig. 3.4 Total national aggregate production versus recycled aggregate production. Modified from European Aggregates Association 2017–2018 Annual Review.

3.2.2 Converting C&DW into new products

Construction and demolition activities or projects produce a large and diversified amount of nonhazardous materials that in European Union mainly consist of inert products (e.g., concrete, ceramic), the rest are noninert products concerning packaging and structure support materials [e.g., plastic, wood (Jiménez-Rivero and Garcia-Navarro, 2017), steel, aluminum scraps, and copper from wires (Duan et al., 2015)].

Low fractions of the C&DW are hazardous elements. These latter are a source of potential environmental and health risks (Duan et al., 2015) and, for example, in EU their management from their point of production to the final point of disposal or recovery is guided by specific regulations of the member states in application of the Waste Framework Directive 2008/98/EC.

Demolition projects generate a larger amount of waste compared to construction projects (Duan et al., 2015). As a result, end-of-life products (EoL) consisting of waste coming from demolition and renovation processes (Jiménez-Rivero and Garcia-Navarro, 2017; Behera et al., 2014) are the main fractions of the overall C&DW of buildings and other construction activities such as in Europe and United States (Mália, 2010).

EoL products can be classified into reusable, recyclable, and mixed (Duan et al., 2015). The first type concerns, for example, products that can be resold as second-hand construction products (Duan et al., 2015). In some cases, these could also have a high value depending on the specificity or type of the product (Da Rocha and Sattler, 2009) and the presence of a resale market for salvaged products or materials (Diyamandoglu and Fortuna, 2015). Recyclable products are mainly regarded as inert such as concrete debris and masonry, steel, aluminum scraps, and copper from wires (Duan et al., 2015).

With regard to inert C&DW, three main types of materials can be derived through the process of recycling: crushed concrete, crushed masonry, and mixed debris. After crushing and beneficiation process in certified recycling plants, the resulting aggregates can be classified into four categories: recycled concrete aggregates (RCA), recycled masonry aggregates (RMA), mixed recycled aggregates (MRA), and construction and demolition recycled aggregates (Behera et al., 2014; Silva et al., 2014). In particular RCA, RMA, and MRA are suitable to be used in the production of concrete from recycled aggregates (RAC) (De Brito and Agrela, 2019).

RCA with a minimum content of concrete equal to 90% can be employed in earthworks, filling, and road subbases, in buildings and other civil works for the production of structural and nonstructural concrete whereas recycled aggregates from mixed wastes (usually with a minimum content of concrete of 50%) can be used in earthworks, filling and road subbases, in buildings and other civil works for the production of nonstructural concrete (Gálvez-Martosa et al., 2018).

The use of RCA for structural applications can be regarded as an upcycling practice as the recycled materials are used for an application of higher value compared to the application of materials from which they derive (Allwood, 2014). In this regard also the issues of substitution ratio should be considered as they could affect the environmental performances of the secondary products from C&DW (De Brito and Agrela, 2019).

So far, according to Di Maria et al. (2018) the lack of quality standard in the waste framework directive 2008/98/EC seems not encouraged by the production of RCA for structural applications and many countries tried to fulfill the requirements of the directive by investing in low-quality applications including the production of RA for road base and filling materials in road construction (BIO Intelligence Service, 2011; Hu et al., 2013; LNE, 2012; Weil et al., 2006).

Consequently, countries such as Belgium and the Netherlands are already facing a problem of saturation of low-quality RA in the aggregates market (Hu et al., 2013; LNE, 2012). Therefore, the adoption of solutions aimed to promote the development of RA into applications of higher quality is essential to advance the research in the field as well as the CE in the sector (Di Maria et al., 2018).

These gaps in the Waste Framework Directive are stimulating the debate at the European political level toward the inclusion of a revision clause that considers setting 2025 and 2030 recycling targets for C&DW (European Aluminum, 2017).

3.3 Governance issues

3.3.1 Barriers to the adoption of circular patterns and business models

The implementation of circular patterns and business models that implies a better management of C&DW including their prevention at the source as well as the use of recycled products from C&DW still face several types of barriers.

In the C&D industry this transition requires the development of knowledge, investments in new technologies, and efforts and mobilization by all stakeholders from designers to constructors and workers (Silva et al., 2017).

The processes of change require time as in the nature of any socio-technical transitions (Geels, 2011). However, the huge impacts of the sector and the worsening of environmental problems certainly call for an acceleration of the transition in the sector and urgent actions (Zutshi and Creed, 2015) aimed at making the stakeholders more responsible and aware (Wang, 2014).

The understanding of these issues is crucial for enabling the transition from the actual linear economy or even the recycling economy to the CE (Fig. 3.5). For example, one of the main aspects that make the difference between the latter two is the role of the design. *In the recycling economy the reuse of materials is mostly regarded as a separate optimization step, which is a (undeliberate) consequence of the choices made in the phase of design, production, and use of a product. In the* CE, *the (re)use of materials is an integrated factor in the optimization of the delivery of functionality* (Van Buren et al., 2016).

Laboratory projects show the capacity of preventing demolition waste through the adoption of the concept of reversible building design (European Union, 2019) that has been developed on the awareness that:

> *Substantial stocks of used building materials are discarded, because it is more expensive or impossible to recover them for reuse with their value intact. Buildings are seldom flexible enough to easily adapt to new requirements. Transformations of building use create considerable amounts of waste and demand of virgin materials, if*

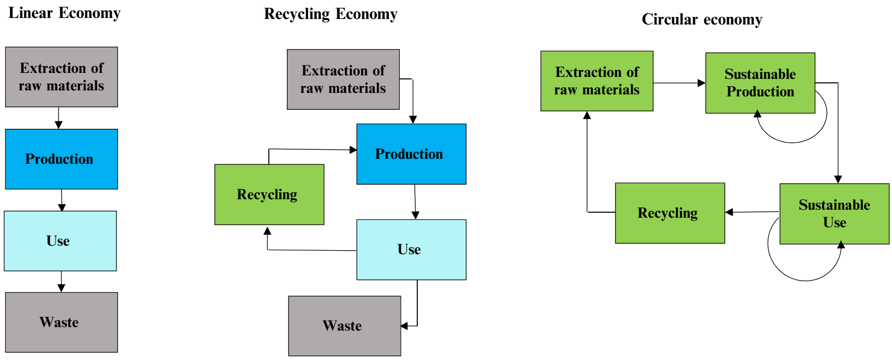

Fig. 3.5 Life cycle stages of a product from the linear to the recycling and circular economy. Modified from Van Buren, N., Demmers, M., Van der Heijden, R., Witlox, F., 2016. Towards a circular economy: the role of Dutch logistics industries and governments. Sustainability 8, 647. https://doi.org/10.3390/su8070647 and Ministry for the Environment, Land and Sea Ministry of Economic Development, 2017. Towards a model of circular economy for Italy—overview and strategic framework. Available at: https://circulareconomy.europa.eu/platform/en/strategies?page=1 (Accessed 27 August 2019).

> *the building is not designed to accommodate the change. For effective use of building materials and to facilitate recovery and reuse of components, products, or materials in buildings, buildings need to be easily reversible (BAMB2020.EU, 2019).*[b]

Clearly, it is evident that reversible building design and circular design goes far beyond the goal of improving the environmental performances of a construction project (be it a building or another type of construction project) as it could stress the concept of conventional eco-design (Den Hollander et al., 2017).

So far, the main goal of construction companies is making profits in a conventional manner and C&DW recovery could be a costly option for them in the short run compared to the disposal in landfills or dumping sites (Jin et al., 2017). In this regard the legal and political framework should incentivize a better construction and demolition waste management (C&DWM) without requiring excessive economic costs for compliance by the companies (Gangolells et al., 2014).

Studies in Catalonia (Spain) (Gangolells et al., 2014) evidence that legislation is a key factor in affecting the recovery and recycling of C&DW by promoting on-waste sorting and the definition of the use of recycled aggregates in structural and nonstructural concrete applications.

The political and legislative system is also a key factor in emerging countries influencing negatively or positively C&DWM. Some cases in China show that the lack of a mature and complete regulation system hampers a better C&DWM affecting the implementation of on-site sorting and their future potential recycling opportunities (Jin et al., 2017; Yuan, 2013, 2017; Duan et al., 2015; Ying et al., 2011; Yuan et al., 2011; Lu and Yuan, 2010), whereas other more successful cases show that the adoption of a good political system (combining top down and bottom up tools) in Hong Kong contributed to reducing the quantity of C&DW going to landfills as well as reducing at the source the proportion of C&DW in the total solid waste in the investigated years (2005–2010) by Lu and Tam (2013).

An effective C&DWM should also be based on the availability of data related to the production of inert waste as in some cases (e.g., Italy) the data are estimated. A useful tool is the adoption of a management plan for C&DW on construction sites as well as the extension to the C&D sector of the extended producer responsibility to achieve a better recovery of C&DW on-site and off-site (Bressi, 2016).

3.3.2 Barriers to the use of recycled products from C&DW

Several authors evidence the existence of cultural barriers in the C&D industry related to lack of knowledge (Silva et al., 2017) and of an adequate information about the

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[b] BAMB's mission is to enable the shift to a circular building sector. Refurbishment, maintenance, and demolition of buildings create large amounts of waste. Substantial stocks of used building materials are discarded, because it is more expensive or impossible to recover them for reuse with their value intact. Buildings are seldom flexible enough to easily adapt to new requirements. Transformations of building use create considerable amounts of waste and demand of virgin materials, if the building is not designed to accommodate the change. For effective use of building materials and to facilitate recovery and reuse of components, products, or materials in buildings, buildings need to be easily reversible (https://www.bamb2020.eu/topics/reversible-building-design/).

quality of recycled products that in turn causes a poor image (Tam et al., 2018) and a negative attitude toward recycled or reused products both from the designers (Oydele et al., 2014) and clients of the construction industry (Tam et al., 2018; Da Rocha and Sattler, 2009).

This evidences the need for accelerating the diffusion of knowledge on the recovered materials for enhancing their development (Rambelli, 2010).

Both reused products (Da Rocha and Sattler, 2009) and recycled products (e.g., recycled aggregates) (Silva et al., 2017) consist of a wide array of products of low and high quality. The quality of the reused products generally depends on the quality of the original products (Da Rocha and Sattler, 2009) and conversely, for example, recycled aggregates on the quality of material used as input in a recycling plant (Rambelli, 2010). Fig. 3.6 depicts salvaged products from a process of selective demolition of a building. In such a way, the recovered products can be reused again in other buildings different from the original.

However, the characterization and certification of the quality of derived aggregates is essential (Silva et al., 2014) to prevent the supply in the market of aggregates of products of poor quality coming from inadequate recycling treatments (Bressi, 2016). This would increase the confidence on recycled aggregates by the stakeholders (Puthussery et al., 2017; Silva et al., 2014, 2017).

The adoption of selective demolition improves the C&DWM increasing the amount of recovered products and reduces the quantity of the materials going to landfills (Akinade et al., 2017; Silva et al., 2017; Duan et al., 2014; Bianchi, 2008). It also improves the quality of the secondary products preventing impurities and not allowed materials in the standards of the sector (Bressi, 2016).

The environmental profiles of C&DW management scenarios involving selective demolition and maximum reuse or recycling of salvaged products and materials are found to be better than business-as-usual scenarios (currently practiced in Europe and USA) with lower fractions of salvaged materials and landfilling for the rest (Diyamandoglu and Fortuna, 2015; Proietti et al., 2013).

Fig. 3.6 Salvaged products recovered in a process of selective demolition. Source: Rinnovabili.it, 2017. Available at: http://www.rinnovabili.it/riciclo/riciclo-materiali-edili-costruzioni/.

Scenarios with selective demolition are also the best for the environment in the life cycle of recycled aggregate (RA) versus the comparison of landfilling scenarios for C&DW with no production of RA, downcycling, and advanced recycling processes for C&DW recovered through the adoption of conventional demolition (Di Maria et al., 2018).

The economic viability of selective demolition is still uncertain (Di Maria et al., 2018) depending on cost factors (operational costs of deconstruction and recycling, transportation costs to the recycling plant, and labor costs), the characteristics of a building, the local context, and the availability of economic incentives (e.g., landfill bans) (Di Maria et al., 2018; Chau et al., 2017; Coelho and De Brito, 2011).

Recycled aggregates also face the problem of lack of economic competitiveness with natural aggregates from virgin materials. In this regard several countries (e.g., Sweden, Denmark, Netherlands, UK, Belgium, Italy, and Finland) have adopted supporting policies consisting in economic tools such as taxes on aggregates to favor the development of recycled products (Söderholm, 2011). The Danish case shows that the introduction of a combination of a tax on raw materials and a waste tax contributed to the increase of recycling of C&DW. This supports the hypothesis of multiple policy instruments addressing both upstream and downstream impacts as more suitable and effective policies for improving the development of recycled products (Söderholm, 2011).

3.4 Supporting decision-making for reuse/recycling of C&DW

3.4.1 Financial analysis and its application to the reuse/recycling of C&DW

This type of analysis is traditionally used by private companies as well as by single individuals (e.g., for investing their money in a portfolio of investments) for evaluating their purchasing or investments' decisions (Nuti, 2010). In particular private companies through the financial analysis assess the convenience of doing an investment on the basis of the yearly cash flow that derives from the difference between cash entrance flows (inflows) and cash exit flows (outflows) (Neto et al., 2017).

Clearly, financial analysis is underpinned by a strict relation between the private operator that is evaluating the different investments' alternatives and their acceptability by the market.

In the case of the C&DW sector, the *inflows* consist of revenues coming from receiving C&DW at the recycling plant as well as from the sales of sorted products within the received C&DW at the recycling plant. The *outflows* refer to the investments or capital costs, working capital, tax payments, fixed and variable operating costs, and depreciation (Neto et al., 2017).

A central indicator for evaluating the feasibility of an investment by private companies and operators is the net present value (NPV) that can be defined as the value *of all future cash flows (positive and negative) over the entire life of an investment discounted to the present* (CFC, 2019):

$$\mathrm{NPV} = \frac{\sum_{i=0}^{n} \mathrm{NCF}_t}{(1+i)t}$$

where NPV is the net present value; NCF_t is the net cash flow at time t (e.g., cash inflow-cash outflow); t is the time of the cash flow; i is the discount rate; N is the number of periods (years).

An investment is worth carried out if the NPV is positive as in this case the project is expected to generate value. On the other side, a negative NPV indicates that the internal rate of return (IRR) of the investment is less than the discount rate and potentially destroy value (CFC, 2019).

Moreover, the analysis also includes the evaluation of the period required to recover through positive cash flows the value of the initial investment of the project (Neto et al., 2017).

We know that the main goal of private companies is making profits and then transforming resources that have a market value in a higher quantity of such resources (Nuti, 2010). The presence of a market price assures that the quantity of resources that private companies decide to invest in a project or in the production process is used efficiently (Turner et al., 2003). However, companies also use resources that do not have a market price. Consequently, the companies in their decisions on how much quantity of such resources they should invest in the production process are not guided by a market price (Turner et al., 2003).

The use of resources without a price such as in the case of environmental resources (e.g., quality of air, water, and soil) does not entail an increase of the variable marginal costs for companies but instead determines an external cost for the society (Turner et al., 2003). The latter occurs under the following conditions:

(1) the activity of an agent causes a loss of welfare of another agent and
(2) the loss of welfare of the agent is not compensated (Pearce and Turner, 1989).

In the presence of externalities, the "rules of social decision" point out that companies should be in charge of the external costs coming from their activity and then of the costs for the use of natural resources or environmental goods for which there is neither a market nor a market price.

This translates in the application of the so-called principle "polluter pays principle" which is a criterion for attributing the damages and costs of the pollution to the agent that causes them and makes the agent responsible in identifying solutions to prevent and control such damages over the whole life cycle of a product (European Commission, 2012; Lindhqvist, 1992).

In legislative terms, the nature of the "polluter pays principle" is twofold as it can be applied in case of not allowed activities (with a sanctionative goal) as well as in the case of allowed activities. In the latter case, the goal is the internalization of the external negative costs discharged to the society by the companies (Lugaresi, 2008).

Of course, when the goal is encouraging the production of positive externalities and then the goal is "externalizing the environmental benefits" provided by virtuous behaviors of companies, public administration, and citizens, the available tools (such as premium systems) incentivize rather than disincentive such virtuous life styles, sustainable processes, activities, and so on (Lugaresi, 2008).

With regard to the C&D sector, recent economic studies evaluate the viability of C&DW recycling plants by calculating costs and benefits and payback period for returning of the investments (Coelho and De Brito, 2013a, b; Srour et al., 2013) as well as analyzing the relation between input gate fee for C&DW to be treated in the recycling plant and the payback period. The results in both studies evidence the importance of the installed capacity of the plant in affecting the profitability and the payback period as well as the strict relation between the input gate fee and the payback period, suggesting in this case to keep as high as possible the fee to avoid longer payback times.

Further results with regard to the economic viability of recycling plants are provided by Neto et al. (2017) by means of financial analysis and discounted cash flow (Neto et al., 2017). These authors compare recycling plants with different sorting technological levels (current advanced, advances, and advanced sorting) and three capabilities of processing C&DW in these plants (100, 300, and 600 thousand tons per year). The results show that the three types of plants are profitable from a level of processing capacity of 300 kt/year. At that level the selling price of 9 €/ton is closer to the market price for aggregates equal to 10 €/ton. The study evidences the difference between the processing capacity of these advanced technologies considered in the study and the processing capacity of existing plants being lower than 100 kt/year which is the chosen capacity for them to be more economically profitable. As a result, they suggest that the transition toward a high technological level producing higher quality recycled aggregates should rely on an adequate local supply of C&DW, an efficient network of infrastructure for C&DW deposits as well as on legislative and economic instruments.

The financial analysis by Wijayasundara et al. (2016) is part of a wider analytical framework that also integrates the accounting of social costs and benefits (direct and indirect) through the cost-benefit analysis (CBA). The goal of their assessment is evaluating the financial viability of manufacturing RAC and the calculation of the price of RAC versus the price of NAC in the Australian context. They found that that price of RAC is strongly affected by the type of manufacturing plant and evidence that the price of RAC could be probably higher than the price of NAC.

Additionally, Tosic et al. (2015) by means of a multicriteria optimization method VIKOR, similar to ELECTRE and PROMETHEE models (Herva and Roca, 2013), compare or make a comparison in environmental and economic terms, the production processes of four concrete types consisting of two types of concrete from recycled aggregates[c] and two types of concrete made with natural aggregates.

They find that in the Serbian condition the two alternatives with recycled aggregates have an advantage on environmental load, mineral resource depletion, and waste production, whereas the alternatives from natural aggregates are more advantageous

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[c] The analyzed types are: recycled aggregate concrete made with fine river aggregate and a 50% substitution of coarse river aggregate with coarse recycled concrete aggregate (RAC50) and recycled aggregate concrete made with fine river aggregate and coarse recycled concrete aggregate (RAC100).

economically due to the lower costs of natural aggregates.[d] This, of course, discourages their replacement with recycled aggregates from C&DW (Tosic et al., 2015).

As a consequence, they further analyze the effects of the adoption of economic instruments such as taxes on river aggregates and on landfilling and subsidies. The analysis shows that an increase of the river aggregate cost by 50% through a tax on river aggregate use, followed by an increase of the landfill tax by 53% would render more competitive the alternative RAC50 concretes achieving the same costs of one of the natural aggregates' counterparts.

Given that the production of RAC provides several environmental benefits that are not accounted on a pure financial or private economic basis compared to the production of NAC suggests that we should rely on assessment methods that are able to reflect these benefits into production costs and prices and complement the financial analysis with the economic analysis as we will explain in the next section.

3.4.2 Cost-benefit analysis of reusing/recycling C&DW

The CBA is a tool for public decision-making that assesses in terms of social well-being the opportunity and efficiency of different types of investment projects. Consequently, in the CBA, compared to the financial analysis, the social well-being is the reference goal that guides the analysis.

In that the CBA refers to social costs and benefits to highlight the fact that these are evaluated and accounted on the basis of social decision rules compared to the costs and benefits (better defined revenues and costs) of the private operator evaluated by the market and its rules.

This entails that the CBA takes into account benefits and costs that are not considered by the market. Moreover, in some cases the market prices of some factors or products can be corrected by adopting the so-called shadow prices. This is done to account for the positive and negative externalities of the investment.

The CBA provides as main indicator the NPV, that is, in the case of CBA, compared to the financial analysis, the net of discounted values of social costs and benefits to society (Wijayasundara et al., 2017).

In the international literature the evaluation by means of CBA of the production of RAC and their use in structural applications such as in buildings has been just developing. The most comprehensive CBA application in the field regards a very recent Australian case study (Wijayasundara et al., 2018) that evaluates and compares the potential use of RAC as an alternative product to NAC for the construction of two buildings as well as extend its replacement throughout the primary life of the buildings.

The purpose of the study is in understanding the economic suitability in replacing the use of NAC. The calculation of the NPV for a unit volume of RAC at the inbound

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[d] Of course, the cost of the latter does not take into account the environmental load on resources without a market price exploited in the production process of natural aggregates such as, for example, land use during their mining or the generated pollution in different forms affecting air, water, and soil quality (Langer and Arbogast, 2003).

gate of a construction application derives from the sum of net incremental financial benefit (NIFB) and net incremental external benefit (NIEB) (Wijayasundara et al., 2018).

In turn, this latter indicator is obtained by the sum of further three indicators. The most significant contribution to the calculation of NIEB, among the three indicators, comes from the economic accounting of the indirect environmental impacts related to the avoidance of landfilling of CW, avoidance of NA quarrying, and the avoidance of transportation.

The results evidence that the monetization of all the benefits in the NPV including the external benefits favor the use of RAC as a product compared to the use of NAC. This entails cost savings for the contractor of the construction projects (buildings) and a decrease of the average price of concrete by 4%–6% due to the replacement of RCA.

The analysis also shows that the incremental price of RAC only calculated on the basis of financial analysis would not favor the use of RAC by the construction contractor as in the opposite case when considering the positive externalities and their shift to the product to reflect the full benefit to society with its production. In this case the associated benefits offset the net increase in financial costs (Wijayasundara et al., 2018).

The integration of CBA with financial analysis in the same evaluation framework provides with the opportunity of showing how both analyses complement each other and widen the understanding of an investment project and its potential feasibility improving the decision-making process.

In this regard, particular attention should be given to the fact that the outcome of financial analysis of the study was negative evidencing that the use of RAC by the contractor would not be profitable compared to the use of NAC whereas the outcome of the CBA is positive and in this case for the society the use of RAC results as a better alternative to NAC. Consequently, the positivity of CBA justifies the adoption of policies and tools aimed to support the development of recycled aggregate in the production of concrete.

3.5 Main conclusions and future trends (expected and planned)

The C&DW sector generates a huge impact on the environment in terms of resources' use, production of waste, and release of emissions. The transition to more sustainable and circular patterns and business models is the response of the C&DW sector to environmental challenges. It is expected that the need for transition will become more and more stringent in the future given that the building stock in the developing countries is still largely to be constructed as evidenced in the convention of RIO 2012 (Zutshi and Creed, 2015).

Certainly, the transition to the CE will also require substantial changes to the sector in terms of C&DWM beyond the usual discharge of C&DW in landfills involving the reuse of products and closing of the cycles through recycling of C&DW. On the other hand, the recycling of C&DW is one of the strategies within the wider framework of sustainable construction aimed to prevent and mitigate the environmental impacts of the sector and should not be considered as an end-of-pipe solution in the future but a deliberate result of the product design stage.

The CE transition stresses the importance through the circular product design to maintain as long as possible the value of products, components, and materials. In that buildings are considered as materials banks, for which constructors or owners should bear the responsibility providing the incentive to design them in a way that their components and materials can be substituted and recovered and reused or recycled and the whole building be adaptable to transformations that avoid the production of unnecessary waste.

At present, the development of recycled aggregates is hampered by several barriers such as cultural, legislative, and economical. With regard to the latter, recycled aggregates face the competitiveness with the natural aggregates. On a purely financial basis, the available studies evidence that the price of concrete from recycled aggregates is higher than the price of natural aggregates. However, the results of a very recent case study in Australia show that widening the analytical framework to include the CBA, the use of recycled aggregates for the constructor of a building is less costly than the use of natural aggregates.

Finally, from a methodological point of view this study evidences the importance of adopting an integrated framework to provide a more comprehensive picture of the investments and analyzed systems as well as the relationships with the natural environment and, in particular, the environmental benefits that circular patterns and recycled products provide in comparison to conventional patterns and products from increasing scarcity virgin raw materials.

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