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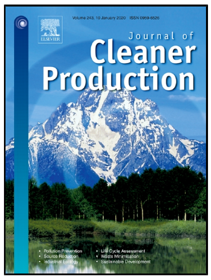

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The circular economy in the construction and demolition waste sector – a review and an integrative model approach

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Keywords: construction and demolition waste, material recovery, waste management, circular economy

Abstract

Construction and demolition waste (CDW) is a priority for many policies at global level. This is due to the high volume of CDW that is produced and its inadequate management. This situation leads to serious environmental effects, which are mainly associated with manufacturing processes for new building materials because of low product recovery rates. In this context, the concept of Circular Economy (CE) is a potential solution in many sectors, as it involves more efficient use of resources and energy, which leads to waste minimization and reduction of the environmental impacts of product cycles. Moreover, it represents potential economic opportunities. The main aim of this study was to identify factors that could influence the adoption of the Circular Economy concept in the construction and demolition sector. A systematic literature review was conducted to understand the main strategies involved in the development of integral circular strategies. The main contribution of this paper is a theoretical framework for the Circular Economy in the construction and demolition sector. The framework is comprised of 14 strategies within the five lifecycle stages of construction and demolition activities. Particularly, the framework emphasizes waste management and recirculation of recovered materials for their use as secondary building materials.

1. Introduction

The construction industry has a strong influence on the three aspects of sustainability: environmental, economic and social. It is a major provider of employment opportunities and a large contributor to gross domestic product (GDP) (Smol et al., 2015). In 2016, the construction sector accounted for 6.2% of world GDP, 6.3% in Europe and 5.7% in Latin America (Eurostat, 2017; FIIC, 2017). However, in addition to its economic and social benefits, the construction sector creates serious environmental problems during the entire lifecycle of buildings, especially during the operation and end-of-life stages. This is mainly due to the generation of construction and demolition waste (CDW) and the manufacturing of building materials (Geng et al., 2017; Ghisellini et al., 2018a).

In this context, CDW is a major challenge for the construction industry due to the increasing volume of waste produced and its associated environmental impacts. CDW is the largest waste stream worldwide (30 to 40% of total solid waste, Jin et al., 2018; Tam and Tam, 2006). In the European Union, CDW accounted for 36% of the total solid waste produced in 2016 (924 million tons, Eurostat, 2018), while in the United States this proportion was close to 67% (534 million tons, EPA, 2016), and in China it was 30–40% (2.36 billion tons, Huang et al., 2018; Zheng et al., 2017) (Figure 1a, b).

Because of the negative impacts of CDW on the environment and the high rates of waste produced, the management of CDW has become a priority for sustainable development programs worldwide (Esa et al., 2017). Associated environmental impacts include land degradation, landfill depletion, carbon and greenhouse gas emissions, water pollution, high energy consumption and resource depletion (Akanbi et al., 2018; Z. Ding et al., 2016). Even though there is increasing interest in implementing recovery practices such as reuse and recycling, in most cases the waste management process is inefficient, resulting in large volumes of waste disposed of in landfills or even illegally dumped without environmental protection measures (Esa et al., 2017; Suárez et al., 2016). This situation is evident: only 20 to 30% of construction and demolition waste is recovered globally (World Economic Forum, 2016). As shown in Figure 1c, the average recovery rate in the European Union is 46% (European Commission [DG ENV], 2011), although the rate varies from 10 to 90% among Member States, e.g. United Kingdom 89.9%, France 47.5%, Spain 37.9% and Germany 34% (European Commission, 2015a; FERCD, 2015). The average is therefore under the 70% recovery and recycling target by 2020 set in the waste Directive 2008/98/EC. In the United States it stands at around 70% (Zheng et al., 2017), while in China the recovery rate remains limited at less than 5% (Huang et al., 2018).

In the light of environmental challenges derived from the current linear economy model of "take-make-consume-dispose", the construction industry requires the implementation of new, enhanced building strategies focused on the problem of CDW (Jaillon and Poon, 2014). In this context, the transition to a Circular Economy (CE) is considered a solution as it would reduce environmental impacts while contributing to economic growth (Lieder and Rashid, 2016). Thus, CE constitutes a novel regenerative system to optimize the use of materials and their value throughout their lifecycle phases, and to minimize waste (Bocken et al., 2016; Brown et al., 2019; Esa et al., 2017).

The CE concept has gained academic, government and organizational recognition. At global level, Germany, Japan, China and Europe are recognized for having developed legislation on the implementation of CE principles (Merli et al., 2018; Su et al., 2013). In the European Union, CE has become a central aspect of the development of policies and strategies, as part of the Circular Economy Action Plan (European Commission, 2018a).

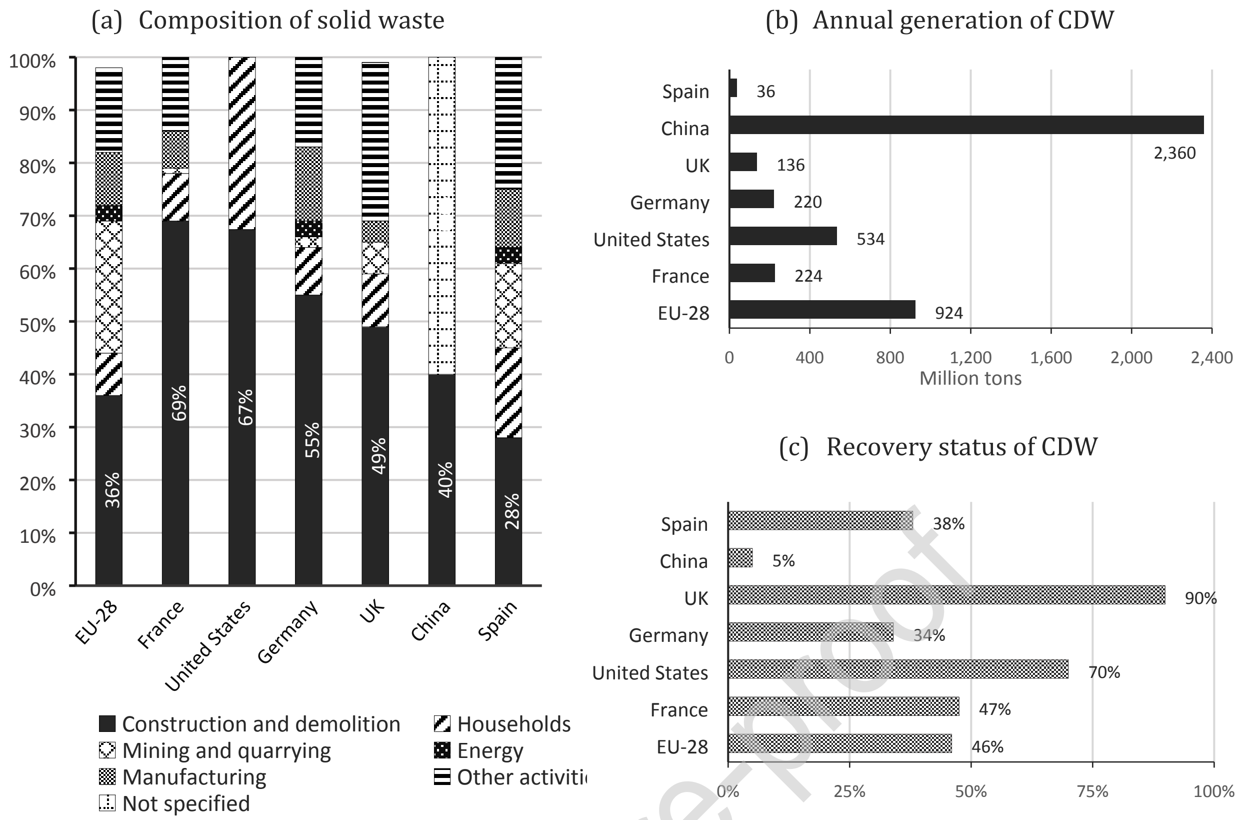

Figure 1. Comparison of generation and recovery status of CDW

Although the construction industry is considered one of the key sectors with the greatest potential for CE adoption (Brambilla et al., 2019) and CDW is identified in CE policies as a priority (European Commission, 2015b), its implementation is a challenging task that requires drastic changes in the structure of industry and society, mainly related to waste management and business operation (Lieder and Rashid, 2016).

Furthermore, research on implementation of the CE model in the CDW sector has not been extensive. Recent studies have analyzed the application of best management practices for CDW (e.g. Gálvez-Martos et al., 2018; Huang et al., 2018), and explored cases of implementation of CE principles in the CDW sector based on the 3R (reduce, recycle, reuse) principle (Ghisellini et al., 2018b). In addition, some efforts have been made to develop frameworks for CDW minimization (e.g. Esa et al., 2017 on Malaysia) and the integration of CE in the built environment (Pomponi and Moncaster, 2017, on the transition to circular buildings). In addition, the analysis of potential barriers to CE implementation in CDW management practices has been addressed (Mahpour, 2018). Other studies have focused on identifying and comparing the best recovery alternatives for specific CDW typologies (e.g. Jiménez-Rivero and García-Navarro, 2017 on gypsum and Lockrey et al. 2016 on concrete). The literature also includes multiple environmental assessments of CDW, including those by Chau et al. (2017) on the lifecycle energy assessment of a concrete-based building in Hong Kong; Coelho and De Brito (2012) on lifecycle analysis of a building in Portugal comparing waste management options; Martínez et al. (2013) on a building in Spain evaluating factors that influence demolition processes; and Ng and Chau (2015) on the evaluation of energy saving potential of recycling, reuse and recovery alternatives for types of CDW from a commercial building. In terms of economic assessments of waste management practices for CDW, studies include a paper by Jung et al. (2015) on concrete waste, Marzouk and Azab, (2014) on the evaluation of recycling and disposing of CDW, and Wijayasundara et al. (2016) on recycled aggregates and their use in ready-mix concrete production.

From a CE perspective, most of the current research is focused on one or more circular principles, and particularly recovery options. However, there is a lack of integrative approaches that consider the application of CE strategies in multiple stages in the lifecycle of construction and demolition products, beyond the 3R principle as a waste management strategy. The study aims to address this gap by evaluating the scientific literature on the construction and demolition sector within the CE concept. The final aim is to develop a theoretical CE framework for the construction industry and particularly the CDW sector. In this study, the exploration of CE strategies on the use of CDW as secondary materials is limited to applications in the construction industry, excluding applications in other industries.

This work is structured in six sections. Section 2 provides a brief literature review of the Circular Economy concept and its principles. In addition, an overview is provided of the current and main existing CE initiatives for the CDW sector in the European context. Section 3 describes the research methodology used to achieve the objectives of this study. Next, Section 4 presents the results of the review, based on categorization of CE strategies according to five lifecycle stages of construction and demolition activities. Derived from these results, Section 5 presents a theoretical framework for implementing the CE concept in the CDW sector. The paper concludes by highlighting the contributions and findings of the study.

2. Background

This section gives a short introduction to the Circular Economy model addressed in this study. It presents a brief description of the concept and the main factors and elements that influence circular models. In addition, it provides an overview of existing initiatives and applications of CE principles with a focus on the CDW sector.

2.1. Circular Economy

Circular economy is a recent concept that has been approached in many ways, depending on the social, cultural and political system (Winans et al., 2017). The CE concept is strongly recognized among scholars and practitioners in industry and society, because it is considered an alternative for operationalizing businesses under the concept of sustainable development (Kirchherr et al., 2017). Hence, the primary objective of CE is to dismantle the relation between economic growth and environmental degradation and resource consumption through new production practices and technological developments, satisfying consumer needs in different, more sustainable ways (Brown et al., 2019; Ellen MacArthur Foundation et al., 2015).

According to the Ellen MacArthur Foundation (2018), Geissdoerfer et al. (2017) and Korhonen et al. (2018), the CE concept is influenced by many schools of thought, such as cradle-to-cradle design, performance economy, biomimicry, industrial ecology, natural capitalism and blue economy. In addition, Pauliuk (2018) identified theoretical influences like regenerative design and ecological and environmental economics. The notion of CE is also based on ideas from scientific and semi-scientific concepts that include industrial symbioses, cleaner production and the concept of zero emissions (Korhonen et al., 2018). Furthermore, the 3R principle (Reduction, Reuse and Recycle) is considered the basis of CE (Ghisellini et al., 2016).

Although there is no one single concept of CE, it can be broadly defined as a model in which the value of materials, products and components remains in the production cycle for as long as possible. Thus, at a product's end-of-life, it can be repeatedly used as a secondary resource while avoiding and reducing the input of raw materials and energy and minimizing waste generation (Ellen MacArthur Foundation et al., 2015; Merli et al., 2018). According to Geissdoerfer et al. (2017), the Circular Economy acts as a regenerative system in which resources, energy, emissions and waste leakage are minimized by slowing, closing and narrowing material and energy loops. This is achieved by implementing actions as part of many strategies of design, reuse, recycling, remanufacturing and, if possible, energy recovery throughout production processes and consumption distribution flows (Kirchherr et al., 2017). Moreover, the use of renewable energy is fundamental to ensure optimal model efficiency (Korhonen et al., 2018a).

According to (Baldassarre et al., 2019), the transition to a CE requires the implementation of a framework based on the three strategies of closing, slowing and narrowing/reducing loops. It is also based on three pillars called technical innovation, business model innovation and collaboration. In this context:

- *Closing loops* consists of creating a circular flow of resources resulting from the use phase that are generally considered waste. This is achieved through recycling processes.
- *Slowing loops* refers to lengthening the use and reuse of a product through actions such as repair, refurbishment and remanufacture.
- *Narrowing loops* is about reducing the use of resources and maximizing efficiency in production processes (Bocken et al., 2016).

2.2. CE initiatives

The CE concept has been implemented through government policies at local, regional and national level. The German government introduced CE principles as part of the Closed Substance Cycle and Waste Management Act in 1996, which was subsequently reorganized in 2012 as an Act to Promote the Circular Economy and Safeguard the Environmentally Compatible Management of Waste (BMU, 2012). In the case of Japan, the government developed the Basic Law for Establishing a Recycling-Based Society, built on the 3R principle (Geissdoerfer et al., 2017). The Government of China incorporated CE as a central pillar of its National Economic and Social Development plans. Later, in 2009, it established the Circular Economy Promotion Law of the People's Republic of China (Merli et al., 2018).

In the European Union, recent strategies have been developed that focus on promoting economic growth, preventing the loss of valuable materials and reducing environmental impacts and greenhouse emissions (Bocken et al., 2016). Directive 2008/98/EC is considered an initial document on the implementation of best waste management practices. In 2014, the European Union issued the Communication "Towards a circular economy: A zero waste programme for Europe" (COM 398, 2014), followed in 2015 by the Communication "Closing the loop. An EU action plan for the circular economy" (COM 614, 2015). Both are part of the "Circular Economy Package", which consists of multiple action plans and legislative proposals focused on each step of the value chain (production, consumption, waste management and secondary raw materials) in five priority sectors: plastics, food waste, critical raw materials, construction and demolition, and biomass and bio-based products (European Commission, 2015b).

In the construction and demolition sector, CE is a tool for fostering more efficient CDW management and for reducing resource and emission leaking from the loops (Mahpour, 2018). In the European context, various approaches include CDW as a central aspect. Table 1 provides an overview of the most important regional and national initiatives and strategies developed in Europe regarding CDW in the Circular Economy.

Table 1. Overview of current CE initiatives in the CDW sector

CE initiative	Highlights
COM (2014) 398 – Towards a circular economy: A zero waste programme for Europe *Context:* European Union *References:* (European Commission, 2014a)	• CDW is a priority waste stream. • The importance of enhancing the market for secondary materials, to increase CDW recycling rates. • Stipulates a framework for assessment of the environmental performance of buildings as outlined in COM (2014) 445 - Resource efficiency opportunities in the building sector. Specifically: - Including actions focused on the stage of preconstruction (specifically design) to improve CDW management and increase recyclability and recycled content in construction materials. • Definition of a set of measures such as the application of economic instruments (e.g. higher landfill taxes) and additional separation obligations during the construction and end-of-life stages to achieve the 70% recycling target 2020 set in Directive 2008/98/EC.
COM (2015) 614 – Closing the loop: An EU action plan for the circular economy *Context:* European Union *References:* (European Commission, 2015b)	• CDW is considered a priority, with a focus on the preconstruction stage. • Three potential measures are established to guarantee resources for the recovery and adequate management of CDW, and to facilitate the environmental assessment of buildings: - Guidelines for predemolition/deconstruction assessment; - Development of a voluntary protocol for recycling; - Design of a framework of key indicators for the environmental assessment of buildings and the development of incentives for their application.
EU Construction & Demolition Waste Management Protocol *Context:* European Union *References:* (European Commission, 2016)	• Framed within the actions of COM (2014) 445. • Part of the CE Package. • The main objective is to enhance user confidence in recycled materials, increase use of recycled materials in the construction industry and improve CDW management practices in compliance with the recovery target of 70% for 2020. • Constitutes a framework of guidelines to develop efficient CDW management plans before and during construction activities. • Includes measures and specifications to enhance identification, segregation, collection, site logistics and treatment practices of CDW.

Gypsum to Gypsum, from production to recycling: a circular economy for the European gypsum industry with the demolition and recycling industry (2013–2015). *Context:* European Union *References:* (Bio et al., 2016; Eurogypsum, 2018; European Commission, 2018b)	• Project funded by the European Commission on the implementation of best management practices for gypsum waste. • Participation of 17 members of the European gypsum industry across eight key Member States (Belgium, France, Germany, Greece, Netherlands, Poland, Spain and the United Kingdom). • Target of 30% reincorporation of recycled gypsum in manufacturing processes. • Main aspects involved are: - Value chain analysis; - Deconstruction of pilot projects; - Gypsum waste reprocessing and qualification of recycled gypsum; - Reincorporation of recycled gypsum in the manufacturing process. • Three main implementation phases: - Analysis and assessment of demolition/deconstruction practices, recycling and manufacturing of gypsum-based products; - Implementation of pilot projects based on the best deconstruction practices, recycling and reincorporation of recycled material; - Qualitative and quantitative assessment of each pilot project and the complete project. • Environmental and economic criteria were considered to determine the best waste management and material production strategies. • The main results were: - For closed-loop recycling of gypsum waste, systematic dismantling practices need to be implemented instead of demolition. On-site sorting is required and compliance with material specifications for reincorporation into the manufacturing process. - Reincorporation of recycled materials into the manufacturing process is mostly influenced by material costs. - The current rate of recycled gypsum reincorporated into manufacturing processes is around 25%. - Political and legislative restrictions are the main barrier for gypsum waste recovery (e.g. landfill fees and requirements for deconstruction).
Spanish Strategy for the Circular Economy 2030. Action plan 2018–2020. *Context:* Spain *References:* (MAPAMA, 2018)	• CDW measures are proposed for the following areas of action: - Manufacturing and design: analysis of technical building regulations to identify possible constraints in the use of recycled materials and integrate aspects for building sustainability. - Waste management: I. Evaluation of Royal Decree 105/2008, which regulates the production and management of CDW, to enhance the identification, traceability and selective segregation of CDW, and to improve management processes. II. Reduction of excavation material from railway projects and its subsequent use in the restoration of degraded areas. Additionally, development of waste management plans for CDW recovery from construction works undertaken by the Directorate of Travel Stations. - Market for secondary materials: use of recovered CDW in road construction and ports. Removal of regulatory barriers to the reuse of construction materials through the analysis of technical regulations for building projects.

Government Construction Strategy 2016–2020 *Context:* United Kingdom *References:* (Infrastructure and Projects Authority, 2016)	• Introduces a program for the adoption of a Building Information Modelling (BIM) 3D system as a strategy for improving productivity and efficiency in construction projects. • Enables the development of more efficient design models. • Provides opportunities for better management of buildings during the construction stage and at the end-of-life stage by sharing precise information throughout the construction value chain. • Influences waste minimization. • Introduces a tool for collecting valuable information related to the lifecycle of buildings.
Waste and Resources Action Programme (WRAP) - Resource Efficient Construction - Halving Waste to Landfill Commitment *Context:* United Kingdom *References:* (WRAP, 2013, 2011)	• Aimed at providing support for local authorities, businesses and individuals in the implementation of practices for waste reduction, recycling and efficient use of resources. • The Resource Efficient Construction approach aims to encourage construction practices that reduce costs, minimize waste and reduce atmospheric emissions. In summary: - It supports manufacturing companies in the improvement of production processes to reduce the associated environmental impacts. - It provides guidance to constructors and other related actors in the implementation of good practices in the preconstruction, construction and end-of-life stages to enhance waste minimization and reuse actions. - Among the common practices are: ▪ Design for waste prevention and deconstruction; ▪ Use of BIM tools; ▪ Use of prefabricated components; ▪ Reuse, recycling and energy and water efficiency; ▪ Quality protocols for recovered materials; ▪ Finance advice. • The Halving Waste to Landfill Commitment is a voluntary agreement among stakeholders from the construction industry supply chain, under a supportive framework for waste reduction. - Specific targets of waste reduction and disposal in landfills are defined. - Supportive actions are implemented to apply good waste management practices.

3. Method

A systematic review provides the basis for enhancing knowledge of the research area and identifying gaps in published studies. Moreover, a systematic review allows specific questions to be answered, and appraises studies objectively (Petticrew, 2001). The methodology applied in this study is an adaptation of Torres-Carrion et al. (2018), which is based on the proposal of Kitchenham and Brereton (2013) for performing systematic literature reviews in engineering, later adapted by Bacca et al. (2014) to other scientific areas. This methodology also includes an adaptation of the "mentefacto conceptual" for improving efficiency and comprehension.

A systematic review was conducted using all the databases in Scopus and Web of Science and the following keywords: "circular economy", "closed-loops" AND "(construction OR demolition) waste", "debris". Data were collected from November 2018 to March 2019. Studies published in the last 15 years (2013–present) were extracted without geographical restrictions. Unpublished studies and conference proceedings were excluded. From these searches, we identified an initial sample of 267 papers to be investigated, 129 from Scopus and 138 from Web of Science. Duplicate papers were excluded. A further selection was made considering the following criteria for the content of abstracts:

- Studies that provide frameworks, models and identification of components of CE applications in the construction and demolition sector.
- Studies that assess and include discussions on the use of recovered materials in the manufacturing of new construction materials from a CE perspective.
- Studies that assess the reuse, recycling and recovery of CDW, and other waste management practices from an environmental and/or economic perspective.
- Reviews on existing initiatives related to the CDW sector in the frame of CE principles.

After reviewing the abstracts, the 53 most representative papers were selected based on the above criteria. Table 2 provides a summary of the database search. Then, a critical review of the resulting research articles was conducted to identify strategies that influenced CE, based on applications in the construction and demolition industry, and focused on waste management and use of CDW as secondary materials in the construction industry. Subsequently, a theoretical framework approach for CE in the CDW sector was developed and analyzed.

From the search results (Table 2), we observed that scientific research on the Circular Economy with a focus on construction and demolition waste is still an emerging topic. This is revealed by the fact that 51% of the studies were undertaken from 2017 to the present. Moreover, most of the studies (36%) were approached from an environmental perspective. An observation of all studies showed that the countries leading research on this area are China, Spain and United Kingdom.

Table 2. Summary of database search

Keywords	Databases search results	Results after revision	Subject area	Country/territory
"circular economy", "closed-loops" AND "(construction OR demolition) waste", "debris"	Scopus (129 articles) Web of science (138 articles)	31 articles duplicated 53 articles selected	Environmental Science (36%) Engineering (19%) Energy (13%)	China Spain United Kingdom

4. Results

4.1. Research focus

This section identifies the most relevant strategies for adopting an integral CE model as an approach for the construction and demolition sector in the following five lifecycle stages, identified in the literature search as the most influential stages in the analysis of CDW:

- preconstruction;
- construction and building renovation;
- collection and distribution;
- end-of-life;
- material recovery and production.

These five main stages are prevalent in studies analyzing CDW from a CE perspective and are associated with a set of 14 strategies for implementing legislative and political CE frameworks, efficient waste management practices, and the use of CDW in the manufacturing of new materials in the construction industry (Table 3).

The identification of these five lifecycle stages is mainly based on the categorization by Akanbi et al. (2018), Esa et al. (2017), Gálvez-Martos et al. (2018) and Yeheyis et al. (2013). Akanbi et al. (2018) conceptualized the CE model in the construction industry in seven stages: *extraction/use of virgin raw materials*, *material inputs*, *design process*, *construction and production process*, *distribution*, *collection* and *recycling.* Esa et al. (2017) outlined five common stages across the value chain of a construction project: *planning*, *design*, *procurement*, *construction* and *demolition*. Moreover, Gálvez-Martos et al. (2018) categorized best CDW management practices in four stages according to the basis of CE: *preconstruction*, *construction*, *demolition* and *waste to products*. Finally, Yeheyis et al. (2013) proposed a CDW management framework based on three stages: *preconstruction (planning and design)*, *construction and renovation* and *demolition* stage.

The literature review showed that the largest proportion of studies addressed *preconstruction* and *material recovery and production* strategies, both in the same proportion (15 articles). This was followed by studies that included aspects related to *collection and distribution* (11 articles) and *end-of-life* strategies (11 articles). Finally, a small proportion of studies focused on *construction and building renovation* strategies (two articles).

From the foregoing results, we provide a synthesis of the review of research on circular economy strategies for the CDW sector according to the outlined categorization of lifecycle stages (preconstruction; construction and building renovation; collection and distribution; end-of-life; and material recovery and production).

Table 3. Summary of relevant CE strategies for CDW

Stages	CE strategy		Author/s
Preconstruction *(5 strategies)*	Policies and strategic frameworks:	• Economic instruments	(Gálvez-Martos et al., 2018; Ghisellini et al., 2018a; Huang et al., 2018; Nussholz et al., 2019; Wang et al., 2018; Yu et al., 2013; Yuan, 2017; Zheng et al., 2017)
	Design:	• Design for waste prevention • Design for disassembly and deconstruction • Use of prefabricated elements	(Akanbi et al., 2018; Brambilla et al., 2019; Ghisellini et al., 2018a; Gorgolewski M., 2008; Huang et al., 2018; Jaillon and Poon, 2014; C. Li et al., 2014; Minunno et al., 2018; Yeheyis et al., 2013)
	CDW management plans		(Douglas, 2016; Jiménez-Rivero and García-Navarro, 2017; Yeheyis et al., 2013)
Construction and building renovation *(1 strategy)*	Site waste management plans, SWMP		(Gálvez-Martos et al., 2018; Jiménez-Rivero and García-Navarro, 2017)
Collection and distribution *(2 strategies)*	Collection and segregation techniques		(Dahlbo et al., 2015; Gálvez-Martos et al., 2018; Ghisellini et al., 2018a; Huang et al., 2018; Jiménez-Rivero and García-Navarro, 2017)
	Transport		(Bovea and Powell, 2016; Brambilla et al., 2019; Coelho and De Brito, 2012; T. Ding et al., 2016; Gálvez-Martos et al., 2018; Jung et al., 2015; Martínez et al., 2013)
End of life *(2 strategies)*	Selective deconstruction		(Akanbi et al., 2018; Brambilla et al., 2019; Chau et al., 2017; Coelho and De Brito, 2012; Gálvez-Martos et al., 2018; Ghisellini et al., 2018a, 2018b; Jiménez-Rivero and García-Navarro, 2016; Nussholz et al., 2019; Schultmann and Sunke, 2007)
	Predeconstruction/demolition audits		(Jiménez-Rivero and García-Navarro, 2017, 2016)
Material recovery and production *(4 strategies)*	Reuse		(Akanbi et al., 2018; Gálvez-Martos et al., 2018; Ghisellini et al., 2018b; Huang et al., 2018; Minunno et al., 2018; Nussholz et al., 2019; Sassi, 2008; Schultmann and Sunke, 2007)
	Recycling		(Akanbi et al., 2018; Bovea and Powell, 2016; Christmann, 2018; T. Ding et al., 2016; Huang et al., 2018; Lockrey et al., 2016; Marzouk and Azab, 2014; Ng and Chau, 2015; Wijayasundara et al., 2016)
	Energy recovery		(Chau et al., 2017; Schultmann and Sunke, 2007)
	Backfilling		(Coudray et al., 2017; Gálvez-Martos et al., 2018)

4.2. *Preconstruction*

In the preconstruction stage, waste minimization and efficient use of material can be achieved by alternatives focused on optimizing the planning, control and management of CDW from future construction activities. Three main categories of strategies are prevalent in this stage: (i) policies and strategic frameworks, (ii) design and (iii) CDW management plans.

4.2.1 *Policies and strategic frameworks: economic instruments*

Most waste management regulations have been developed for household waste, while regulations for CDW are often limited (Yuan, 2017). Hence, the development and enhancement of policies and strategic frameworks contribute to a sustainable construction strategy. A legislative CE framework provides an opportunity to manage the environmental challenges resulting from increasing CDW generation (Ghisellini et al., 2018a). In this context, regulatory instruments, such as economic instruments, are identified in the literature (Gálvez-Martos et al., 2018; Ghisellini et al., 2018a; Huang et al., 2018; Nussholz et al., 2019; Wang et al., 2018; Yu et al., 2013; Yuan, 2017; Zheng et al., 2017) as the main influencing strategy among the policies and frameworks applied in the CDW sector for CE. Thus, economic instruments are an effective measure to encourage waste minimization and material recovery.

Among the economic instruments, a CDW disposal charge is identified as one of the more successful strategies to reduce the amount of waste disposed of in landfills (Ghisellini et al., 2018a; Wang et al., 2018). A low landfill fee discourages the adoption of reduction and recovery actions and favors disposal in landfills (Ghisellini et al., 2018a; Huang et al., 2018). In contrast, disposal charging schemes encourage waste producers to prioritize reduce, reuse and recycle practices over disposal, as they can reduce disposal costs (Wang et al., 2018; Yu et al., 2013). These schemes are based on the polluter pays principle, in which polluters are responsible for environmental impacts and receive economic pressure to implement recovery practices throughout the construction and demolition processes (Yu et al., 2013). As an example, and according to Ghisellini et al. (2018a) and Yu et al. (2013), the implementation of the Construction Waste Disposal Charging Scheme in Hong Kong is considered one of the most influential policies for CDW reduction. As a result of its adoption, the amount of CDW disposed of in landfills has been reduced by around 60%. However, despite the multiple environmental benefits of increasing material recovery, high disposal fees may result in an increase in illegal dumping (Huang et al., 2018; Yuan, 2017). Another economic instrument is the application of taxes on primary materials, which can be used as an instrument for enhancing the market of secondary materials (Nussholz et al., 2019).

The analysis of CDW management practices undertaken by Gálvez-Martos et al. (2018) and Huang et al. (2018) recognizes the application of appropriate incentives for CDW treatment companies as a potential alternative for enhancing and promoting efficient recycling and recovery methods, and to expand the production of building products using recovered materials (e.g. financial subsidies for recycling companies, low land rental fees for CDW management companies). Moreover, a study by Li et al. (2014) demonstrates that policies focused on increasing subsidies for the construction process based on prefabrication are a major factor for promoting the adoption of prefabricated elements.

4.2.2 *Design*

Design is a strategic component that influences waste generation in construction projects. Three main strategies are identified in this category: (i) design for waste prevention, (ii) design for disassembly and deconstruction and (iii) use of prefabricated elements.

4.2.2.1 *Design for waste prevention*

Design for waste prevention provides one of the best opportunities to reduce waste generation and strengthen reuse and recycling practices from the early stage of construction planning and throughout the entire value chain. A lack of preventive measures and limited knowledge of construction and constructability increases the waste generated, hinders its control and affects the cost and time of waste management (Esa et al., 2017; Jin et al., 2018; Yeheyis et al., 2013). In this context, reuse should be a priority to be researched by the design team to use appropriate components in construction projects. Engineers, architects and demolition and salvage companies must develop working relationships to enhance the potential of the reuse market. Although there are associated cost savings, additional labor costs are often generated by project management practices and the additional costs of off-site storage should also be considered (Gorgolewski M., 2008).

The availability of accurate and reliable forecasts of CDW generation and its detailed composition are essential during the planning and design stage of construction projects (Yuan, 2017). Studies by Akanbi et al. (2018), Huang et al. (2018), Minunno et al. (2018) and Yeheyis et al. (2013) identified Building Information Modelling (BIM) as an effective technique to estimate the type and volume of recoverable materials and their potential treatment (reuse, recycling, recovery, landfilling processes) during the design stage. BIM-based tools facilitate the management of buildings throughout their entire lifecycle and constitute an opportunity in terms of the circular economy, due to their capacity to accumulate lifecycle information and the significant potential for waste reduction. In addition, BIM plays a key role in the design of future disassembly of buildings and facilitates estimation of the circularity degree of building materials. Moreover, specifications of materials during the design stage constitute a major factor for determining the level of reusability and recyclability of recoverable building materials at the end-of-life stage.

4.2.2.2 *Design for disassembly or deconstruction*

Design for disassembly or deconstruction constitutes a fundamental strategy for achieving more sustainable buildings by promoting a closed-loop system for building components. It has a significant influence on the amount of potential reusable and recyclable materials and facilitates the operation of recovery practices (Jaillon and Poon, 2014). The implementation of design for deconstruction is closely linked to the use of prefabricated components. It has the potential to reduce at a significant rate the waste produced during the construction and renovation stage and during demolition/deconstruction activities (Ghisellini et al., 2018b; Jaillon and Poon, 2014). Apart from environmental benefits, this practice involves lower working time and lower construction costs. However, this is a modern construction method and is not widely applied in the building sector (Jaillon and Poon, 2014), since its application depends on specific site conditions (Ghisellini et al., 2018b). In addition, there is a need for developing quality standards for the industry of prefabricated components (Huang et al., 2018).

4.2.2.3 *Use of prefabricated elements*

The use of prefabricated elements consists in the adoption of prefabricated items such as facades, dry walls, precast slabs and staircase units. These products are produced, assembled and prefinished in external facilities. An empirical study by Li et al. (2014) highlights that the use of prefabricated elements can reduce labor-intensive construction trades (e.g. concreting, bricklaying and plastering), which minimizes various waste streams such as concrete and wood from concreting. In general, 65 to 80% of total CDW can be reduced by the adoption of prefabricated systems (Gálvez-Martos et al., 2018; Jaillon and Poon, 2014).

4.2.3 CDW management plans

In line with the above practices, CDW management plans should be developed during the design phase (Yeheyis et al., 2013). These plans comprise a strategy for project planning and establish waste management measures for waste reduction before, during and after construction activities (Douglas, 2016; Jiménez-Rivero et al., 2017). In Europe, the development of waste management plans is a common practice, as it is mandatory and required for each construction project (Gálvez-Martos et al., 2018). An integral CDW management plan includes the development of a waste management report, WMR (in the design stage) and a site waste management plan, SWMP (in the construction planning stage) (Jiménez-Rivero et al., 2017).

According to the EU Construction and Demolition Waste Management Protocol, this waste management model should include detailed information regarding:

a) Demolition/deconstruction procedures
b) Type of wastes to be generated
c) Preventive measures to reduce CDW
d) Transport procedures
e) Identification of final treatment for CDW that is generated (reuse, recovery or landfill disposal)
f) Measures for mandatory on-site segregation
g) Blueprints of CDW treatment facilities

Moreover, it should describe safety issues and procedures to restrict environmental impacts (e.g. risk of leakage and dust), as well as a distinction between the planned treatment of hazardous and non-hazardous waste. The application of these plans also complies with the requirements of assessment models such as BREEAM, which is an effective framework for the application of CE strategies in terms of waste prevention and minimization (Douglas, 2016).

4.3. Construction and building renovation

4.3.1 Site waste management plans

From a CE perspective, Esa et al. (2017) highlights the adoption of site waste management plans (SWMP) as the main strategy influencing the stage of construction and building renovation. In this stage, the amount of waste produced depends on the type of management. Thus, inefficient management practices imply larger volumes of CDW. Generally, the waste produced in this stage comes from reinforcement steel-bar cut-offs, imprecise concrete elements, damaged materials (e.g. bricks and tiles), and sand loss due to transport (Minunno et al., 2018).

The design and implementation of a SWMP is considered an effective strategy to improve CDW management operations, and it is applied in any construction and renovation activities, even in the end-of-life stage during demolition and deconstruction activities. Similarly to CDW management plans, the adoption of a SWMP provides opportunities for waste reduction and for increasing the rates of recovered materials. These models identify and estimate the waste types that will be produced and provide a detailed plan for waste management. This involves integration of best waste management procedures (e.g. segregation, storage, transportation type and treatment method) and management technologies to recover or dispose of the estimated waste. Moreover, it comprises detailed information regarding targets, responsibilities, instruments for monitoring, communication strategies and cost estimation for potential savings (Gálvez-Martos et al., 2018; Jiménez-Rivero and García-Navarro, 2017).

4.4. Collection and distribution

The collection and distribution stage distinguishes between two main aspects: (i) collection and segregation techniques and (ii) transport processes.

4.4.1 Collection and segregation techniques

In general, most of the CDW collected from construction and demolition sites is mixed or contaminated due to the lack of sorting at source (Huang et al., 2018). This situation reduces the potential and efficiency of reuse and recycling practices (Ghisellini et al., 2018a). In contrast, proper waste collection at source generates clean waste fractions, which increases their potential for use as secondary materials (Nussholz et al., 2019). A study by Huang et al. (2018) shows that scrap steel, bricks and elements such as doors and windows are usually collected onsite, but most of the CDW that is produced is dumped. In their study, Gálvez-Martos et al. (2018) identified a set as a common basis for standard collection practices. Regarding waste collection bins, proper identification by waste stream and adequate size, number and labelling are essential. Temporary collection points should be placed next to construction or demolition sites. Moreover, hazardous waste must be collected in a separate point with adequate protection measures (e.g. wind and rain protection). These collection points must be identified in the SWMP and be available to all relevant actors.

Segregation techniques are effective strategies to divert CDW from landfills, as they facilitate preparation for re-use, recycling and other recovery alternatives (Ghisellini et al., 2018a). These practices involve separate collection of end-of-life products after dismantling or during construction activities, according to the physicochemical characteristics of the waste (Jiménez-Rivero and García-Navarro, 2017; Zheng et al., 2017). Sorting can take place on the construction/demolition site (on-site sorting) or in external transfer stations (off-site sorting) when on-site sorting is not possible (Jiménez-Rivero and García-Navarro, 2017). The enhancement of segregation techniques leads to a significant increase in material recovery efficiency, better quality of waste (low impurity levels), lower rates of CDW disposed of in landfills and reduction of environmental impacts, as well as economic benefits for contractors. In particular, on-site sorting has been identified by Dahlbo et al. (2015), Ghisellini et al. (2018b) and Jiménez-Rivero and García-Navarro (2017) as a preferred option over off-site sorting if site conditions permit. This is a relevant factor for ensuring optimal production of recycled materials (Bovea and Powell, 2016).

4.4.2 Transport processes

Distribution comprises all the transport processes required to assure the proper flow of resources throughout the value chain of building materials, from a waste management and product supply perspective. Transport processes can be disaggregated into the following types:

a) Transport of CDW from a demolition/deconstruction site to storage deposits
b) Transport of CDW from a demolition/deconstruction site directly to treatment facilities (e.g. recycling plants, incineration plants)
c) Transport of treated waste to storage sites
d) Transport of treated waste directly to manufacturing industries
e) Transport of secondary materials (recycled/reused products) to construction sites
f) Transport of waste to backfill sites
g) Transport of residual waste (remaining CDW materials with no potential for recovery treatments) to final disposal sites.

Several studies analyzing waste management practices for CDW from a Lifecycle Analysis perspective (Bovea and Powell, 2016; Brambilla et al., 2019; Coelho and De Brito, 2012; T. Ding et al., 2016;

Jung et al., 2015; Martínez et al., 2013) found that transport processes are one of the most influential elements in environmental impacts and condition the application of recovery alternatives. Thus, transport distances represent the threshold between environmental benefits and loads (Brambilla et al., 2019).

The environmental assessment developed by Jung et al. (2015) highlights the influence of transport distances in on-site recycling and off-site recycling processes for concrete waste. Similarly, Ding et al. (2016) identified this influence in their analysis of recycled aggregates. Martínez et al. (2013) present the results of an assessment of demolition scenarios in the Spanish context to identify the most significant process in terms of environmental damage. They identified transport as the most influential factor in conventional and selective demolition. Similarly, Coelho and De Brito (2012) stated that transport is a conditioning factor in the environmental effects of building demolition practices. In their review, Bovea and Powell (2016) identified the best environmental practices for CDW management and emphasized that transport type and distances are factors that affect the environmental benefits of recycling compared to final disposal.

4.5. End-of-life

The end-of-life stage is characterized by high volumes of CDW, the highest in the entire lifecycle of construction activities. There are two general practices in this stage: conventional demolition and selective demolition or deconstruction. In this stage, the opportunities for material recovery depend on the type of demolition technique that is used and the type of building (Schultmann and Sunke, 2007). Some authors such as Akanbi et al. (2018), Chau et al. (2017) and Coelho and De Brito (2012) have assessed the environmental impacts of demolition/deconstruction techniques, in which deconstruction provides more environmental benefits than conventional demolition. This stage is focused on two main strategies for CE in the demolition sector: (i) selective deconstruction and (ii) predeconstruction/demolition audits.

4.5.1 Selective deconstruction

Conventional demolition is a common method for the end-of-life of buildings, even when it reduces the possibilities for salvaging valuable materials by hampering the differentiation of materials (Jiménez-Rivero and García-Navarro, 2016). In contrast, selective deconstruction consists of a reverse process of systematic building disassembling to maximize and facilitate recovery of building components and materials, enhancing opportunities for closing material loops (Chau et al., 2017; Jaillon and Poon, 2014; Schultmann and Sunke, 2007). Two phases are prevalent in this strategy: soft-stripping of recoverable materials and demolition of structural elements, which is preceded by separation of hazardous materials (Jiménez-Rivero and García-Navarro, 2016).

Selective deconstruction can be applied through various techniques depending on the availability of workers skilled in waste handling and of construction equipment (Schultmann and Sunke, 2007). However, the amount and quality of recovered materials are influenced by the technical organization of the deconstruction process and the availability of verified CDW forecasts (Höglmeier et al., 2017; Schultmann and Sunke, 2007).

The environmental benefits of deconstruction practices generally include energy savings in the production of new building materials by providing clean and recyclable waste fractions, a reduction in landfill burdens and less environmental pollution (Chau et al., 2017). However, the effect on the environment can also be negative (e.g. additional energy consumption due to the operating time of machinery) and varies according to the type of recovery process and material (Schultmann and Sunke, 2007). Moreover, selective demolition is not widely implemented as a common end-of-life practice (Nussholz et al., 2019). A study by Coelho and De Brito (2012) compares the environmental impacts of various scenarios based on the demolition technique and the recyclability of building materials in Portugal. Their results show a reduction of 76.9% in climate change impacts when full deconstruction and the subsequent reuse or recycling of materials is implemented instead of conventional demolition. Nevertheless, the work of Brambilla et al. (2019) evaluates the environmental benefits of demountable steel-concrete composite floor systems in buildings, in which the application of deconstruction resulted in a higher warming potential compared to conventional demolition. This is mainly due to the high operating time of the heavy equipment used in deconstruction activities. In particular, the activity of gutting is identified as the main factor in increasing duration.

From an economic perspective, there are potential savings when selective deconstruction is used instead of demolition. Deconstruction techniques can have lower costs than conventional demolition when we consider the total associated costs, mainly due to the influence of the outlet cost, which typically corresponds to landfill fees (Chau et al., 2017). However, high operational time, skills and labor hinder the application of this practice (Gálvez-Martos et al., 2018). Thus, adequate taxation of landfill fees plays an important role in the selection of demolition or deconstruction practices (Chau et al., 2017).

4.5.2 Predeconstruction/demolition audits

Although the application of predeconstruction/demolition audits is not mandatory, they represent an enforcement measure for minimizing waste from end-of-life activities. This practice allows the planning and implementation of more efficient waste management strategies and maximizes the volume, quality and potential saving costs of recovered materials, while it reduces waste generation (Jiménez-Rivero et al., 2016). Like SWMP and CDW management plans, predeconstruction/demolition audits should identify the volume, quality, recovery rates and location of the range of materials expected to be produced during demolition or deconstruction activities. In addition, it should provide detailed information regarding which materials must be segregated at source, which ones can be re-used or recycled, and which management procedures will be employed for non-hazardous and hazardous waste (European Commission, 2016; Jiménez-Rivero and García-Navarro, 2017).

4.6. Material recovery and production

Although landfilling is the least preferable management alternative in terms of environmental impacts, it is the most common management practice globally (Chau et al., 2017; Huang et al., 2018). The adoption of a circular economy framework based on reuse, recycling and other recovery practices in the construction and demolition sector has the greatest potential for environmental benefits and business opportunities (Brambilla et al., 2019; Smol et al., 2015). The recirculation of recovered resources in the lifecycle allows their use in the production of new building materials, while avoiding the use of virgin raw materials. This leads to environmental benefits such as energy savings and a reduction in the use of natural resources and pollution (Yeheyis et al., 2013). Nevertheless, the construction sector encounters more difficulties than other industries, due to multiple factors influencing the application of recovery strategies (Schultmann and Sunke, 2007). Strategies include the adoption of selective demolition, adoption of recovery practices in the early stage of design, individuality of buildings, location, characteristics of treatment facilities, etc. (Nussholz et al., 2019).

On that basis, this stage addresses four strategies identified as the most influential in terms of waste management of CDW and its future recirculation in construction projects: (i) reuse, (ii) recycling, (iii) backfilling and (iv) energy recovery.

4.6.1 Reuse

Reuse strategies consist of using harvested materials, construction elements and building materials again to meet their original or a different function (Huang et al., 2018). Thus, materials and components can be directly reused or can require little reprocessing through the application of three actions (Schultmann and Sunke, 2007):

a) *Repair* is focused on returning used products to working conditions and is limited to assembly and reassembly of fixed parts.
b) *Refurbishment* consists of improving the quality of used products by simple actions of disassembling, inspection and replacing of components.
c) *Re-manufacture* is aimed at providing quality for used products, according to specific standards which are as rigorous as those for new products.

Common construction products and building elements that are often reused in new building activities are bricks, tiles, concrete slabs, beams, wood frames and auxiliary materials such as wood from formworks, pallets and auxiliary structures (Gálvez-Martos et al., 2018). However, some products such as ceramic sanitary ware and electrical plugs can be reused but not reprocessed. Therefore, their useful life is limited to reuse actions (Sassi, 2008).

The implementation of reuse is considered one of the best waste management practices for the recirculation of materials in the CE model (Minunno et al., 2018; Nussholz et al., 2019). Generally, in terms of environmental and economic benefits, reuse is preferred over recycling because of its lower energy usage and the avoidance of environmental impacts implied in the manufacture of new building materials (Akanbi et al., 2018; Gorgolewski M., 2008; Sassi, 2008). The exploration of best CDW management practices in the European context developed by Gálvez-Martos et al. (2018) identifies that reuse of building components can imply savings of around 40% of embodied energy and 60% of the carbon footprint in concrete structures, based on prefabricated elements. However, Huang et al. (2018) argue that secondary building materials from reused CDW are not widely accepted in the market. This is mainly because of the lack of material standards, which leads consumers to doubt the quality of reused materials. Moreover, adequate supply is not always guaranteed.

4.6.2 Recycling

Besides reuse, the application of recycling methods is a fundamental strategy in CE, as the use of recycled content in the manufacturing of construction materials has environmental benefits over the use of raw materials. In addition, it constitutes a key way to reduce CDW disposed of in landfills and the demand for natural resources. Furthermore, it reduces the energy consumption of manufacturing processes for the building industry (Bovea and Powell, 2016; Chau et al., 2017; T. Ding et al., 2016) and other industries (Huang et al., 2018).

In comparison to landfill as a CDW management option, recycling has significant economic benefits in terms of the total externalities related to this practice. It reduces costs through mitigating environmental and human health damage, and by avoiding the cost of constructing new landfills (Marzouk and Azab, 2014). However, despite the application of a waste hierarchy in which recycling is preferred over landfill disposal, recycling is not always suitable for all CDW typologies (Bovea and Powell, 2016; Minunno et al., 2018). A study by Ng and Chau (2015) analyzes management alternatives for CDW from a commercial building in Hong Kong. Their results show that there are potential energy savings of 53% in the construction value chain through the application of recycling methods, but savings vary according to the material type. For concrete-based elements, the best alternative is recycling, while for metal-based elements reuse seems to be the best option. Nevertheless, according to Christmann (2018), the implementation of recycling processes in the manufacturing stage of metal products can achieve energy savings of 95% for aluminum, 85% for copper, 62–74% for steel and over 50% for non-ferrous metals. From an economic perspective, the production costs of recycled aggregates could be higher than natural aggregates, due to the additional processing methods required, which represent around 64% of production costs. However, this condition varies depending on the scale of the industry and can result in lower costs for recycled products (Wijayasundara et al., 2016).

Recycling of CDW can be achieved through two techniques: on-site recycling and recycling in treatment plants. Bovea and Powell (2016) identified on-site recycling as the most efficient option considering environmental aspects when other CE strategies such as on-site sorting are applied. In addition, improvements in the efficiency of recycling processes are necessary and can be achieved by implementing new, enhanced technologies that reduce environmental impacts and energy consumption (Huang et al., 2018).

In a general framework, recycling treatments can be applied through three typologies:

a) Closed-loop recycling, in which the salvaged material can substitute the original virgin material in a 1:1 ratio.
b) Semi closed-loop recycling, in which the salvaged material can partially substitute the original virgin material, but raw materials must be added to comply with quality requirements.
c) Open-loop recycling, in which the salvaged material is used as a partial substitute in the manufacturing of different materials (Huysman et al., 2017).

On this basis, steel can be cyclically recycled without losing its mechanical properties (closed-loop recycling), which produces less carbon emissions than manufacturing from raw materials. In contrast, concrete waste can be crushed and transformed into aggregates for producing new concrete elements, but at restricted rates according to the technical specifications of concrete mixtures (Minunno et al., 2018).

According to Akanbi et al. (2018), the level of reusability and recyclability of recoverable building materials is influenced by factors such as the environment, design and construction, as well as operational and management factors. Hence, specification of reusable and recyclable building materials during design and construction stages is one of the most influential factors. Other factors include the use of prefabricated elements, use of nuts and bolts instead of nails and gluing in assemblies, minimization of types of building components and layering of building elements according to anticipated lifespan. In addition, the avoidance of secondary finishes is a major factor, as the use of finishes on building materials reduces their possibility of recovery. Finally, the avoidance of toxic and hazardous materials is fundamental for ensuring the possibility of recycling materials from buildings at the end-of-life stage.

However, the use of recovered materials in the construction industry is restricted by several factors such as economic, legislative and managerial barriers (Ghisellini et al., 2018b). In this context, one of the obstacles for marketing secondary materials in the building industry is the lack of quality standards for recovered materials. Thus, consumers may not trust secondary materials, since their quality cannot be guaranteed due to a lack of technical information about the products (Huang et al., 2018; Nussholz et al., 2019). Other major barriers for secondary materials include: unstable, insufficient supply of recovered materials (Huang et al., 2018); lack of market demand for secondary materials (Lockrey et al., 2016; Nussholz et al., 2019); low cost and low taxation of virgin raw materials (Dahlbo et al., 2015; Ghisellini et al., 2018b); higher prices of secondary building products than original materials (Ghisellini et al., 2018b; Huang et al., 2018); lack of awareness and culture about the environmental costs of waste management (Lockrey et al., 2016); and lack of regulations and codes for CDW waste management (Lockrey et al., 2016; Nussholz et al., 2019). Moreover, there are management barriers such as a lack of contractor awareness, a lack of incentives for treating and recycling CDW from regulatory authorities (Huang et al., 2018), low landfilling fees, a lack of economically viable treatment facilities and a lack of budget for waste management in construction projects (Lockrey et al., 2016).

4.6.3 Energy recovery

In addition to reuse and recycling strategies, the possibility of applying other recovery alternatives such as energy recovery should be analyzed. This strategy can be applied to materials with high caloric potential (e.g. wood and plastics) by incineration to produce energy that could be reintroduced into the system and used in power plants and heat delivery centers (Chau et al., 2017; Huysman et al., 2017; Schultmann and Sunke, 2007). Thus, when reuse and recycling strategies are limited or have greater effects on the environment, energy recovery can be implemented before final disposal (Schultmann and Sunke, 2007).

4.6.4 Backfilling

Lastly, CDW can be used as a substitute for natural resources for backfilling embankments (Coudray et al., 2017). This is a common practice for materials such as recycled aggregates produced in large demolition works, where demolition waste is crushed and used to fill open sky cavities. From a technical perspective, high dimensioned coarse aggregates are acceptable for backfilling. Currently, the highest substitution rates of recycled aggregates are achieved in low grade applications such as backfilling and bases and sub-bases for roads (Coudray et al., 2017; Gálvez-Martos et al., 2018).

5. Conceptualization of an integrative CE framework in the CDW sector

In this section, a theoretical framework approach is proposed for the adoption of the Circular Economy concept in the CDW sector. This theoretical framework is based on the results of the literature review presented in previous sections. To ensure that it is implemented in a practical way in the entire value chain of building materials, the approach maximizes the value of building materials through 14 strategies identified and outlined in five lifecycle stages for construction and demolition activities. These stages are (i) preconstruction, (ii) construction and renovation, (iii) collection and distribution, (iv) end-of-life and (v) material recovery and production. The framework approach operates through 14 strategies identified from the top-down, in which the CE basis of narrowing, slowing and closing loops (from the framework for the implementation of CE models, Section 2.1) are included at different stages, depending on their relevance. Then, their application and interactions in the stages of the construction and demolition cycle are identified. This top-down approach follows a hierarchy in which previous strategies for the beginning of construction and demolition activities have a major influence on waste reduction, and facilitate CDW recovery practices. Hence, the proposed framework in this research is focused on the adoption of CE as an approach to reduce waste generation and maximize recovery of CDW and its use as secondary materials in the construction industry. Figure 2 illustrates the proposed theoretical framework for CE in the construction and demolition sector.

The point of departure is prior to the start of construction and renovation activities. Hence, the development of adequate legislative and regulatory instruments is crucial to provide a solid base for the enhancement of CDW management strategies and to encourage the production of secondary materials.

Thus, in the **preconstruction stage (1)**, government policies and strategic frameworks set the legal basis and obligations for construction and demolition companies for further construction projects, according to CE principles. In this context, economic instruments serve as an effective strategy for reducing landfilling and for enhancing the market of secondary materials obtained from CDW. Through their application, designers and contractors are guided to prioritize waste recovery practices and to use secondary materials in construction projects. Economic instruments can be applied at this stage through three measures: a CDW disposal charge to reduce the waste disposed of in landfills; taxation on primary raw materials to incentivize the demand for secondary building materials; and incentives for CDW management companies to reduce the high cost of recycling and recovery treatments. The application of CDW disposal charges has a direct influence on the adoption of practices such as on-site sorting in the *collection and distribution stage (3)* and the selection of deconstruction practices at the *end-of-life stage (4)*.

Moreover, similar to economic instruments, the development of effective design strategies leads to waste minimization, increased rates of recovered materials and increased use of recovered materials in other construction projects, since important decisions affecting *construction and building renovation (2)* and *end-of-life (5)* stages are made at this level. In this area, there are three main strategies: design for waste prevention, design for disassembly or deconstruction and use of prefabricated elements. Design for waste prevention contributes to incorporating appropriate materials and components in construction projects. It constitutes a useful tool for demolition and salvage companies, as it provides detailed data on the waste that will be produced. Design for disassembly or deconstruction and the use of prefabricated elements are associated strategies. Their adoption leads to the application of selective deconstruction in the *end-of-life stage (4)* and facilitates the collection and segregation of CDW at the *collection and distribution stage (3)*, resulting in cleaner fractions of CDW and facilitating its recovery and further recirculation as secondary materials. For better results, design should be accompanied by the design of CDW management plans. For European practitioners, the development of such a plan is mandatory in each construction project. For this purpose, the EU Construction and Demolition Waste Management Protocol provides detailed information and guidance on the development of waste management plans. In addition, integral CDW management plans include the development of an on-site waste management plan (SWMP), which is applied at the **construction and building renovation stage (2)** and during demolition and deconstruction activities. Thus, the end routes for the CDW that is produced are identified in these plans.

At the **collection and distribution stage (3)**, collection and segregation practices are applied to the waste produced during activities from both *construction and renovation (2)* and *end-of-life (3)* stages. The adoption of these strategies enhances the application of re-use, recycling and other recovery alternatives for CDW at the *material recovery and production stage (5)*. It is important to prioritize on-site sorting over external sorting when site conditions allow it, because of its greater environmental benefits.

The distribution of resources in the value chain of building materials is involved in all the lifecycle stages of the framework, except the preconstruction stage. Thus, transport processes are implied in the supply of material inputs for construction and renovation activities and in the flows of CDW from construction and end-of-life activities to treatment facilities. They are also involved in the transportation of treated waste to manufacturing industries and in the recirculation of secondary materials. Special attention must be paid to transport in its various modalities, since transport distances condition the application of recovery strategies in terms of environmental impact.

At the **end-of-life stage (4)**, selective deconstruction might be preferred over conventional demolition, even though conventional demolition is the most widespread technique for the end-of-life of buildings. As described before, the application of selective deconstruction accompanied by proper collection and segregation techniques maximize efficiency in the recovery of building materials and components. Despite the environmental and economic benefits of selective deconstruction, its application must be analyzed based on the material type and operational factors. In addition to this strategy, the adoption of predemolition audits is an effective tool for enhancing CDW management practices, providing opportunities for material recovery. These audits are not mandatory, and their requirements are similar to those of SWMP and CDW management plans.

Finally, at the **material recovery and production stage (5)**, four alternatives can be applied: reuse, recycling, energy recovery and backfilling. Even though reuse seems to be a preferred option over other strategies in terms of economics and environmental benefits, its application depends mainly on the type of waste. Moreover, an evaluation of the economic and environmental aspects of each of the four strategies is required to determine the most suitable alternative according to the specific operational and technical conditions of the zone in which the framework is applied. This is a very important stage in terms of CE, as it allows loops to be closed and narrowed.

Some material can be directly reused without additional treatment processes or by applying reprocessing methods such as repairing, refurbishing and remanufacturing practices. Recycling alternatives can be implemented considering three main types (closed-loop recycling, semi closed-loop recycling and open-loop recycling) depending on the material and the quality standards required to produce new materials. When recycling and reuse is not possible, energy recovery (depending on the caloric potential and hazardousness of waste) and backfilling (commonly for recycled aggregates) can be applied. Lastly, as the least preferable alternative, CDW with no viable recovery options and residual waste from recovery processes is disposed of in landfills.

As a result, from the integral implementation of the CE strategies for the CDW sector, four potential outputs are identified: (i) recovered materials that 100% substitute original raw materials; (ii) recovered materials with partial recycled content to substitute components of the same material; (iii) recovered materials with partial recycled content to substitute components of a different material; and (iv) energy. These outputs are cyclically reintroduced into the flow of materials and energy of the value chain of building materials.

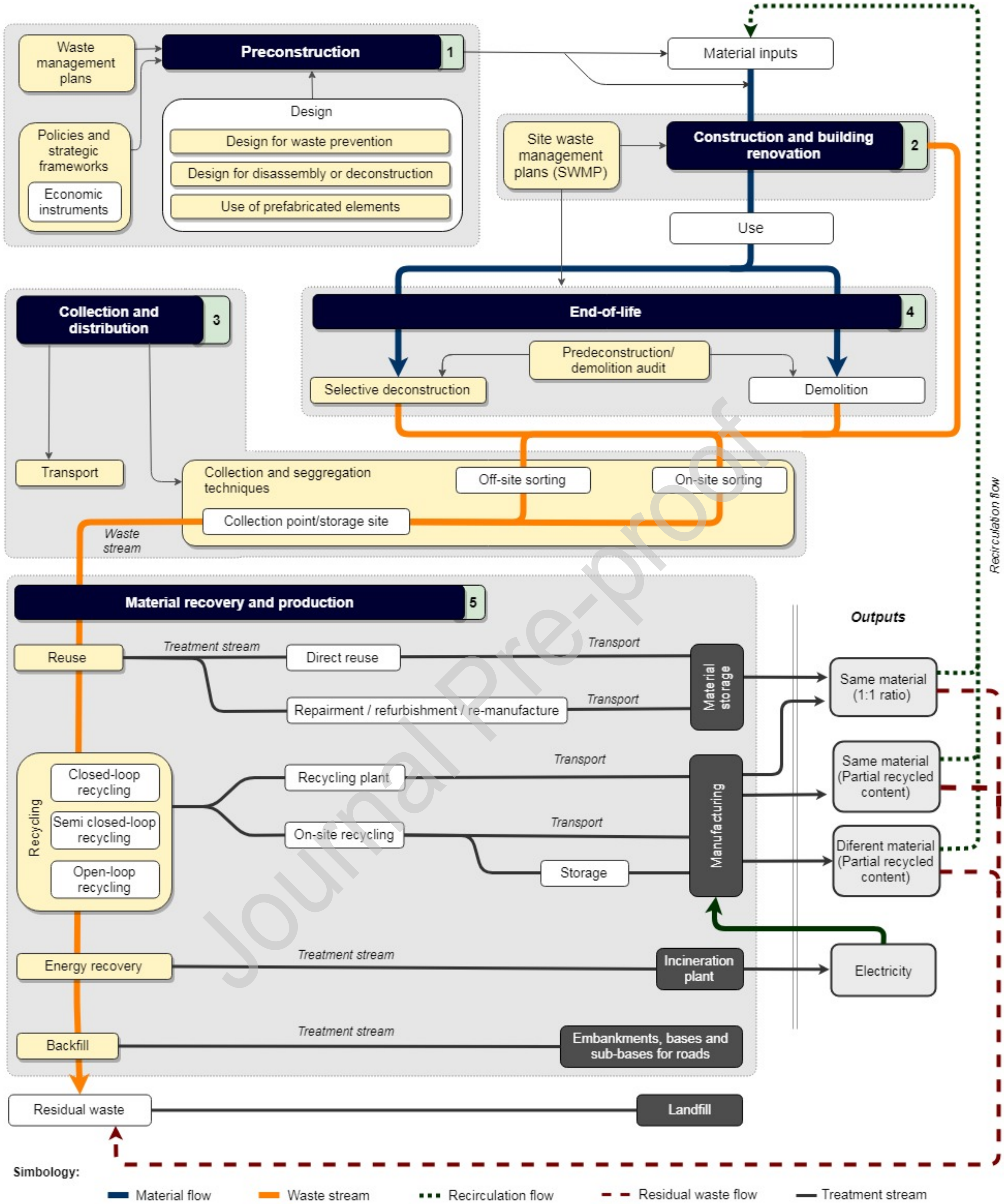

Figure 2. Theoretical model approach for CE implementation in the CDW sector

6. Conclusions

This study proposes a theoretical framework approach to the adoption of the CE concept in the CDW sector. The systematic review that was conducted concluded that CE is a relevant, innovative concept that is gaining attention in the current scientific landscape. However, this concept has not been addressed widely in the CDW sector. Research in this sector has mainly focused on aspects regarding reuse and recycling from an environmental performance perspective. Few studies analyze a larger range of CE principles for the construction and demolition sector, and integral approaches have not been described that consider the application of preventive and operational measures before, during and after construction and demolition activities. Moreover, the integration of economic criteria is still limited. Hence, an integral framework is required to guide and support CE implementation in the CDW sector sustainably.

The proposed theoretical framework outlines the main aspects involved in CE from the perspective of waste minimization and waste management efficiency in construction and demolition activities. This framework takes into account influential CE strategies and their interaction through the five main lifecycle stages of the sector: preconstruction, construction and renovation, end-of-life, collection and distribution, and material recovery and production. The main findings include the following. In the preconstruction stage, economic instruments play a key role in enhancing the market of secondary materials in the construction industry, since recovery strategies are enhanced and prioritized over landfilling. In addition, design strategies provide a waste minimization approach and facilitate the salvaging of materials at the end-of-life of buildings. Selective deconstruction in the end-of-life stage has environmental and economic benefits. However, its application and benefits depend on specific aspects such as technical, operational and managerial factors. Moreover, this method is not widely used, since most existing buildings have not been designed for disassembly. In the stage of material recovery and production, the application of recovery strategies depends on the type of material, since the environmental and economic benefits vary among CDW typologies. Moreover, the benefits of recovery strategies over landfilling are conditioned by the transport type and distances. Material recovery is a crucial stage in terms of CE, since reuse, recycling and other recovery treatments contribute to closing and narrowing loops in the sector. However, the potential of the secondary materials market is currently restricted by consumers' reservations about using recovered materials, because of the lack of standards that guarantee quality. The market is also limited by the low demand and higher prices of secondary materials over primary raw materials. In general, strategies in phases prior to construction and demolition works have a major influence on CE operation, as they provide a waste minimization approach and enhance the recovery and use of CDW as secondary materials in the sector.

This framework could be used as guidance for academics to expand the knowledge on the potential applications of the CE concept. It could also be used by practitioners in the implementation of CE practices in the construction and demolition sector. Further analysis of complementary aspects of CE models are necessary to provide a more comprehensive dimension of the theoretical framework (e.g. analysis of stakeholders; economic, technical and social barriers; and bussines model applications). Moreover, further assessment of the proposed framework is required to provide solid estimations of the potential results from the transition to a CE in the CDW sector, and to test its viability. This must be achieved from an environmental and economic perspective in which environmental benefits are in balance with economic growth. Solid results can enhance the transition to a CE by encouraging business and public actors to adopt more efficient practices in the sector.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights

- A systematic literature review on CE within the CDW sector is provided
- Key strategies for CE on CDW are identified and classified in five lifecycle stages
- An integrative framework approach for CE adoption in the CDW sector is provided
- Preconstruction/demolition strategies have the highest influence on CE operation