Barcelona, September 2021

UNIVERSITAT POLITÈCNICA
DE CATALUNYA
BARCELONATECH

PhD Thesis

Implementation and evaluation of the Circular Economy model in the construction and demolition waste sector

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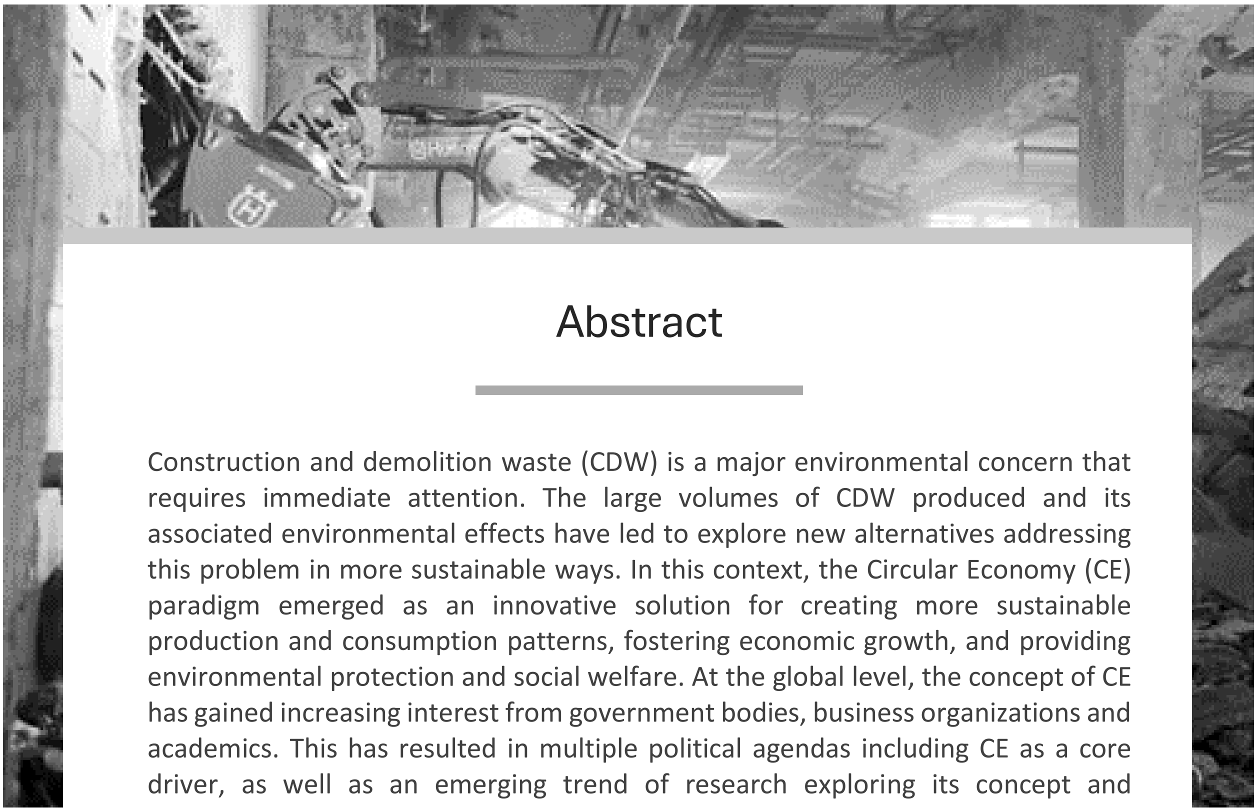
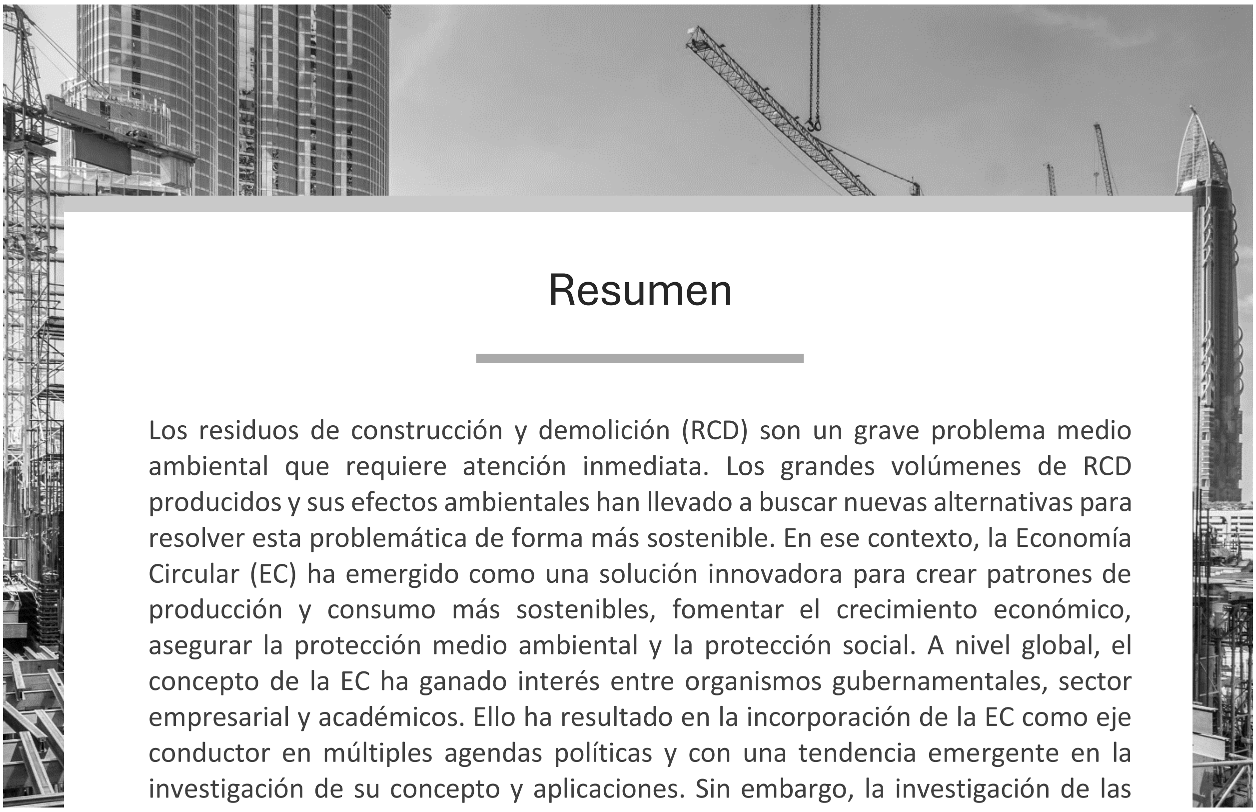
Acknowledgements

I would like to thank to my thesis supervisors, Xavier Roca and Santiago Gasso for their continuous support, guidance, and motivation. I also want to thank to the Government of Mexico’s National Council of Science and Technology (CONACYT) for the funding provided to study this PhD. Thanks to my family that even from the distance gave me unconditional motivation and support in all my decisions, they are my inspiration to keep working in my goals. Thanks to all the amazing people I had the privilege to share with and learn during this journey, and those who motivated me and become family in my second home Barcelona.



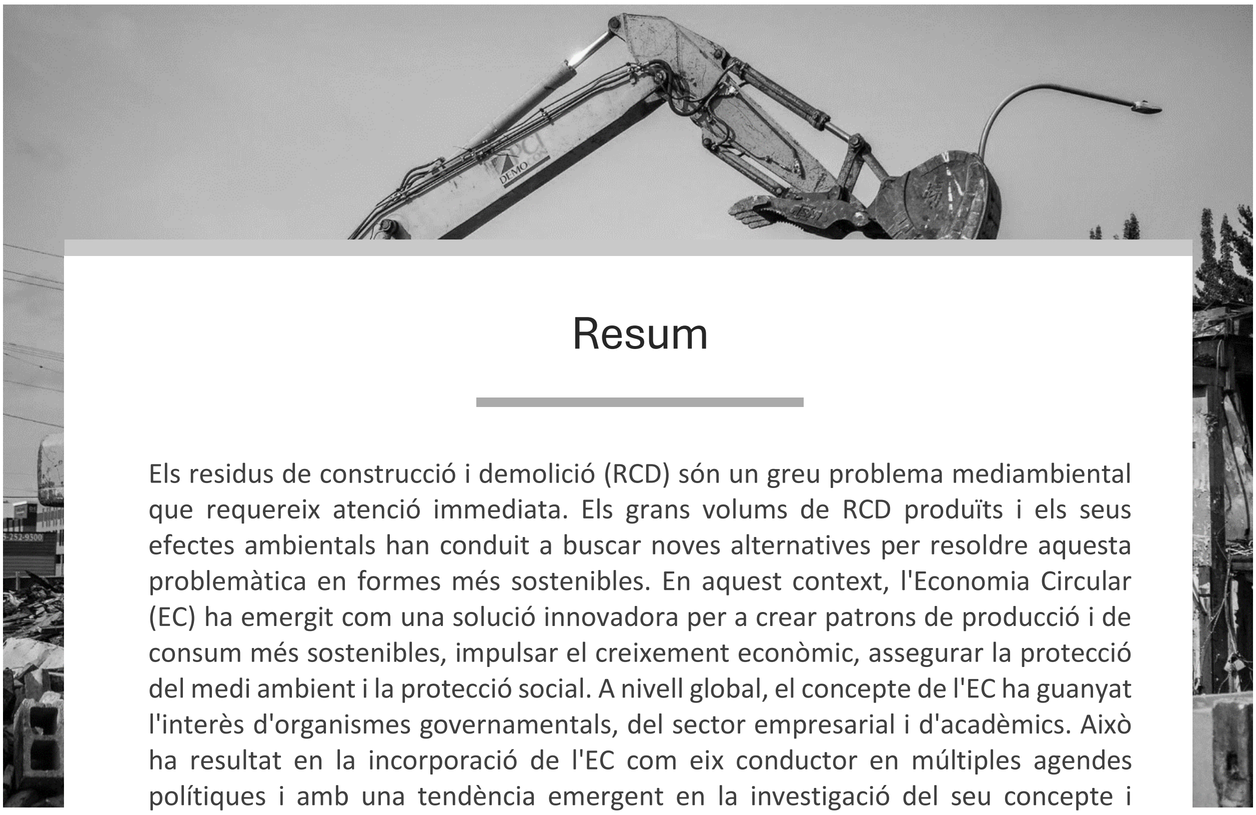
Abstract

Construction and demolition waste (CDW) is a major environmental concern that requires immediate attention. The large volumes of CDW produced and its associated environmental effects have led to explore new alternatives addressing this problem in more sustainable ways. In this context, the Circular Economy (CE) paradigm emerged as an innovative solution for creating more sustainable production and consumption patterns, fostering economic growth, and providing environmental protection and social welfare. At the global level, the concept of CE has gained increasing interest from government bodies, business organizations and academics. This has resulted in multiple political agendas including CE as a core driver, as well as an emerging trend of research exploring its concept and applications. However, because of the novelty and dynamism of the concept, research developments on practical applications and quantitative assessments are at an early stage. The main aim of this study was to propose an approach to integrate the CE concept in the construction and demolition sector, as well as providing the basis for evaluating the environmental and economic effects of circularity strategies and to monitor their implementation. For this purpose, an integrative framework of strategies for CE adoption in the CDW sector is proposed. This together with a methodological proposal to evaluate and compare the environmental and economic performance of different circularity alternatives incorporating multi-criteria decision analysis. In addition, this work proposes a system of indicators for measuring CE features for CDW products. The proposed framework identifies 14 influential strategies for the circularity of the CDW sector and describes their interaction throughout its lifecycle stages. The methodological proposal incorporates the Life Cycle Analysis (LCA) methodology to assess the environmental dimension., while the economic criteria adopt a complex cost method. The multicriteria VIKOR method was used to perform the multi-criteria analysis. The methodology is applied to evaluate the use of concrete waste in high-grade applications, specifically the production of structural and non-structural concrete mixes in the region of Catalonia, Spain. The indicators framework incorporates a systematic approach considering the most relevant factors and parameters for successful measurement of CE interventions. It consists of 22 measures within the three dimensions of environment, economic and innovation/materials. Preconstruction strategies are highlighted as the most influential in the circularity of the sector. CE strategies presented better environmental and economic performance; however, results are conditioned by the particular context of the study. Transportation and landfilling are identified as the most conditioning parameters affecting both environmental and economic performance.



Resumen

Los residuos de construcción y demolición (RCD) son un grave problema medio ambiental que requiere atención inmediata. Los grandes volúmenes de RCD producidos y sus efectos ambientales han llevado a buscar nuevas alternativas para resolver esta problemática de forma más sostenible. En ese contexto, la Economía Circular (EC) ha emergido como una solución innovadora para crear patrones de producción y consumo más sostenibles, fomentar el crecimiento económico, asegurar la protección medio ambiental y la protección social. A nivel global, el concepto de la EC ha ganado interés entre organismos gubernamentales, sector empresarial y académicos. Ello ha resultado en la incorporación de la EC como eje conductor en múltiples agendas políticas y con una tendencia emergente en la investigación de su concepto y aplicaciones. Sin embargo, la investigación de las potenciales aplicaciones y su evaluación se encuentran en una fase temprana de desarrollo debido a la novedad y dinamismo del concepto. El objeto principal de este estudio fue el de desarrollar una propuesta de integración del concepto de EC en el sector de la construcción y la demolición, así como proveer las bases para evaluar los efectos económicos y ambientales de estrategias de circularidad y monitorear su implementación. Para ello, se propone un marco integrativo de estrategias para la adopción de la EC en el sector de los RCD, además de una propuesta metodológica para evaluar y comparar el desempeño económico y ambiental de diferentes alternativas de circularidad incorporando análisis de decisión multi-criterio. Asimismo, este trabajo propone un sistema de indicadores para medir características de circularidad de los RCD. El sistema propuesto identifica 14 estrategias de influencia para la circularidad del sector de los RCD, describiendo su interacción a lo largo de sus etapas de ciclo de vida. La propuesta metodológica de evaluación incorpora la metodología de Análisis de Ciclo de Vida (ACV) para el criterio ambiental, y el análisis de costes complejos para el criterio económico. Mientras que para el desarrollo del análisis multi-criterio fue utilizado el método VIKOR. La metodología es aplicada en la evaluación del uso de residuos de concreto en aplicaciones de alto grado, específicamente en la producción de hormigón estructural y no estructural en la región de Cataluña, España. El marco de indicadores incorpora un enfoque sistémico que considera los factores y parámetros más relevantes para la adecuada medición de estrategias de EC. Este consiste en 22 medidas contenidas en tres grupos o dimensiones: ambiental, económica y de innovación/materiales. Las estrategias durante la etapa pre-constructiva son identificadas como las más influyentes en la circularidad del sector. Resultados de la evaluación muestran un mejor desempeño económico y ambiental de las alternativas de EC, sin embargo, éstos son condicionados por el contexto específico de la zona de estudio. En particular, el transporte y el vertido son identificados como los parámetros más condicionantes tanto para el aspecto ambiental, como el económico.



Resum

Els residus de construcció i demolició (RCD) són un greu problema mediambiental que requereix atenció immediata. Els grans volums de RCD produïts i els seus efectes ambientals han conduit a buscar noves alternatives per resoldre aquesta problemàtica en formes més sostenibles. En aquest context, l'Economia Circular (EC) ha emergit com una solució innovadora per a crear patrons de producció i de consum més sostenibles, impulsar el creixement econòmic, assegurar la protecció del medi ambient i la protecció social. A nivell global, el concepte de l'EC ha guanyat l'interès d'organismes governamentals, del sector empresarial i d'acadèmics. Això ha resultat en la incorporació de l'EC com eix conductor en múltiples agendes polítiques i amb una tendència emergent en la investigació del seu concepte i aplicacions. No obstant això, la investigació de les potencials aplicacions i la seva avaluació es troben en fase primerenca de desenvolupament degut a la novetat i dinamisme del concepte. L'objectiu principal d'aquest estudi va ser el desenvolupar una proposta d'integració de l'EC en el sector de la construcció i la demolició, així com proporcionar les bases per avaluar els efectes econòmics i ambientals d'estratègies de circularitat i monitoritzar la seva implementació. Per això, es proposa un marc integratiu d'estratègies per a l'adopció de l'EC en el sector dels RCD. A més, d'una proposta metodològica per avaluar i comparar el rendiment econòmic i ambiental de diferents alternatives de circularitat incorporant un anàlisi de decisió multi-criteri. Seguidament, aquest treball proposa un sistema d'indicadors per mesurar característiques de circularitat dels RCD. Aquest sistema identifica 14 estratègies d'influència per la circularitat del sector dels RCD, descrivint la seva interacció al llarg de les etapes de cicle de vida. La proposta metodològica d'avaluació incorpora la metodologia d'Anàlisis de Cicle de Vida (ACV) per al criteri ambiental, i l'anàlisi de costos complexos per al criteri econòmic. Mentre que per al desenvolupament de l'anàlisi multi-criteri s'ha utilitzat el mètode VIKOR. La metodologia s'aplica en l'avaluació del ús de residus de formigó en aplicacions d'alt grau, específicament en la producció de formigó estructural i no estructural en la regió de Catalunya, Espanya. El marc d'indicadors incorpora un enfocament sistèmic que considera els factors i paràmetres mes rellevants per a l'adequada mesura d'estratègies d'EC. Aquest consisteix en 22 mesures agrupades en 3 grups o dimensions: ambiental, econòmica i d'innovació/materials. S'identifica que les estratègies de l'etapa pre-constructiva són les més influents en la circularitat del sector. Els resultats de l'avaluació demostren que les alternatives d'EC presenten millor rendiment econòmic i ambiental, però, aquests són influenciats per les condicions particulars de la zona d'estudi. Particularment, el transport i abocament són identificats com els paràmetres més condicionants tan per el criteri ambiental, com per l'econòmic.

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Chapter 1 Introduction

1.1 Motivation

The construction sector is one of the most important for the world economy and social welfare, but also inherently highly impactful for the environment. The increasing population growth has led to massive construction activities to meet housing and infrastructure demands, exerting great pressure on the environment and human health (Bao and Lu, 2020; Braga et al., 2017). Environmental impacts include large consumption of natural resources and non-renewable energy, greenhouse gas emissions and generation of considerable amounts of waste (Ghisellini et al., 2018a; Suárez Silgado et al., 2018; Tangtinthai et al., 2019). In quantitative terms, construction and civil works are responsible for about 50% of global raw material consumption (especially for the concrete and metal industries) and 15% to 20% of total anthropogenic gas emissions (Gallego-Schmid et al., 2020; Joensuu et al., 2020). Moreover, around 30% to 40% of the total waste generated originates from construction and demolition activities (Jin et al., 2018; Kabirifar et al., 2020; Rosado et al., 2017).

Particularly, construction and demolition waste (CDW) is a major challenge for the construction industry, becoming one of the biggest environmental concerns for multiple governments around the world. Hence, there has been an increasing interest in implementing more efficient waste management and recovery practices, however, in most cases these processes are inefficient, resulting in large volumes of waste disposed of in landfills or even illegally dumped without environmental protection measures (Esa et al., 2017a; Suárez Silgado et al., 2016). Furthermore, these practices usually lack a holistic approach including additional aspects such as waste reduction measures and new, enhanced strategies to reconfigure the value chain of building materials for keeping their value and avoid material losses.

To address this issue, the Circular Economy (CE) concept has emerged as a solution to sustainability problems and limitations of the current linear approach. Furthermore, CE is a tool for reducing the input of raw materials and energy into the system, optimizing the use of materials, and minimizing waste production in the system (Bocken et al., 2016; Brown et al., 2019; EMF, 2015). Policy makers, practitioners, private business communities and academics recognize this new circular model as an innovative solution towards sustainability in the construction sector. Recently, various countries have adopted political programs on CE, including the construction industry as a priority: United Kingdom (Infrastructure and Projects Authority, 2016; WRAP, 2013, 2011), the Netherlands (Government of the Netherlands, 2016), and Spain (MAPAMA, 2018). In the European Union, the building industry (including CDW) is a key sector for attention in both first and new CE Action Plans (European Commission, 2020a, 2015a).

In scientific discussion, several authors highlighted the building industry as one of the sectors with the greatest potential for CE implementation (Akanbi et al., 2019; Brambilla et al., 2019; Nußholz et al., 2020). Some efforts have been made to develop frameworks for CDW minimization (Esa et al., 2017b), the adoption of CE principles in the CDW sector (e.g. Ghisellini et al. (2018b) on the 3 R principle, reduce, recycle, reuse), and the integration of CE in the built environment (Joensuu et al., 2020; Munaro et al., 2020; Pomponi and Moncaster, 2017). In addition, recent studies have analyzed the implementation of best management practices for CDW (Gálvez-Martos et al., 2018; Gangolells et al., 2014; Huang et al., 2018), the identification of best recovery strategies for CDW (Jiménez-Rivero and García-Navarro, 2017; Lockrey et al., 2016) and the use of CDW for the manufacturing of new building products (Ginga et al., 2020; Orsini and Marrone, 2019; Sormunen and Kärki, 2019). Moreover, the analysis of potential barriers to CE implementation in the building sector (Bilal et al., 2020; Mahpour, 2018) and current research trends (Hossain et al., 2020) has been addressed. In addition, some studies have analyzed strategies for adaptative reuse of buildings (Foster, 2020) and developed new business models for the reuse of building materials (e.g. Nußholz et al. (2020) on reuse of windows, wood cladding, and concrete materials in Scandinavia). Other studies have focused on identifying critical success factors for effective CDW management practices (e.g. Akinade et al. (2017) on material recovery through Design for Deconstruction, Wang et al. (2010) on on-site sorting of CDW) and for the reuse of components from building structures (Rakhshan et al., 2020). Despite research efforts contributing to the implementation of the circularity approach in the construction industry is considerably increasing, it is a complex, dynamic field of study that involves multiple areas of analysis. Consequently, the scientific literature is still in its infancy stage, showing a lack of integrative approaches considering the interaction of CE strategies throughout the different lifecycle phases of construction and demolition activities.

In addition to the need for developing knowledge bodies and understanding of key circularity factors, the use of assessment and monitoring tools is essential for supporting the transition towards a CE by providing quantification and measurement on the effects of implementing CE strategies (Bilal et al., 2020; Moraga et al., 2019; Rincón-Moreno et al., 2021; Saidani et al., 2017). In this regard, evaluation of the environmental and economic performance of circularity alternatives allows determining if their adoption is viable and sustainable, providing a solid basis for better decision-making processes during their planning and application (Eberhardt et al., 2019; Zuo et al., 2016). According to the work of Ghisellini et al. (2018b) and Hossain et al. (2020) there is a limited share of research assessing these two dimensions within the CDW sector, instead, most of the evaluations are focused on the single environmental dimension. Moreover, most of the environmental studies barely adopt a circularity perspective or do not include all the relevant impact categories for CE evaluation. Furthermore, for the economic dimension the existing related research is scarce (Zuo et al., 2016) and mainly focused on the financial and economic feasibility of CDW treatment plants, rather than analyzing the performance of alternatives or addressing circularity factors (Ghisellini et al., 2018b; Hossain et al., 2020).

Similarly, the advancement of research on CE measurement and monitoring tools is still in progress and currently there are no globally accepted or standardized indicators especially developed within the CE concept (Kristensen and Mosgaard, 2020; Saidani et al., 2019). Indicators and monitoring systems are essential to measure the change effect connected to an intervention. Thus, the lack of these tools might constrain the adoption of circularity initiatives (Mahpour, 2018; Moraga et al., 2019; Nuñez-Cacho et al., 2018). In the business community, there are some recognized measuring tools such as the Material Circularity Indicator (MCI), Circulytics, the Circular Transition Indicators (CTI) framework, the Cradle to Cradle Certified and the CE monitoring framework developed by the European Commission. In particular, for the CDW sector, some research on indicators has been conducted (Akinade et al., 2015; Bilal et al., 2020; Foster and Kreinin, 2020; Fregonara et al., 2017; Heisel and Rau-Oberhuber, 2020; Jiménez-Rivero and García-Navarro, 2016; Vefago and Avellaneda, 2013; Yeheyis et al., 2013), however, they are mainly focused on one or more circularity criteria for buildings, rather than providing a holistic integration of CE parameters.

The present research work intends to address these gaps by analyzing and determining CE approaches that can be adopted in the CDW sector. The main purpose is to provide the basis for the uptake of the concept from a perspective of waste prevention, waste management and production of secondary materials. Moreover, it intends to provide guidelines for the assessment and monitoring of circularity strategies for CDW products.

1.2 Research objective

The main purpose of this research is to investigate how the circular economy concept can be implemented in the construction and demolition sector. Further, it aims to provide directions for the assessment and monitoring of circularity strategies for better decision-making processes, considering the environmental and economic dimensions. The exploration of CE has a special focus on strategies for waste prevention, CDW management and material recirculation in the construction industry.

In deeper detail, this thesis aims to:

- To analyze and identify the most influential aspects for circularity in the CDW sector, and the assessment and monitoring of CE strategies.
- To develop a framework of key strategies for the adoption of the CE concept in the CDW sector within its lifecycle.
- To propose a methodology to support the analysis and decision-making in the selection and implementation of circularity alternatives based on their environmental and economic performance.
- To apply the proposed methodology to a CDW typology for identifying the best CE alternatives and to estimate the potential environmental and economic benefits.
- To develop a framework of indicators to measure and monitor the progress on the implementation of CE in the CDW sector, as well as to measure the circularity performance of individual circularity interventions.

1.3 Thesis outline

To achieve the proposed objectives, this thesis is structured in six sections. A scheme of the research work is presented in **Figure 1**. **Chapter 2** provides a literature review on theories, conceptual foundations, and core aspects of the CE concept and its adoption in construction and demolition activities, with a particular focus on CDW. The need and application of assessment methods and CE indicators are also introduced. Next, the core of this thesis document consists of chapters 3 to 5, which correspond to three different scientific studies. In the following, the summary content of each chapter is presented.

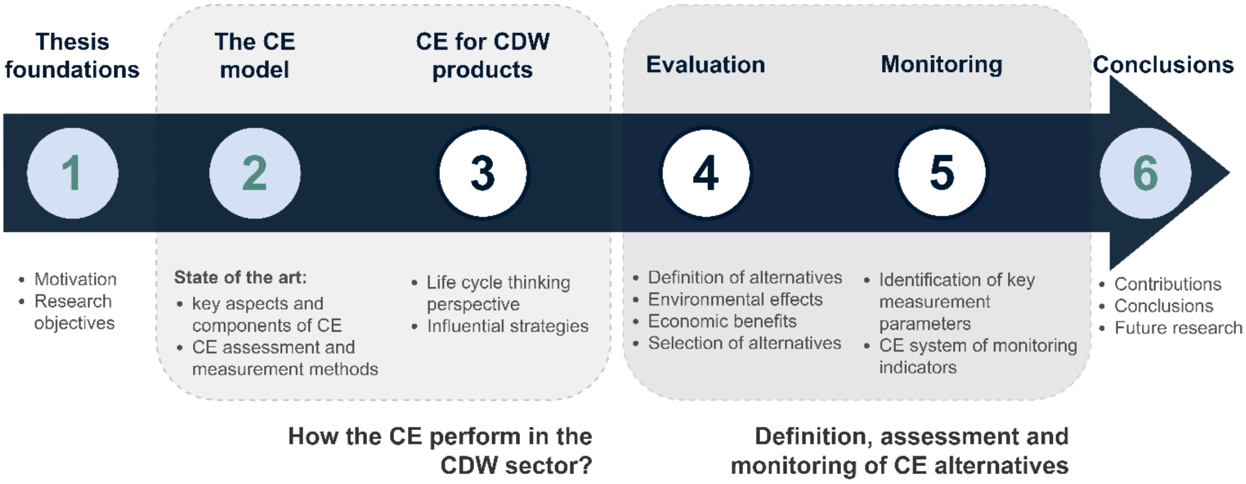

Figure 1. Outline of the research work

Chapter 3 presents a framework approach for circularity in the CDW sector based on the CE principles of narrowing, slowing and closing loops. The most influential aspects and strategies are defined and described in detail. These circularity strategies are categorized into five lifecycle phases for construction and demolition activities. Then, their application and interaction along the lifecycle stages of the proposed framework are illustrated. In addition, a brief overview of current related initiatives developed in the context of Europe is provided. This chapter corresponds to a scientific article published at Journal of Cleaner Production:

- *The circular economy in the construction and demolition waste sector – A review and an integrative model approach*. Journal of Cleaner Production 248 (2020)

  DOI: 10.1016/j.jclepro.2019.119238

  JCR (Q1) – Environmental engineering

Chapter 4 gives proof of the potential economic and environmental benefits of CE interventions in the CDW sector. For this purpose, a set of four methodological steps is proposed to identify the best circularity alternatives for CDW products in terms of their environmental and economic performance. To verify the feasibility of this methodology, a real case scenario is used to evaluate concrete waste in the region of Catalonia in Spain. First, a circularity matrix and mapping of material flows are developed to identify the available alternatives for the selected CDW typology according to the current state of technology and technical/regulatory conditions. This step is based on the strategies and parameters identified in the CE framework from chapter 3. Secondly, the environmental performance of the different CE alternatives identified is assessed considering four key categories prevalent in the environmental analysis of CE. This is followed by the estimation of the economic cost of each alternative. Then, a multicriteria evaluation is proposed as a decision-making method for identifying the best alternatives based on results from the environmental and economic evaluations and considering three different preference criteria. Lastly, results are analyzed to identify the conditioning parameters in the environmental effects and cost of concrete waste alternatives. This chapter corresponds to a scientific article submitted for publication at Resource, Conservation & Recycling. On the date of submission of this thesis, this study is under review

- *Multicriteria analysis of the environmental and economic performance of circularity strategies for construction and demolition waste – An application to concrete waste in Spain*.
  Waste Management (2021)

  JCR (Q1) – Environmental engineering

Chapter 5 closes the goal of this thesis by providing a reference for measuring and monitoring the adoption of CE strategies aimed to address the problem of CDW. CE practices can be monitored using the system of indicators proposed in this chapter. With this objective, key factors and parameters for the measurement of CE applications are identified and used to construct the framework of indicators. A comprehensive analysis of CE indicators, measuring systems and CE parameters was performed for this identification. In addition, it was supported by the understanding of the CE performance in the CDW sector provided in chapter 3, and from the analysis of environmental factors involved in the performance of CE interventions from chapter 4. The monitoring framework consists of a three-dimensional hierarchy measuring the CE dimensions of environment, economic and innovation/materials. This chapter corresponds to a scientific article submitted for publication at Journal of Cleaner Production. On the date of submission of this thesis, this study is under review

- *An indicator framework for monitoring circularity in the construction and demolition waste sector*.
  Journal of Cleaner Production (2021)
  JCR (Q1) – Environmental engineering

Finally, in **chapter 6**, the major contributions and conclusions obtained from this thesis are presented, together with potential ideas and directions for further research.

Chapter 2 State of the art

At a global level, circular economy has been strongly recognized and promoted as a solution to series of environmental challenges while bringing social and economic benefits. However, this is an emergent topic of research and developments exploring its foundations and applications to sectors including the construction industry are still in progress. Therefore, this chapter analyses relevant scientific literature and reports on circular economy to clarify its concept, core principles and to understand how it performs. Moreover, this background briefly summarizes existing methods for evaluating and comparing CE strategies from an environmental and economic perspective, as well as available measuring tools and indicators.

2.1 The circular economy framework

2.1.1 Concept and origins

In the last years, the circular economy has emerged as a need for changing the traditional linear economic model that currently predominates. This linear approach is based on “take-make-consume-dispose” patterns, which creates a close, not sustainable relation among economic growth, resource consumption and environmental degradation (Merli et al., 2018). Aiming to decouple this relation, the CE model is recognized as an innovative alternative for developing more sustainable business alongside sustainable consumption patterns (Kirchherr et al., 2017; Riba et al., 2020; Tunn et al., 2019). Thus, the vision of CE is not only about ensuring environmental quality but also fostering economic prosperity and social benefits (EMF, 2021; Palafox-Alcantar et al., 2020).

The circular economy concept has been constructed from different theoretical influences, however, the origin of this term is attributed to Pearce and Turner (1990)**.** In their work, the authors studied the interlinkages between the economy and the environment, illustrating the linear economy (open-loop system) and its transition to a closed-loop system based on the laws of thermodynamics, in which material and energy flows are kept in the cycle (Ghisellini et al., 2016; Merli et al., 2018; Su et al., 2013)**.** This way, based on the work of Boulding (1966), the planet performs as a closed system with limited availability of resources and limited capacity to absorb pollutant emissions (Geissdoerfer et al., 2017; Su et al., 2013)**.** Nevertheless, Winans et al. (2017) highlight that no system can be 100% closed due to the entropy law.

The conceptualization of CE is based on multiple ideas from different schools of thought, such as cradle-to-cradle design, performance economy, biomimicry, industrial ecology, natural capitalism and blue economy (Ellen MacArthur Foundation, 2018; Geissdoerfer et al., 2017). In addition, it is influenced by other theoretical influences like regenerative design and ecological and environmental economics (Pauliuk, 2018). Furthermore, the notion of CE also relies on ideas from scientific and semi-scientific concepts that include industrial symbioses, cleaner production and the concept of zero emissions (Korhonen et al., 2018).

Although the CE approach was rapidly popularized, its conceptualization has evolved differently among the different stakeholder groups (practitioners and academia) but also depending on the political, cultural and social systems (Winans et al., 2017). Therefore, Korhonen et al. (2018b) identified CE as an essentially contested concept, in which there exists agreement on the goals of the concept but disagreements on its definition, units of analysis, key conceptual foundations and methodology.

Over the last decades, policy makers and government bodies have embraced CE. Countries such as Germany (1996), Japan (2002) and China (2009) were pioneers in developing policies based on CE principles (BMU, 2012; Geissdoerfer et al., 2017; Moraga et al., 2019). In the European Union, CE has been embedded in its economic policies through the enactment of a first Circular Economy Action Plan in 2015 (European Commission, 2015a), recently amended by the COM (2020) 98 final – A new Circular Economy Action Plan for a cleaner and more competitive Europe (European Commission, 2020a). To date, this circular strategy is playing a key role in the evolution of economic and environmental policies at the European Community level, as well as supporting the development of circular business approaches and notably promoting the concept of CE at international level.

On that basis, policy maker bodies conceptualize CE as an approach to foster sustainable business creation, innovative models, sharing and collaborative economy, digitalization, and less dependency on primary materials. All these, while ensuring competitiveness and supported by a regulatory framework streamlined to achieve a sustainable future (European Commission, 2020a). For private business communities, this vision gives special emphasis to economic prosperity (Kirchherr et al., 2017).

Further, regarding non-governmental organizations, the work of the Ellen MacArthur Foundation (EMF) is highly recognized at the international level. This foundation has been pivotal in the development of bodies of knowledge about CE and their diffusion among private stakeholders, policy makers and scholars. In addition, the EMF provides collaborative support to stakeholder groups for creating CE opportunities (Bocken et al., 2017; Çetin et al., 2021). Then, according to its theory, CE is defined as *"an industrial system that is restorative or regenerative by intention and design. It replaces the end-of-life concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models"* Ellen MacArthur Foundation (2013).

In academia, significant efforts have been developed in the analysis and conceptualization of CE, presenting an emerging trend of research since 2015. This is attributed to the intensive diffusion of the concept by the EMF and the launching of the European CE Action Plan. Nevertheless, research developments on CE are still in their infancy. Among the current scientific literature, the work developed by Bocken et al. (2017, 2016), Geissdoerfer et al. (2017), Kirchherr et al. (2017) and Korhonen et al. (2018b) stand out as the most relevant contributions to the foundations and conceptualization of the CE. Based on their studies, CE can be defined as an economic, regenerative system that is based on business models in which materials, products and components keep their value, while resource input, waste, emissions, and energy leakage are minimized. The end-of-life is then replaced with *slowing* (prolonging use and reuse of goods through long-lasting design and product life extension), *closing* (creating circular flows of resources through recycling processes) and *narrowing* (reducing resource use and maximizing efficiency in production processes) strategies for material and energy loops in production and consumption processes. All together with a transition to renewable energy sources to ensure optimal model efficiency.

2.1.2 Key principles

According to (EMF, 2013), the CE model consists of two different approaches according to the type of material, distinguishing between technical and biological cycles. In the biological cycle, biologically based materials and consumables like food are kept in the cycle through strategies like composting and anaerobic digestion. Thus, biological nutrients regenerate natural capital and provide new renewable resources. In technical cycles, products and materials such as metals and plastics are maintained in use through processes such as designing for durability, repair, remanufacture or recycling. Nevertheless, in practice, both types of material are often mixed. In this study, CE is approached from the technical cycle perspective.

Furthermore, in general, the implementation of the CE concept relies on three main principles (EMF, 2021; Santagata et al., 2020):

a) Design out waste and pollution (preventive design)
b) Keep products and materials in use (feedback loop of materials)
c) Regenerate natural systems

Design out waste and pollution or preventive design is one of the best opportunities to reduce externalities and strengthen further recovery strategies (Jin et al., 2018). It is intended to ensure waste and pollution from economic activities are not created in the first place (EMF, 2021), as well as to contribute to narrow loops by reducing the use of resources (Bocken et al., 2016).

Keep products and materials in use (feedback loop of materials) is steered to maintain the value of products, components and materials at the highest utility in the economy (EMF, 2021). This is achieved by prolonging the lifespan of a product (slowing loops) through actions such as designing for durability, repair, refurbishment and remanufacture. Moreover, this principle also relies on closing loops through recycling processes and sharing (Baldassarre et al., 2019; Bocken et al., 2016; EMF, 2021). In sharing schemes, products and services are combined to fulfil the final customer needs through delivering user functionality (sharing services) instead of creating new products. This is the named instrument of Product Service-Systems (PSS) and distinguishes between three application categories: product-oriented (e.g. maintenance), use-oriented (e.g. leasing, sharing and pooling), and result-oriented services (e.g. pay-per-service unit or functional result) (Joensuu et al., 2020; Tukker, 2015). The latter was identified by Tukker (2015) as the most promising to facilitate a shift to a circular economy because of its focus on results rather than products.

Lastly, *regenerate natural systems* relies on the substitution of non-renewable resources with renewable ones to support regeneration. Additionally, the transition to a renewable energy system is prioritized. However, far from a fully renewable system, they still rely on non-renewable resources. Thus, this principle intends to control finite stocks and balance renewable resources (EMF, 2021; Santagata et al., 2020).

2.1.3 Drivers/enabling factors

In a CE, several stakeholders are needed to collaborate at all scales, from individuals and small businesses to local and global organizations (Baldassarre et al., 2019; EMF, 2021). Moreover, the complexity of CE systems involves interaction among seven dimensions: governmental/policy, economic, environmental, behavioural/management, societal, technological and innovation/materials (Hossain et al., 2020; Pomponi and Moncaster, 2017). Therefore, the success of the transition to a CE depends on multiple enabling factors acting simultaneously to guide and reinforce the transition process (European Environment Agency, 2016). The main enabling factors required to support this change of paradigm are listed as following:

Design

Design is a relevant enabler acting at the very beginning of the value chain. Design processes improve the circularity of products by using fewer resources and facilitating their reuse, refurbishment. maintenance and recycling, as well as avoiding hazardous materials (Elia et al., 2017a). For this driver, Bovea and Pérez-Belis (2018) distinguish among five circular design guidelines groups:

a) Extending life span: it includes design guidelines for promoting life span and product durability to ensure the product can be used as long as possible (e.g. timeless design, adaptability, upgrading).
b) Design for disassembly: regarding guidelines for facilitating disassembly of products and their components (e.g. minimize the type of joints, modular design).
c) Design for product reuse: oriented to facilitate the reuse of products by maintenance and repairing processes (e.g. use of components with similar life span).
d) Components reuse: oriented to facilitate the reuse of components (e.g. use of standardized components, minimize the type of parts).
e) Material recycling: aimed to facilitate the identification, separation and recycling of materials (e.g. mono-material designs, minimize the use of hazardous materials).

Business model innovation

Innovative business models incorporating CE principles are crucial for helping companies to achieve economic and environmental sustainability (Adams et al., 2017; Tunn et al., 2019). The development of circular business models requires the definition of new partnerships and collaborative networks with a perspective on resource value (Lieder and Rashid, 2016). According to Bocken et al. (2016), there are six key strategies for circular business models:

a) Access and performance model (sharing schemes): value proposition focused on services rather than ownership (e.g. clothing rental services, car rental and pooling)
b) Extending product value: exploiting the residual value of products through remanufacturing and refurbishing practices.
c) Classic long-life model: long-lasting products designed for durability and repair.
d) Encourage sufficiency: prolonging product life to reduce end-user consumption, through a non-consumerist approach and principles like longer use of high-quality products, repair and warrantee services.
e) Extending resource value: transform wasted materials and resources into new forms of value.
f) Industrial symbiosis: waste outputs from an industrial process becomes inputs for another process, product line or industry.

Responsible consumption and green public procurement

Responsible consumption patterns are crucial to support businesses with less negative influence on the environment while also creating positive social impact (Ghisellini et al., 2016; Kalmykova et al., 2018). In this context, eco-labelling for products and services are recognized as functional instruments to promote green consumption (Ghisellini et al., 2016). Moreover, green public procurement requirements aimed to procure more sustainable goods and services constitute a relevant enabler for CE transition, in particular, because of the high contribution of public procurement to Gross Domestic Product (Adams et al., 2017; Ghisellini et al., 2016; Kalmykova et al., 2018). Furthermore, these drivers are closely linked to awareness and promotion of research as essential enablers on circularity transition (Adams et al., 2017; Langen et al., 2021).

Collaboration

This driver emphasizes the need of building a cross-sectoral collaboration (internal and external) across the new value chain, identifying stakeholders and new actors to implement and operate successful CE systems that create mutual value (Baldassarre et al., 2019; Carolina et al., 2021; Elia et al., 2017a).

Policies and regulations

Institutional and regulatory drivers are key elements in the transition towards CE. Governments have the power to enact and adopt innovative policies to guide producers and consumers towards a new economic system based on the use of new technologies, enhanced production models, and encourage more sustainable consumption patterns. Public policy measures can include certifications and quality regulations, legal frameworks, and economic instruments like taxation and incentives (De Jesus and Mendonça, 2018; Langen et al., 2021).

Material recovery

This enabler is concerned with interventions focused on supporting closed-loop and semi-closed loop cycles, enabling the recovery of materials and components through cascade/reverse skills, upcycling, downcycling or energy recovery processes. All this is accompanied by the enhancement of the market of secondary products (Adams et al., 2017; Elia et al., 2017a; Kalmykova et al., 2018).

2.2 CE in the construction and demolition industry

This section provides a picture of current developments on CE within the construction and demolition industry, including an overview of available approaches for the assessment and monitoring of CE strategies. For this study, CE assessment is addressed in terms of the environmental and economic dimensions of CE.

2.2.1 CE assessment as a pathway for better decision-making

Environmental dimension

Estimation of environmental impacts is crucial to understand the behaviour of circular systems within the construction industry in the short and long run (Asif et al., 2016; Dong and Ng, 2015). The enactment of policies and legislation regulating the environmental performance of construction activities in different countries around the world has led to growing concern and interest in developing assessment methods to evaluate building design, construction processes and CDW management practices (M. D. Bovea and Powell, 2016). This is reflected in an increased number of studies addressing this subject from 2015 (Ghisellini et al., 2018b).

Pomponi and Moncaster (2017) identified Life cycle assessment (LCA) methodology and material flow analysis (MFA) as two well-established techniques for environmental studies in the built environment. MFA consists of “a systematic assessment of the flows and stocks of materials within a system defined in space and time” (Elia et al., 2017a). Therefore, MFA allows quantifying materials and study their potential for recovery and recycling (Schiller et al., 2017). However, MFA is not commonly adopted for CE assessment, as it does not provide a complete environmental analysis (Elia et al., 2017a; Sassanelli et al., 2019). In contrast, LCA is a widely recognized tool adopted by multiple researchers and practitioners for evaluating the environmental performance of a product or system (M. D. Bovea and Powell, 2016; T. Ding et al., 2016; Dong and Ng, 2015; Hou et al., 2015; Rosado et al., 2019; Sassanelli et al., 2019).

LCA methodology is an effective, comprehensive tool that provides a reliable quantification of environmental impacts, which can be interpreted through multiple impact categories and using different methods depending on the nature of the analysis (Dong and Ng, 2015; Rosado et al., 2019). In the practice, ISO 14040 and ISO 14044 standards (ISO, 2006a, 2006b) provide guidelines for developing LCA studies.

In the construction sector, LCA has been intensively recommended and used to assess the environmental performance of buildings (Geng et al., 2017a) and construction projects (Dong and Ng, 2015), rehabilitation and demolition processes (Alba-Rodríguez et al., 2017) and the use of prefabricated components (Chou and Yeh, 2015). Moreover, LCA has been also applied to evaluate CDW management systems and processes (Butera et al., 2015; Coelho and De Brito, 2012a; Ortiz et al., 2010; Rosado et al., 2019), on-site and off-site recycling processes (Jung et al., 2015), reuse and recycling practices (Jain et al., 2020; Minunno et al., 2020), and production of secondary building products (T. Ding et al., 2016; Lockrey et al., 2018; Suárez Silgado et al., 2018; Tošić et al., 2015). Furthermore, LCA can be extended to other CE strategies or research (Pomponi and Moncaster, 2017), aiming to provide ideas for creating closed-circular solutions and for reducing their impacts (Civancik-Uslu et al., 2019; Puig et al., 2013). In addition to the wide adoption of the LCA method in scientific studies, the *Level(s) framework* from the European Commission (2021) establishes the use of the LCA methodology to measure the sustainability performance of buildings, together with a set of 16 indicators monitoring sustainability of buildings.

Apart from LCA, life cycle energy analysis (LCEA) is commonly used to evaluate the environmental performance of buildings (Cabeza et al., 2014). Some studies have performed a LCEA to evaluate CDW management alternatives. For example, Chau et al. (2017) analyzed recycling, reuse and incineration alternatives for materials and elements from a concrete office building in Hong Kong. Similarly, Ng and Chau (2015) evaluated these three end-of-life management alternatives for a concrete commercial building. However, this assessment method is focused on the single impact category of energy, neglecting other relevant categories for CE evaluation.

Economic dimension

A better understanding and knowledge of the cost-benefit of applying CE strategies are needed to successfully achieve circularity in the sector (Eberhardt et al., 2019). The concept of CE relies on the creation of both environmental and economic benefits, thus reliable proofs about the potential economic savings and feasibility of circularity alternatives are necessary to encourage business communities and society to adopt CE alternatives. Despite this, existing related research within CE principles and their application in the CDW sector is reduced.

Some studies have focused on evaluating the financial effect or feasibility of CDW treatment facilities. This is the case of Coelho and De Brito (2012b) on the feasibility analysis of a recycling plant in Portugal, Oliveira Neto et al. (2017) on financial analysis of different recycling processes in a treatment plant, and Srour et al. (2013) performing an investment analysis for a proposal of a recycling plant in Lebanon. In addition, Wijayasundara et al. (2016) explored the feasibility of a recycling facility for concrete waste in Australia.

The literature review performed by Cabeza et al. (2014) identified life cycle cost analysis (LCCA) as a common method among researchers in the construction industry. This method consists of an economic evaluation that determines the total cost of owning and operating a facility over a period of time and is applied to buildings or isolated building systems. Moreover, other authors like Hao et al. (2019), Z. Ding et al. (2016) and Marzouk and Azab (2014) adopted a System Dynamics (SD) model to evaluate CDW management systems. This model analyzes the interrelationships of influential factors through different subsystems and is recommended for evaluating economic, environmental, social and managerial systems of great complexity and interrelation.

Lastly, some authors such as Suárez Silgado et al. (2018), Alba-Rodríguez et al. (2017) and Jung et al. (2015) have adopted tailored economic evaluations based on complex costs. This method consists of multiple disaggregated simple costs (e.g. fixed costs, variable costs, management costs) calculated separately and then grouped into a total cost. This approach provides comprehensive detail of the economic performance of the system analyzed.

Decision-making tools

Multi-criteria decision making (MCDM) methods have become popular tools to determine the optimal alternatives in a range of options while integrating the different perspectives and priorities of stakeholder groups (Palafox-Alcantar et al., 2020). MCDM consists of five main steps: definition of alternatives, the establishment of the criteria (attributes), evaluation of alternatives, assessment of criteria weights, and application of the ranking system (Jahan et al., 2011)**.**

According to Sassanelli et al. (2019), MCDM is one of the most used methodologies for assessing CE. This approach has been adopted in various disciplines for decision making. Some authors have incorporated MCDM considering sustainability and CE principles. For example, Kazancoglu et al. (2018) proposed a green supply chain management performance assessment framework incorporating CE principles, Niero and Kalbar (2019) applied the multi-criteria approach to assess CE strategies at the product level (case study on the packaging), Wang et al. (2009) conducted a literature review to identify the existing methods for sustainable decision making on energy, and Bertoni (2019) investigated the application of MCDM methods for sustainable product-service systems.

Moreover, the MCDM approach comprises various methods based on different mathematical principles. The following are identified as the most applied in the literature (Bertoni, 2019; Jahan et al., 2011; Wang et al., 2009):

- *Analytic hierarchy process (AHP):* is one of the most popular methods because of its easiness of application by the decision-making team. It is based on the logic of the pair-wise comparison model for determining the weights for each criterion. It is widely used in multiple systems: social, economic, ecological and energy systems.
- *TOPSIS:* is used as a weighting method, but also is included as a MCDM method. It relies on a simple principle that provides a score from 0 to 1, which is easy to interpret.
- *Elimination et choice translating reality (ELECTRE) method*: uses pair-wise comparisons among alternatives under each criterion separately. This method is based on the study of outranking relations, exploitation notions of concordance. It can work with different scales of heterogeneous criteria, without performing normalization processes. However, the lack of a common measuring scale could be inconvenient for this method.
- *Preference ranking organization method for enrichment evaluation (PROMETHEE):* it is proved to perform well in systems with a finite number of alternatives, which have to be ranked considering several, sometimes-conflicting criteria. Like ELECTRE, it also performs a pair-wise comparison of alternatives to rank them. This method has been widely used in energy planning projects (geothermal, renewable energy).
- *VIKOR method:* focuses on ranking and selecting from a set of alternatives with conflicting criteria. Thus, alternatives are compared based on the measure of closeness to the ideal solution(Jahan et

al., 2011). This method has been proved to be appropriate for analyzing recycled concrete products (Suárez Silgado et al., 2018; Tošić et al., 2015) and for material selection in engineering (Jahan et al., 2011).

2.2.2 Measurement and monitoring tools

The application of indicators and monitoring systems are essential for achieving a successful transition to CE. Their use enables us to understand and capture the effects of the CE implementation and to identify the direct and indirect influence of circularity interventions in the different measurement criteria (Bilal et al., 2020; Moraga et al., 2019; Rincón-Moreno et al., 2021; Saidani et al., 2017). In this regard, practitioners and academics around the world recognized the necessity of developing adequate monitoring tools. To date, there are no international standardized CE indicators, however, a series of ISO standards on CE are expected to be concluded in 2021, including guidelines for circularity measurement.

Some approaches have gained traction in practice: the Material Circularity Indicator (MCI), Circulytics (EMF, 2020; EMF and GRANTA, 2015), the Circular Transition Indicators (CTI) framework (WBCSD, 2021) and the Cradle to Cradle Certified (Cradle to cradle products innovation institute, 2016). Moreover, academics have explored the creation of monitoring systems and individual indicators focused on eco-design (Mesa et al., 2020; Vanegas et al., 2018), resource efficiency (Di Maio et al., 2017), resource duration (Figge et al., 2018; Franklin-Johnson et al., 2016), reuse (Cong et al., 2019; Mesa et al., 2020; Park and Chertow, 2014), recycling (Adibi et al., 2017; Di Maio and Rem, 2015; Huysman et al., 2017; Linder et al., 2017; Mesa et al., 2020; Mohamed Sultan et al., 2017), energy recovery (Huysman et al., 2017) and cost savings (Cong et al., 2019).

For the construction industry, the Joint Research Centre (JRC) from the European Commission developed the Level(s) common framework of indicators for measuring the sustainability of office and residential buildings (European Commission, 2021). It focused on the evaluation of the environmental performance of buildings, their health and comfort, cost, value and the potential risks through 6 macro-objectives. Although it is intended to provide and standardized measurement of buildings, its practical implementation could be hindered by the extensivity and complexity of user guides.

In the scientific literature, a very reduced number of studies have focused on the construction industry, also lacking holistic integration of CE parameters. Current related approaches include the Building Information Modelling based Deconstructability Assessment Score (Akinade et al., 2015), the Mitigation framework to evaluate the level of implementation of the CE in the building sector for developing countries (Bilal et al., 2020), the Bridge Circularity Indicator (Coenen et al., 2021), the Predictive Building Circularity Indicator (Cottafava and Ritzen, 2021), Key environmental indicators for adaptive reuse of cultural heritage buildings (Foster and Kreinin, 2020), the Synthetic economic-environmental indicator for the end-of-life of buildings (Fregonara et al., 2017), the Circularity Indicator Building Score (Heisel and Rau-Oberhuber, 2020), best performance indicators to measure the management performance of end-of-life gypsum (Jiménez-Rivero and García-Navarro, 2016), the Circular Economy measurement scale for building industry (Nuñez-Cacho et al., 2018), the Index of recyclability of buildings (Vefago and Avellaneda, 2013), and the Construction waste LCA-based sustainability index (Yeheyis et al., 2013).

These approaches are described in deeper detail in chapter 5.

2.2.3 Barriers

Even though the CE concept is a potential solution for the environmental problems of the construction industry, mainly for the problem of CDW, studies show that to date there are series of challenges and barriers restricting its adoption (Aslam et al., 2020; Calvo et al., 2014).

According to Brown et al. (2019), Calvo et al. (2014) and Ghisellini et al. (2018b), these barriers can be broadly categorized into five key groups: (i) technical, (ii) economic, (iii) market, (iv) political/regulatory, and (v) social. These barriers are listed in detail in **Table 1.**

Table 1. Main barriers for circularity in the CDW sector

Group	Category	Barriers
i. Technical	Designing and use of materials	• Lack of standards for building design and construction (Gangolells et al., 2014; Huang et al., 2018). • Lack of end-of-life considerations during building's design (Adams et al., 2017). • Lack of standards to guide and enhance the use of Building Information Modeling (BIM) (Gangolells et al., 2014; Huang et al., 2018). • Lack of industry standards for the quality of secondary building materials and prefabricated elements (Calvo et al., 2014; Gangolells et al., 2014; Huang et al., 2018).
	Infrastructure and technology	• Lack of economically viable treatment facilities (Lockrey et al., 2016). • Difficulties to maintain constant input flows in recycling factories because of the high treatment costs and presence of illegal dumping (Yuan, 2017). • Availability of recycling technology to produce a wide variety of secondary products with different quality and values (Bilal et al., 2020; Huang et al., 2018).
	Effectiveness of CDW management practices	• Absence of waste management plans (Calvo et al., 2014). • Insufficient attention to waste management during the construction stage (Aslam et al., 2020). • Absence of effective direction for the dismantling, collection, sorting, transporting and recovering processes of waste (Aslam et al., 2020; Gangolells et al., 2014; Huang et al., 2018; Mahpour, 2018). • Illegal dumping (Gangolells et al., 2014). • Lack of space in construction and demolition sites for CDW management (Calvo et al., 2014; Gangolells et al., 2014).
	Lack of fundamental data, knowledge and awareness of stakeholders in the supply chain	• Lack of fundamental data in C&D waste (AEDED, 2016; Bilal et al., 2020; Calvo et al., 2014; Mahpour, 2018; Rodríguez-Robles et al., 2015; Yuan, 2017): – Reliable and accurate data about the amount of waste generated and its detailed composition. – Accessibility to data and non-standardized CDW reporting. – Data on recovery and recycling rates. • Lack of knowledge and awareness (Bilal et al., 2020; Calvo et al., 2014; Gangolells et al., 2014; Ghisellini et al., 2018b; Huang et al., 2018; Mahpour, 2018): – Limited awareness, understanding, and insight into the circular economy in C&D waste management. – Lack of knowledge and standards for reuse and recovery alternatives. – Lack of proper training and CE skills. – Limited availability of studies focused on production methods of secondary building materials. – Lack of knowledge and control over CDW waste management plans approved by national and regional governments. • Lack of standardized indicators to measure and monitor circularity actions (Bilal et al., 2020; Mahpour, 2018; Nuñez-Cacho et al., 2018).

ii. Market	Business and supply chains	• Under-developed market for secondary products (Gálvez-Martos et al., 2018). • Fragmented supply chain: unstable, an insufficient supply of recovered materials (Adams et al., 2017; Gálvez-Martos et al., 2018; Huang et al., 2018). • Higher prices of secondary building products than conventional-virgin based materials (AEDED, 2016; Bilal et al., 2020; Ghisellini et al., 2018b; Huang et al., 2018). • Lack of market demand for secondary materials (Lockrey et al., 2016; Nußholz et al., 2019).
	Acceptability & perception	• Lack of trust in 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).
iii. Economic	Cost and finance	• Deficiency of financial support (Aslam et al., 2020; Bilal et al., 2020). • Lack of budget for waste management in construction projects (Lockrey et al., 2016). • Lack of funding to implement the circular economy in C&D waste management (Mahpour, 2018) • Cost of complying with the current legal framework (Gangolells et al., 2014). • Significant extra cost to develop individualized waste management plans for each construction demolition site (Gangolells et al., 2014). • The property developer perceives obligatory waste management to be a costly requirement (Rodríguez-Robles et al., 2015).
iv. Political/ regulatory	Legislative, policies and regulations	• Lack of mature regulatory framework with clear targets defined, visions and specific legislation to move toward circular economy in C&D waste management (Adams et al., 2017; Bilal et al., 2020; Calvo et al., 2014; Gangolells et al., 2014; Mahpour, 2018; Yuan, 2017). • Legislation at a regional level is independent and tend to disperse (Calvo et al., 2014). • Existing regulations are not well executed (Yuan, 2017). • Lack of specific regulations on the use of secondary materials (Rodríguez-Robles et al., 2015).
	Economical instruments	• Low taxation on virgin raw materials (Dahlbo et al., 2015; Ghisellini et al., 2018b). • Lack of incentives to treat and recirculate construction materials, as well as support governments to implement new construction and waste management methods (Aslam et al., 2020; Huang et al., 2018; Mahpour, 2018). • Disposal and treatment fees. Low landfilling fees could hinder the preference for recovery alternatives, while high disposal fees can cause illegal dumping (Gangolells et al., 2014; Lockrey et al., 2016).
v. Social	Organizational	• Lack of communication and coordination among agents involved in the planning, design, execution and management of construction and demolition activities (Aslam et al., 2020; Bilal et al., 2020; Calvo et al., 2014; Jiménez-Rivero and García-Navarro, 2017). • Difficulties to control and manage the CDW produced by subcontractors (Gangolells et al., 2014). • Poor collective engagement (Mahpour, 2018).
	Behavioural	• Lack of awareness among stakeholders, contractors, and workers: proper quantification of CDW by project designers and more effective CDW management practices from a circular perspective is not a serious concern for the participants (Aslam et al., 2020; Calvo et al., 2014; Gangolells et al., 2014; Huang et al., 2018; Mahpour, 2018; Rodríguez-Robles et al., 2015). • Lack of public/customer awareness (Bilal et al., 2020). • Lack of commitment by top stakeholders, managers and workers to implement circularity alternatives (Mahpour, 2018). • Proper CDW management and circular practices are perceived by building contractors and project managers as unnecessary, bureaucratic procedures which demand excessive effort and time (Rodríguez-Robles et al., 2015). • To date, consumers prefer conventional materials over secondary building products (Mahpour, 2018).

Chapter 3 The circular economy in the construction and demolition waste sector - A review and an integrative model approach

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.

3.1 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., 2017b; 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 2a, 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., 2017a). 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., 2017a; Suárez Silgado 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 2c, 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., 2017a).

The CE concept has gained academic, government and organizational recognition. At a 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, 2020b).

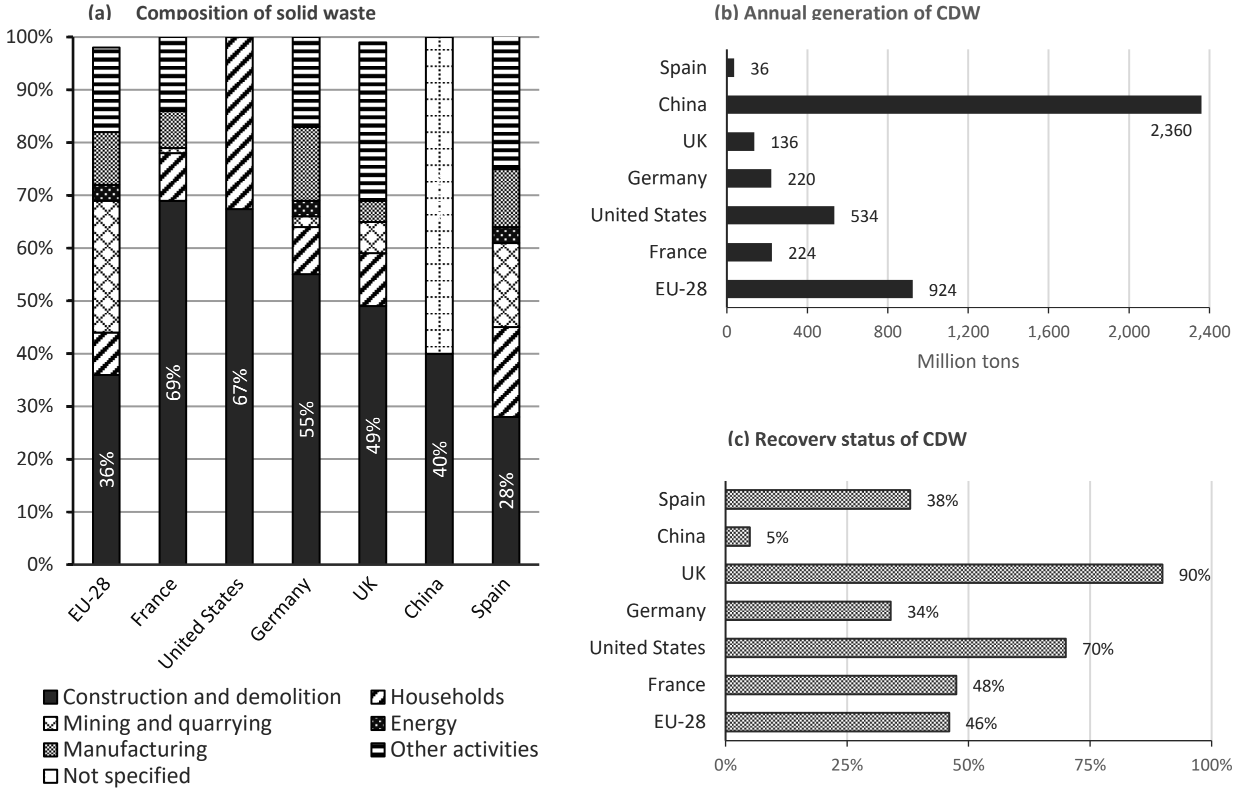

Figure 2. Comparison of generation and recovery status of CDW

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, 2015a), 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 3.2 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 3.3 describes the research methodology used to achieve the objectives of this study. Next, Section 3.4 presents the results of the review, based on the categorization of CE strategies according to five lifecycle stages of construction and demolition activities. Derived from these results, Section 3.5 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.

3.2 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.

3.2.1 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; EMF and GRANTA, 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 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 (EMF and GRANTA, 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).

3.2.2 CE initiatives

The CE concept has been implemented through government policies at local, regional and national levels. 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, 2015a).

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 2** provides an overview of the most important regional and national initiatives and strategies developed in Europe regarding CDW in the Circular Economy.

Table 2. 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, 2015a)	• 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 the 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, 2018a)	• 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.

3.3 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 3** 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 the 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 3**), 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. Observation of all studies showed that the countries leading research on this area are China, Spain and United Kingdom.

Table 3. 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

3.4 Results

3.4.1 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 4**).

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 4. 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)

3.4.2 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.

3.4.2.1 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 favours 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.

3.4.2.2 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.

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., 2017a; 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 labour 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 the 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.

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).

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 labour-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).

3.4.2.3 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 a 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).

3.4.3 Construction and building renovation

3.4.3.1 Site waste management plans

From a CE perspective, Esa et al. (2017) highlight 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 are 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 the 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).

3.4.4 Collection and distribution

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

3.4.4.1 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 the 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 at 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 a 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, a 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 the optimal production of recycled materials (Bovea and Powell, 2016).

3.4.4.2 Transport processes

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

g) Transport of CDW from a demolition/deconstruction site to storage deposits
h) Transport of CDW from a demolition/deconstruction site directly to treatment facilities (e.g. recycling plants, incineration plants)
i) Transport of treated waste to storage sites

j) Transport of treated waste directly to manufacturing industries
k) Transport of secondary materials (recycled/reused products) to construction sites
l) Transport of waste to backfill sites
m) 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 the final disposal.

3.4.5 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.

3.4.5.1 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).

3.4.5.2 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 potentially 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).

3.4.6 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, the 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.

3.4.6.1 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.

3.4.6.2 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 aluminium, 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, the specification of reusable and recyclable building materials during the 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 glueing 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, an 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).

3.4.6.3 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 centres (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).

3.4.6.4 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 opben 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).

3.5 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 practically 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 3.2.1**) 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 3** 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 are 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 partially recycled content to substitute components of the same material; (iii) recovered materials with partially 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.

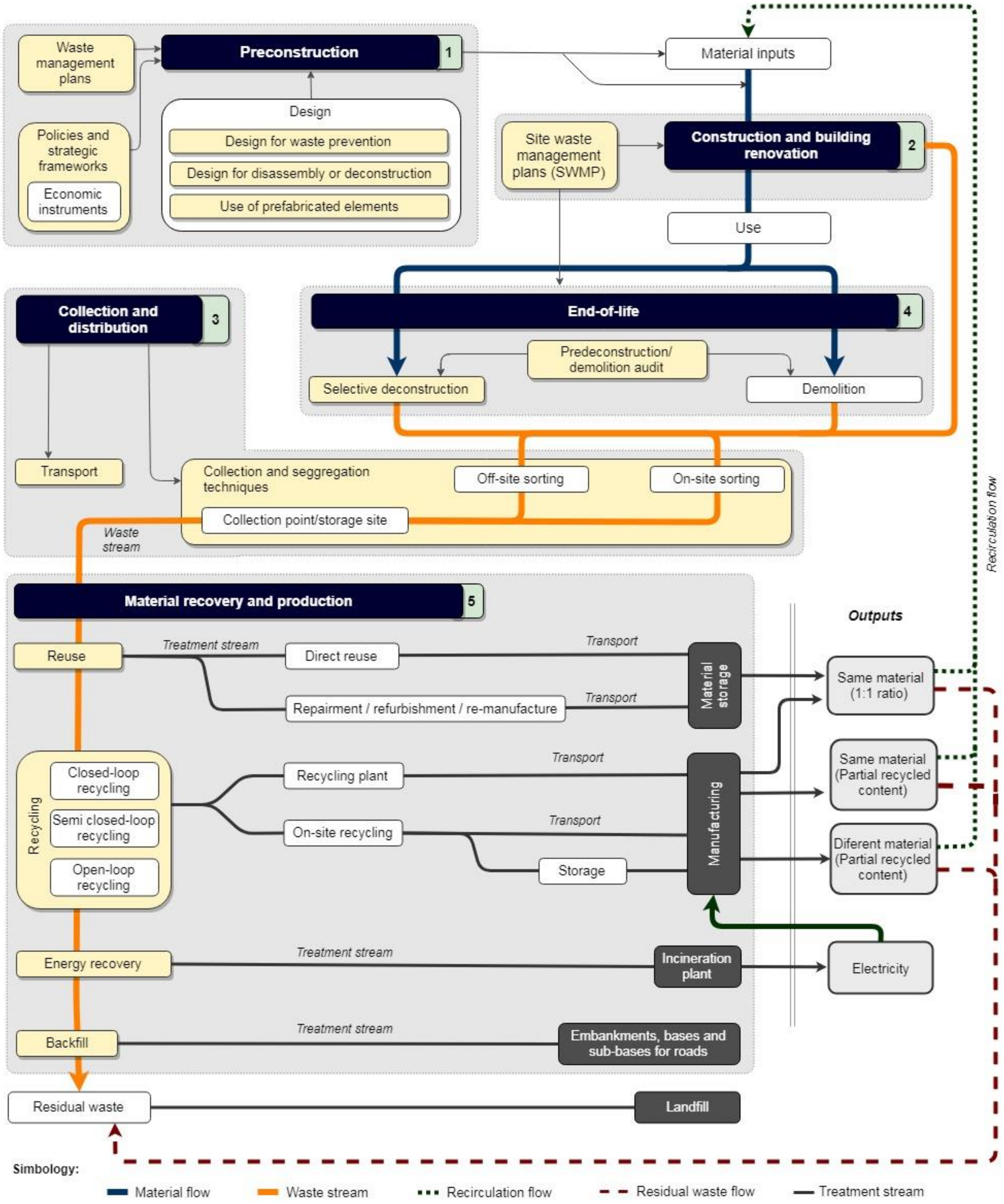

Figure 3. Theoretical model approach for CE implementation in the CDW sector

3.6 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 their 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 is necessary to provide a more comprehensive dimension of the theoretical framework (e.g. analysis of stakeholders; economic, technical and social barriers; and business 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.

Chapter 4 Multicriteria analysis of the environmental and economic performance of circularity strategies for construction and demolition waste – An application to concrete waste in Spain

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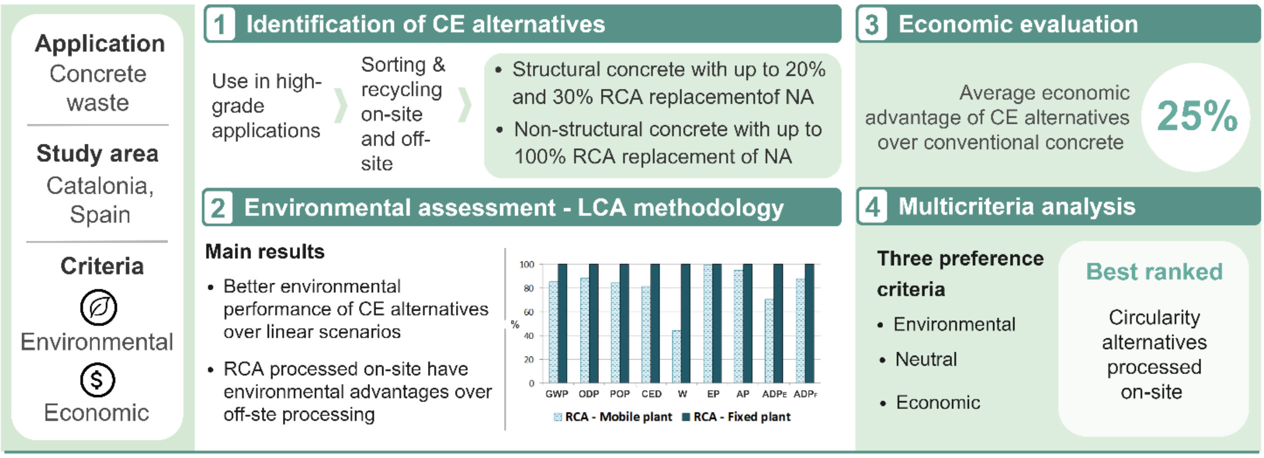
Abstract

Construction and demolition waste (CDW) is identified by multiple circular economy (CE) policies as a key sector for implementing circularity strategies due to the high volume of waste produced and the large consumption of raw materials for producing new construction products. However, CE is not widely applied in the sector because of the lack of solid estimations on its environmental and economic viability. The main aim of this study was to propose a set of methodological steps to identify the optimal circularity alternatives for CDW products based on a multicriteria analysis of their environmental and economic performance. This methodology is applied to evaluate concrete waste. In specific, high-grade applications of concrete were analyzed comprising the processing into recycled coarse aggregates (RCA) for their use in structural and non-structural concrete. Multiple scenarios with different RCA replacements (20%, 30% and 100%) and different types of sorting and recycling (on-site and off-site) were evaluated in accordance with the specific site conditions of the region of Catalonia, Spain. The Life Cycle Analysis methodology was used to perform the environmental analysis, while a detailed cost analysis was conducted for the economic aspect. The multicriteria VIKOR method was used for the selection of alternatives considering three different criteria. The results of this study showed environmental and economic advantages of CE scenarios based on the use of RCA over conventional concrete, since landfilling is avoided, and transport distances are reduced. RCA produced on-site showed a better performance than RCA from fixed plants.

Multicriteria analysis of circularity alternatives for CDW products



Application
Concrete waste

Study area
Catalonia, Spain

Criteria
Environmental
Economic

1 Identification of CE alternatives

Use in high-grade applications 〉 Sorting & recycling on-site and off-site 〉

- Structural concrete with up to 20% and 30% RCA replacementof NA
- Non-structural concrete with up to 100% RCA replacement of NA

2 Environmental assessment - LCA methodology

Main results

- Better environmental performance of CE alternatives over linear scenarios
- RCA processed on-site have environmental advantages over off-ste processing

3 Economic evaluation

Average economic advantage of CE alternatives over conventional concrete **25%**

4 Multicriteria analysis

Three preference criteria

- Environmental
- Neutral
- Economic

Best ranked

Circularity alternatives processed on-site

4.1 Introduction

The construction industry is one of the most important sectors for economic growth and the provision of employment opportunities (Bao and Lu, 2020; Smol et al., 2015). However, it is also a major contributor to environmental degradation (Esa et al., 2017a). The construction and maintenance of buildings and infrastructure account for about 50% of global material consumption and 20% of GHG emissions (Gallego-Schmid et al., 2020). Materials are responsible for more than 50% of the carbon footprint of buildings and infrastructure, and 40% of the GHG emissions related to total material manufacturing result from materials used in the construction industry (Hertwich et al., 2019). In addition to the high consumption of natural resources and energy, and to the emission of polluting gasses (Braga et al., 2017; Suárez Silgado et al., 2018), this sector produces the largest waste stream worldwide (Akanbi et al., 2019).

Construction and demolition waste (CDW) mainly consist of inert waste and minor shares of other materials such as metals, wood and plastics (Ji et al., 2018; Suárez Silgado et al., 2018). In general, the major component of CDW consists of concrete, which ranges from 40% to 85% of the total CDW generated by weight (Gálvez-Martos et al., 2018; Yuan, 2017; Zhang et al., 2020). However, its composition varies between regions and projects due to different factors (economy, culture, climate, building style and construction practices) (Wu et al., 2019; Zheng et al., 2017).

Despite the large amounts of waste produced, there is a lack of sufficient waste management capacity (Bao and Lu, 2020). Even though CDW has a high potential for recovering, approximately 80% of which could be reused or recycled (Aslam et al., 2020; Islam et al., 2019; Ortiz et al., 2010), only 20-30% of this waste is recovered globally (World Economic Forum, 2016). Furthermore, although the application of recovering alternatives is preferred over landfilling because of their better environmental performance (Li et al., 2020), disposing of in landfills is still a very common waste management practice (Chau et al., 2017) At the global level, approximately 54% of CDW generated is landfilled (Gallego-Schmid et al., 2020). Moreover, CDW is often illegally dumped to avoid transportation costs and fees from regulated disposal facilities (Duan et al., 2019; Seror and Portnov, 2018).

Given this scenario and considering that the urban built environment is expected to grow 60% by 2050 (Gallego-Schmid et al., 2020), the construction sector needs to find new, enhanced strategies for reducing its environmental impacts by more efficient management of CDW and more sustainable production and use of construction materials. With this aim, the circular economy (CE) approach is a promising solution (Ghaffar et al., 2020), and according to several authors, the building industry is one of the key sectors with the greatest potential for implementing CE strategies (Akanbi et al., 2019; Brambilla et al., 2019; Nußholz et al., 2020) and also a priority in CE policies (European Commission, 2015a).

Research efforts within the adoption of the CE in the construction sector have gained significant attention showing the increasing environmental concerns and the increasing political attention to this industry. However, this is a recent topic of research and most of the publications have been developed since 2017 (Benachio et al., 2020; Eberhardt et al., 2020; Hossain et al., 2020; López Ruiz et al., 2020). Furthermore, for the CDW sector, there is a lack of integrative approaches analyzing the application of the CE in multiple stages of the construction and demolition’s lifecycle and considering both environmental and economic dimensions of the CE (Hossain et al., 2020; Pomponi and Moncaster, 2017). According to the work of Ghisellini et al. (2018b) on the analysis of different cases of implementation of the CE approach in the CDW management sector, only 3% of the available studies apply a multidimensional analysis. A recent study by Hossain et al. (2020) revealed that most of the existing studies on CE adoption in the construction industry are reviews, frameworks and analytical type papers, while a limited share of research (16%) evaluates multiple dimensions of the CE and about 17% are focused on the single environmental dimension.

Every circular option should balance the environmental benefits with the costs (Ghisellini et al., 2018b), and requires the evaluation of these two aspects to provide a unified vision that properly supports the implementation of CE strategies (Zuo et al., 2016). The application of integrative decision-making processes helps to capture the different perspectives and priorities of stakeholder groups and integrates multiple dimensions and the basis of the CE. However, its application is currently limited in the practice (Palafox-Alcantar et al., 2020).

For the environmental aspect, life cycle thinking has become a key element in the evaluation of products or business models aimed at the CE concept (Civancik-Uslu et al., 2019; Puig et al., 2013). In this regard, Life Cycle Assessment (LCA) represents a valuable and widely recognized tool for analyzing the environmental performance of a product or system (T. Ding et al., 2016; Hou et al., 2015) and is very well suited to assess and build more robust CE strategies (Life Cycle Initiative, 2020). In the construction sector, there is an increasing interest in incorporating LCA methods to optimize construction processes and the use of environmentally preferable products (Cabeza et al., 2014). Despite this, most lifecycle studies consist of energy-focused approaches, without evaluating the core environmental parameters of the CE.

Moreover, as stated before, for evaluating CE implementation it should be determined if its adoption is economically sustainable. Thus, a better understanding and knowledge of the cost-benefit of applying CE strategies are needed to successfully achieve circularity in the sector (Eberhardt et al., 2019). Despite this, the existing related research within the construction industry is still very limited (Zuo et al., 2016) and mainly focused on the financial and economic feasibility of CDW recycling plants, instead of integral economic valuations (Ghisellini et al., 2018b; Hossain et al., 2020).

This study aims to evaluate the potential environmental and economic benefits of circularity strategies in the CDW sector, particularly focused on the different CDW management options and alternatives for producing/obtaining secondary products for the construction industry. For this purpose, this paper proposes a set of methodological steps to identify the available and potential circularity alternatives for CDW products and to assess their environmental and economic performance. Lastly, it is proposed a multicriteria analysis to identify the optimal alternatives based on both economic and environmental results. This methodology is suitable to evaluate any CDW typology and is applicable to any region. For practical purposes, this study evaluates concrete waste, particularly in the region of Catalonia, Spain.

To achieve the objectives defined, this work consists of three main sections. Section 4.2 describes the methodology used to identify, evaluate (environmental and economic), and compare circularity alternatives. Section 4.3 provides the results for the chosen alternatives within the three evaluations. Lastly, section 4.4 highlights the main findings of the study.

4.2 Methodology

The methodology proposed in this study comprises four major steps to evaluate the environmental and economic performance of circularity alternatives for CDW products and to select the optimal solutions in terms of both economic and environmental criteria. These methodological steps are presented in **Figure 4**, and described as following:

1. **Identification and definition of CE alternatives:** analyze and define the circularity options and material flows incorporating the Life Cycle Thinking (LCT) approach.
2. **Environmental assessment:** assess the environmental performance of alternatives including four key environmental parameters for circularity (gas emissions, energy, water, and use of resources). LCA methodology is adopted.
3. **Evaluation of the economic criteria:** estimates product cost to identify potential economic savings among alternatives.
4. **Identification of optimal alternatives:** implements a multicriteria evaluation to support the decision-making process of selection of alternatives based on environmental and economic aspects.

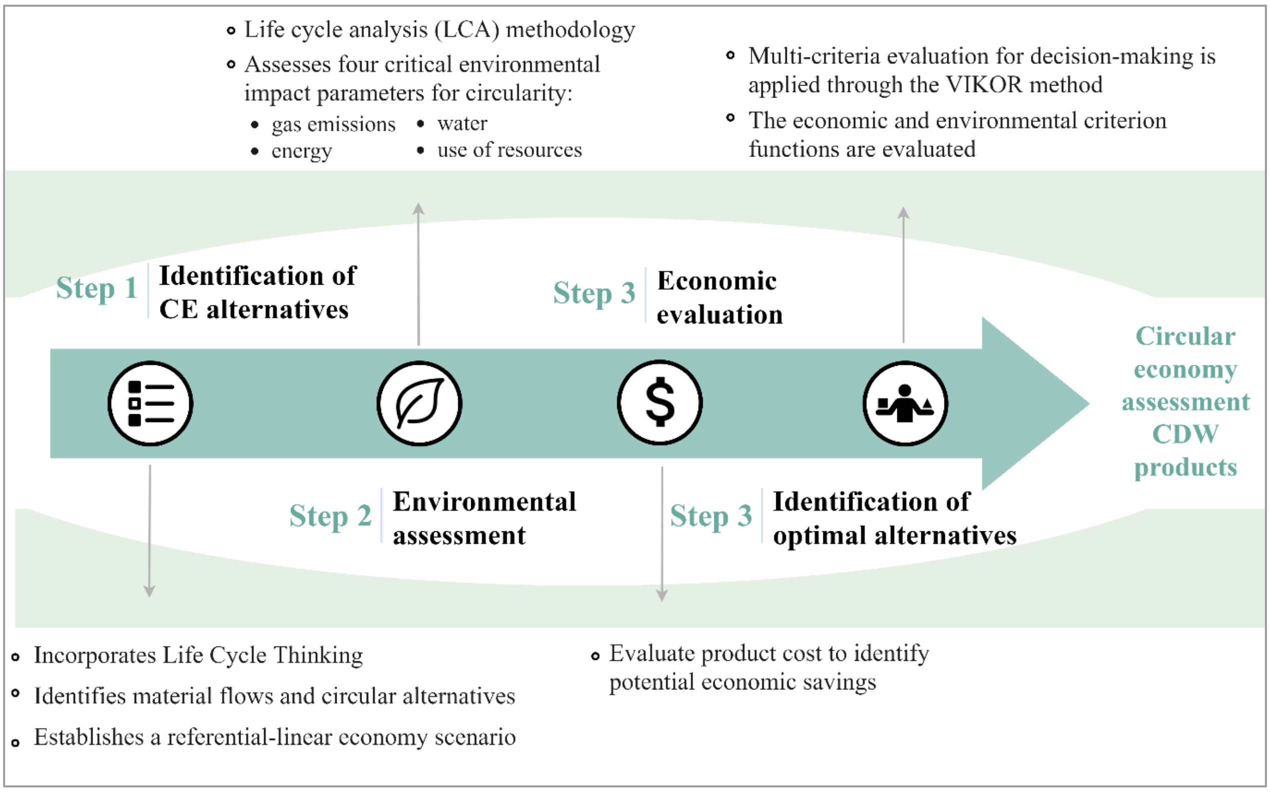


Figure 4- Proposed methodology to assess circular economy alternatives for CDW products

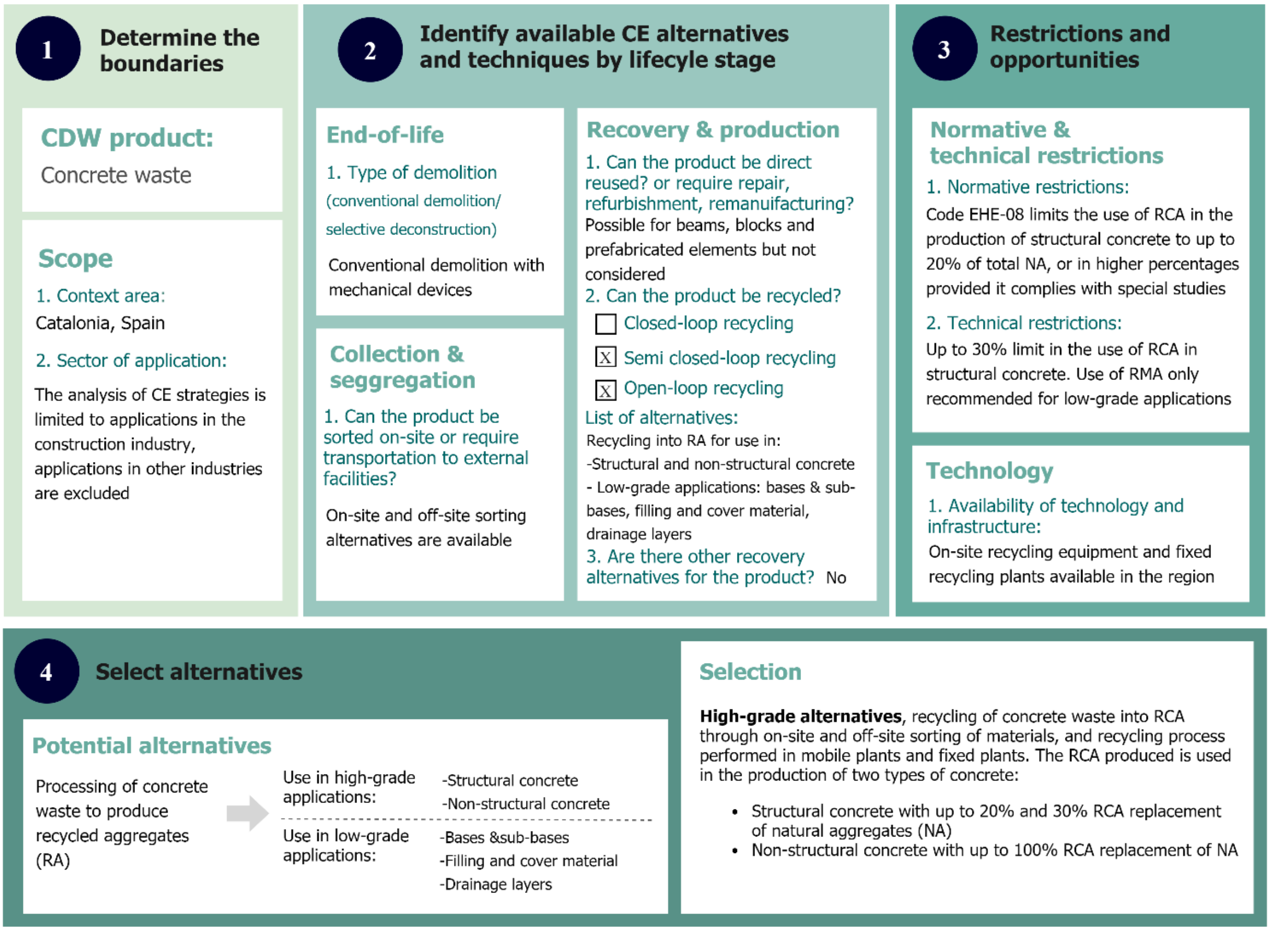
4.2.1 Identification and definition of CE alternatives to evaluate

4.2.1.1 Identification of circularity alternatives

In this step, a matrix for the identification and definition of potential CE alternatives throughout the lifecycle of CDW products was developed. This matrix is based on the influential aspects and strategies defined in the framework from chapter 3 for the circularity of the CDW sector, in particular for the lifecycle stages of end-of-life, collection and distribution, and material recovery and production. Thus, the matrix is intended to maximize the value of CDW products by identifying the best waste management practices and best alternatives for their recirculation as secondary products in the construction industry.

For practical purposes, this study is focused on concrete waste in the region of Catalonia, Spain. Catalonia is the largest producer of CDW in Spain, accounting for 4.3 million tons in 2018 with a recovery rate of 54.3% of controlled CDW(Catalan Waste Agency, 2018a). This is under the recovery target of 75% of CDW by 2020 (Catalan Waste Agency, 2018b).

The representation of the circularity matrix and its application to concrete waste is presented in **Figure 5**. As a result, three different groups of alternatives were identified: reuse opportunities, recycling into high-grade applications and downcycling into low-grade applications. For practical purposes, the alternatives selected to be evaluated correspond to high-grade applications: processing of concrete waste into recycled concrete aggregates (RCA) to produce structural and non-structural concrete.



1 Determine the boundaries

CDW product:
Concrete waste

Scope
1. Context area:
Catalonia, Spain
2. Sector of application:
The analysis of CE strategies is limited to applications in the construction industry, applications in other industries are excluded

2 Identify available CE alternatives and techniques by lifecycle stage

End-of-life
1. Type of demolition (conventional demolition/ selective deconstruction)
Conventional demolition with mechanical devices

Collection & seggregation
1. Can the product be sorted on-site or require transportation to external facilities?
On-site and off-site sorting alternatives are available

Recovery & production
1. Can the product be direct reused? or require repair, refurbishment, remanuifacturing?
Possible for beams, blocks and prefabricated elements but not considered
2. Can the product be recycled?
☐ Closed-loop recycling
☒ Semi closed-loop recycling
☒ Open-loop recycling
List of alternatives:
Recycling into RA for use in:
-Structural and non-structural concrete
- Low-grade applications: bases & sub-bases, filling and cover material, drainage layers
3. Are there other recovery alternatives for the product? No

3 Restrictions and opportunities

Normative & technical restrictions
1. Normative restrictions:
Code EHE-08 limits the use of RCA in the production of structural concrete to up to 20% of total NA, or in higher percentages provided it complies with special studies
2. Technical restrictions:
Up to 30% limit in the use of RCA in structural concrete. Use of RMA only recommended for low-grade applications

Technology
1. Availability of technology and infrastructure:
On-site recycling equipment and fixed recycling plants available in the region

4 Select alternatives

Potential alternatives

Processing of concrete waste to produce recycled aggregates (RA)	Use in high-grade applications:	-Structural concrete -Non-structural concrete
	Use in low-grade applications:	-Bases &sub-bases -Filling and cover material -Drainage layers

Selection

High-grade alternatives, recycling of concrete waste into RCA through on-site and off-site sorting of materials, and recycling process performed in mobile plants and fixed plants. The RCA produced is used in the production of two types of concrete:

- Structural concrete with up to 20% and 30% RCA replacement of natural aggregates (NA)
- Non-structural concrete with up to 100% RCA replacement of NA

Notes: RA, recycled aggregates; RCA, recycled concrete aggregates; RMA, recycled mixed aggregates

Figure 5. Matrix for defining circularity alternatives for CDW products – Application to concrete waste

For structural concrete, an alternative of 20% substitution of natural coarse aggregates with RCA was defined according to results from studies analyzing recycled concrete characteristics (Batayneh et al., 2007; Marie and Quiasrawi, 2012; Zhou and Chen, 2017), and following the recommendation of the Spanish Code on structural concrete EHE-08 about limiting the content of RCA up to 20% by weight out of the total coarse aggregate. With this replacement limit, the mechanical properties and durability of recycled concrete are similar to that of conventional concrete. In addition, a 30% RCA content alternative was considered based on the studies from Abd Elhakam et al. (2012), Parekh and Modhera (2011), Xiao et al. (2012a), Xiao et al.

(2012b) and Zhou and Chen (2017). According to these authors, when the RCA replacement is up to 30%, the reduction in compressive strength is not significant. Moreover, this higher percentage is also allowed by the EHE-08, provided it complies with special studies and complementary experiments for this application. For non-structural concrete, 100% use of RCA was considered, as it is allowed by the EHE-08.

Reuse alternatives for concrete waste during the recovery and production stage are not included in the selection of alternatives to evaluate due to their current limited application (Gálvez-Martos et al., 2018; Zhang et al., 2020), difficulties to separate concrete elements and technical/dimensional restrictions for their use in new buildings (Zhang et al., 2020).

The graphical representation of circular material flows for concrete waste is presented in **Figure 6**. Additional details and technical specifications derived from the analysis of the lifecycle phases and related strategies for constructing the matrix and circularity flows are provided in **Appendix A, section I.**

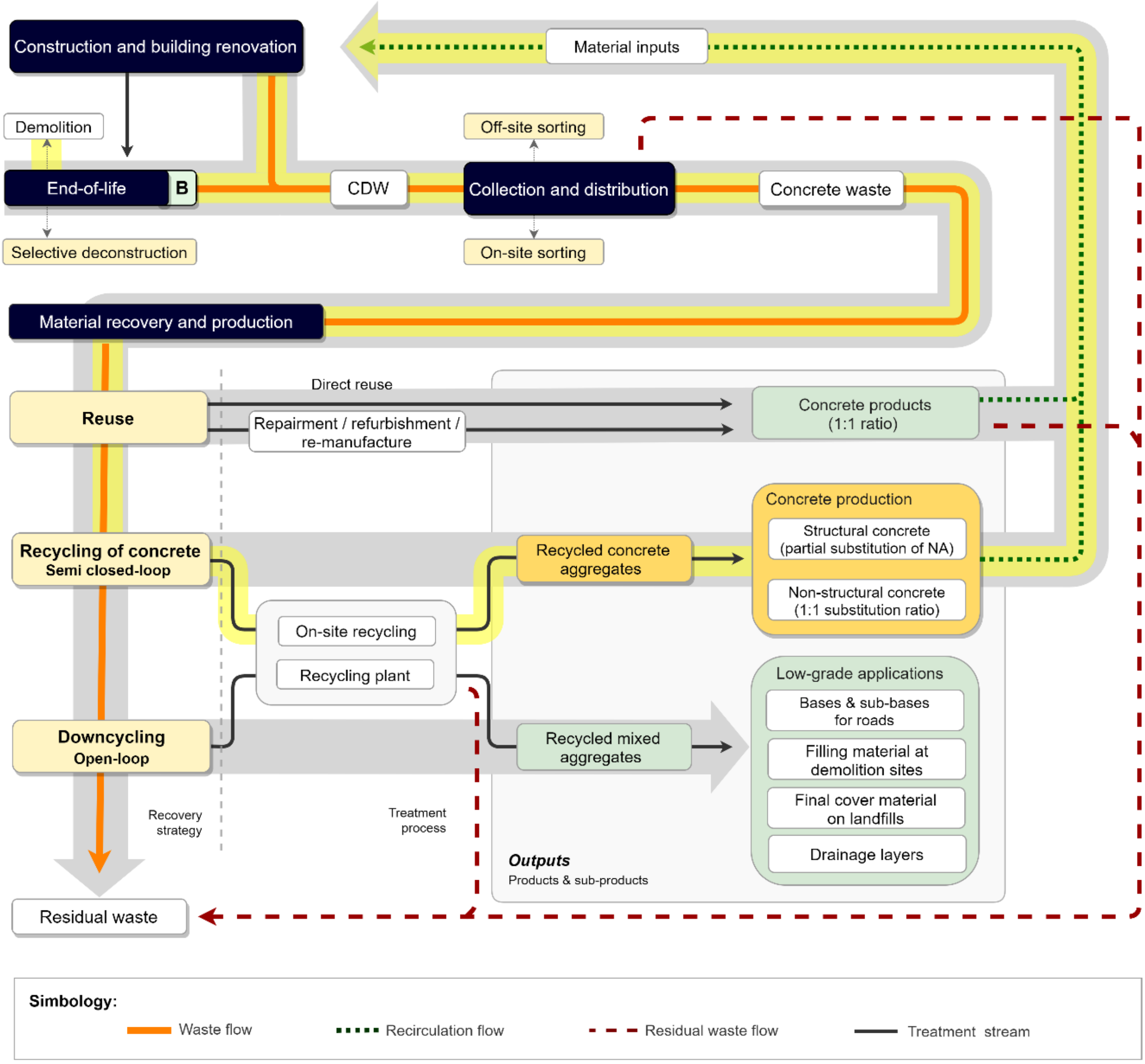
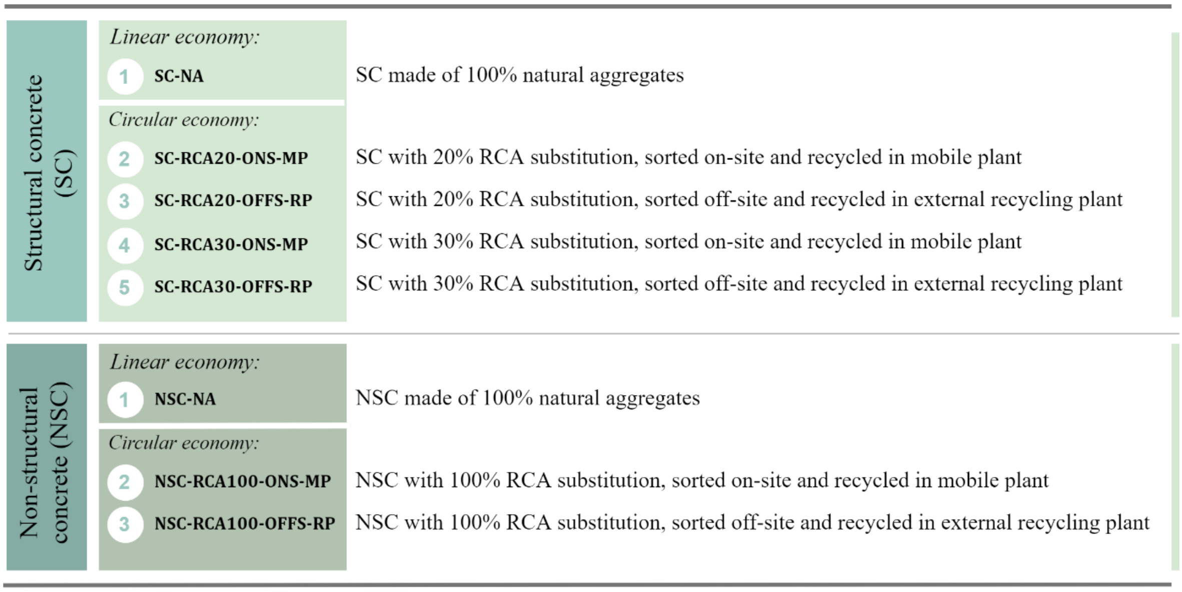


Figure 6. Circularity material flow of alternatives for concrete waste

4.2.1.2 Definition of alternatives to evaluate: description and system boundaries

Four circular alternatives for structural concrete (SC) and two for non-structural concrete (NSC) were defined based on the different substitution ratios of natural coarse aggregates (NCA) with RCA (20%, 30% and 100%), and the type of segregation and recycling (on-site or off-site). A linear economy alternative was included for both SC and NSC to provide a referential basis for comparison. Thus, this study considers the evaluation of five alternatives for structural concrete and three for non-structural concrete (**Figure 7**).

For structural concrete, compressive strength classe C30/37 was used in compliance with the limit of 40 MPa for structural concrete made with RCA and specified in the Code EHE-08. For non-structural concrete, compressive strength of 16 MPa (C16/20) was considered. Mix proportions for both SC and NSC alternatives are presented in **Appendix A, section I.**



Structural concrete (SC)	*Linear economy:*		
	1	**SC-NA**	SC made of 100% natural aggregates
	Circular economy:		
	2	**SC-RCA20-ONS-MP**	SC with 20% RCA substitution, sorted on-site and recycled in mobile plant
	3	**SC-RCA20-OFFS-RP**	SC with 20% RCA substitution, sorted off-site and recycled in external recycling plant
	4	**SC-RCA30-ONS-MP**	SC with 30% RCA substitution, sorted on-site and recycled in mobile plant
	5	**SC-RCA30-OFFS-RP**	SC with 30% RCA substitution, sorted off-site and recycled in external recycling plant
Non-structural concrete (NSC)	*Linear economy:*		
	1	**NSC-NA**	NSC made of 100% natural aggregates
	Circular economy:		
	2	**NSC-RCA100-ONS-MP**	NSC with 100% RCA substitution, sorted on-site and recycled in mobile plant
	3	**NSC-RCA100-OFFS-RP**	NSC with 100% RCA substitution, sorted off-site and recycled in external recycling plant

Figure 7. Definition of alternatives to be evaluated

Linear economy alternatives (**Figure 8**): **SC-NA** and **NSC-NA** represent the primary production of conventional concrete using virgin materials. At the end-of-life, it has been considered the application of complete demolition of concrete elements. The resultant concrete waste was assumed to be disposed of in landfills without any segregation or recovery practice. The construction/renovation stage and use stage are not considered.

Circular economy alternatives (**Figure 9**, **Figure 10**): **SC-RCA20-ONS-MP**, **SC-RCA30-ONS-MP** and **NSC-RCA100-ONS-MP** consider that after demolition/selective deconstruction, the resultant waste is segregated in the demolition/construction site and then recycled using a mobile plant to produce RCA. It was assumed that if on-site sorting is implemented, then site conditions may be adequate to perform on-site recycling. For the alternatives, **SC-RCA20-OFFS-RP**, **SC-RCA30-OFFS-RP** and **NSC-RCA100-OFFS-RP**, the waste produced is transported to external facilities for its segregation and recycling. The RCA produced is used as a partial and full substitute of NA (in the percentages indicated for each scenario) in the production of new concrete mixes. Based on the study by Marie and Quiasrawi (2012), it was considered that 60% of concrete waste can be transformed into coarse recycled aggregates and the remaining is disposed of in landfills and not used for other applications. In addition, the alternatives for SC consider the production of NA, as the use of RCA is limited by technical regulations.

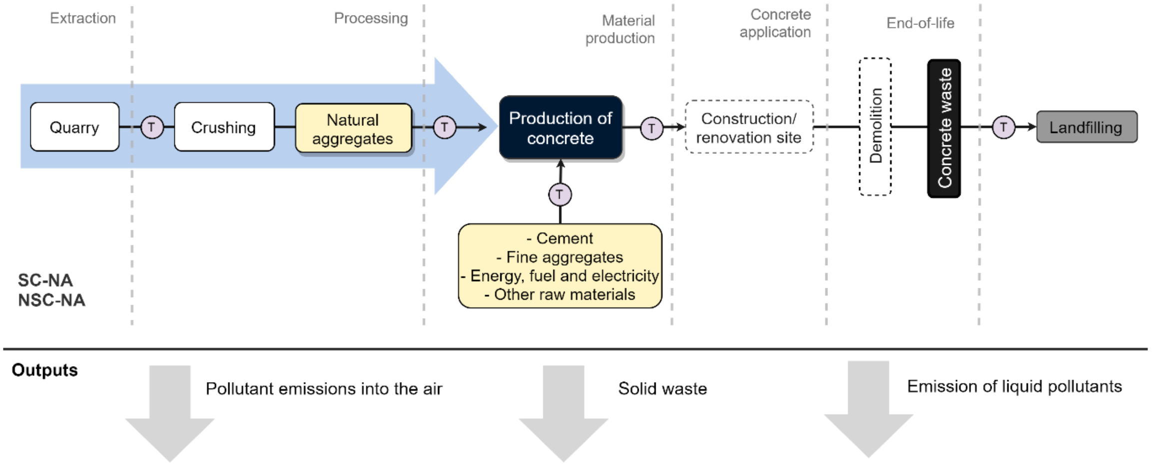


Figure 9. System boundaries for structural and non-structural concrete alternatives – linear economy (SC-NA; NSC-NA)

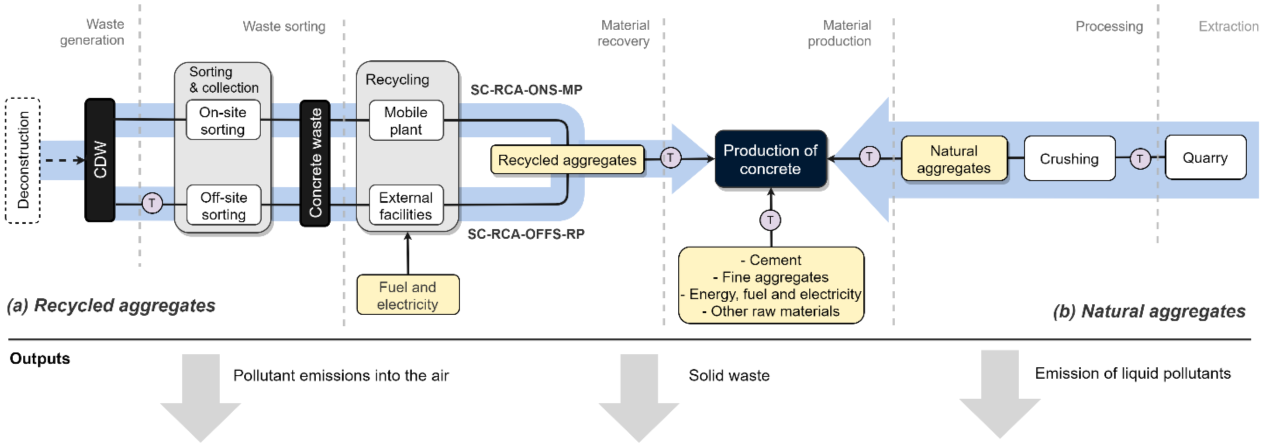


Figure 8. System boundaries for structural concrete alternatives using RCA – circular economy (SC-RCA20-ONS-MP, SC-RCA20-OFFS-RP, SC-RCA30-ONS-MP, and SC-RCA30-OFFS-RP)

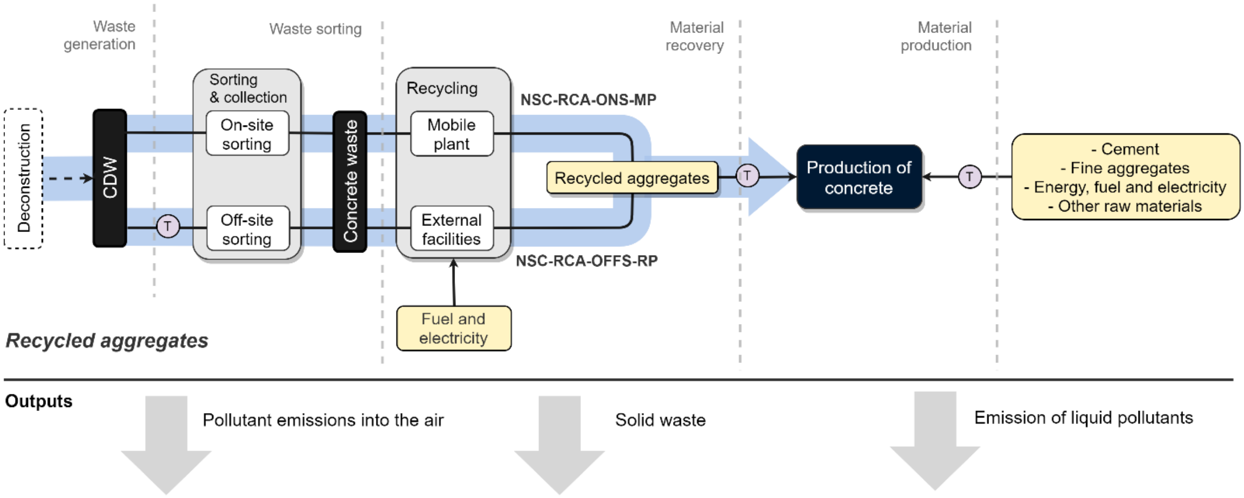


Figure 10. System boundaries for non-structural concrete alternatives using RCA – circular economy (NSC-RCA100-ONS-MP and NSC-RCA100-OFFS-RP)

4.2.2 Environmental evaluation: life cycle assessment (LCA)

LCA methodology was used to evaluate the environmental criteria in this study. LCA is considered one of the best tools to assess the environmental performance of buildings (Geng et al., 2017a), CDW management systems, recovered products (Butera et al., 2015; Rosado et al., 2019; Suárez Silgado et al., 2018), and also can be extended to other CE strategies or research (Pomponi and Moncaster, 2017).

LCA methodology in this study follows the guidelines of ISO 14040 and ISO 14044 standards (ISO, 2006a, 2006b) consisting of four steps: goal and scope definition, inventory analysis, impact assessment and interpretation. The interpretation of the results is presented in **section 4.3**.

4.2.2.1 Goal and scope definition

The LCA study aims to assess and compare the environmental impacts of using recovered concrete waste in the production of structural and non-structural concrete from a circular economy perspective, and the production of conventional concrete. The functional unit is 1 m3 of conventional concrete and recycled concrete. This functional unit is consistent with that of similar studies (Braga et al., 2017; Colangelo et al., 2020, 2018; T. Ding et al., 2016; Lockrey et al., 2018). The considered study area is the region of Catalonia, Spain.

The scope includes RCA production; extraction, processing, and supply of required materials; energy and fuels required for considered processes; transportation; and waste disposal. No impacts from parent concrete are allocated to RCA. For circular economy alternatives, two waste sorting processes (on-site and off-site) and two types of recycling plants (mobile plant and fixed plant) are included. Recycling consists of the mechanical treatment “Compression & Impact Process”. The required processes to perform demolition, segregation and recycling activities are listed in **Table 5**. The considered alternatives and corresponding system boundaries are described in **section 4.2.1.2**.

4.2.2.2 Life cycle inventory

The inventory data were collected from public referential data of Spanish and Catalan associations such as the Spanish Confederation of Associations of Construction Products Manufacturers (CEPCO), the Spanish Association of Ready-mix Concrete Manufacturers (ANEFHOP), and other related organizations cited in the specific processes of this inventory description. Moreover, LCA and technical studies involving relevant input and output data on the production of structural and non-structural concrete, natural aggregates, recycled concrete aggregates, transportation, and final disposal were analyzed and included. As well as data from the Ecoinvent V3 database adapted to the Spanish context.

The data from López Gayarre et al. (2016) regarding the manufacturing of natural and recycled aggregates were used as they correspond to real case conditions of production facilities in Spain. Specific data is provided on consumptions and specifications of the machinery and installations involved in the processes of recycling, as well as for extracting and processing natural aggregates. The electricity inventory is based on the Spanish electric mix (REE, 2020).

RCA production

Specifications and energetic consumption data of machinery used to produce RCA in both mobile plants and fixed plants are based on López Gayarre et al. (2016) and summarized by process (demolition, segregation and recycling) in **Table 5**.

The use and maintenance of the sorting/ recycling facility, conveyor belts and mobile machinery, as well as the water employed in the processes and the final disposal of residual waste in landfills, were based on data from Ecoinvent V3. For fixed plants, recycling plant type II was considered as it has a production line specifically for concrete waste (Mercante et al., 2012). The transport distance from the demolition/construction site to the fixed recycling plant was 18 km. For mobile plants, roundtrip transportation of machinery is required. The distance from the rental company to the demolition site is estimated at 18 km.

Table 5. Specifications on activities and energetic consumption for RCA production in fixed and mobile plants

Process	Mobile plant		Fixed plant	
	Activities	**Consumption**	**Activities**	**Consumption**
Demolition	Building demolition (hydraulic excavator CAT 325D UHD)	0.4 l diesel/t	Building demolition (hydraulic excavator CAT 325D UHD)	0.4 l diesel/t
	Preparation of waste (hydraulic excavator. CAT 318D)	0.394 l diesel/t	Loading of the truck with CDW for transportation to a recycling plant (hydraulic excavator. CAT 325D)	0.356 l diesel/t
Recycling process	Load of the feed hopper (hydraulic excavator. CAT 325D)	0.355 l diesel/t	Preparation of waste (hydraulic excavator. CAT 318D)	0.395 l diesel/t
	Screening (mobile screening plant power screen Warrior 1400)	0.14 l diesel/t	Load of the feed hopper (wheel loader. CAT 928G)	0.317 l diesel/t
	Crushing (mobile jaw crusher - power screen Pegson XA400S)	0.22 l diesel/t	Screening and crushing in recycling plant type II (dry)	8.602 MJ/t
			Additional electricity consumption for the use of offices and workshops*	1.02 kWh/t
Load for transportation	Load of the truck with RCA for transportation to concrete plant (wheel loader CAT 928G)	0.237 l diesel/t	Load of the truck with RCA for transportation to concrete plant (wheel loader. CAT 928G)	0.238 l diesel/t

(*) Additional electricity consumption from Suárez Silgado et al. (2018).

Concrete production

The inventory of natural coarse and fine aggregates production has been developed based on adaptations of processes and data from Ecoinvent V3, covering extraction and supply of raw materials, quarry operation, processing, internal transports, infrastructure, energy, maintenance, and treatment of the derivative waste an oil. To produce coarse aggregates, the fuel consumption of machinery for works at the quarry corresponds to 0.345 l diesel/t, and electric consumption at the production plant to 9.396 MJ/t (López Gayarre et al., 2016). Production plant capacity for both coarse and fine aggregates was assumed of 400,000 t and had a 50-year lifespan. Transport from the aggregate production plant to the concrete mixing plant was estimated at 36 km, and 80 km to the municipal landfill for the solid waste derived from the processes.

Data on raw materials (cement and water), infrastructure, and energy and fuel consumption for concrete production were obtained from Ecoinvent V3. Transport of solid waste derived from the production process was estimated at 84 km to the municipal landfill and 64 km to the inert landfill.

Additional processes

End-of-life concrete was assumed to be performed through demolition with mechanical devices. The consumption of fuel in the demolition works is 0.4 l diesel/t, and 0.356 l diesel/t for the load of the truck with CDW for transportation to the disposal site. Data on the use and maintenance of the machinery were based on Ecoinvent V3.

Disposal of demolished concrete was assumed to be 100% for linear economy alternatives. Burdens from inert landfilling were obtained from the Ecoinvent database and comprise infrastructure, maintenance, and energy used for operation. The distance from the demolition site to the inert landfill was estimated at 60 km.

Transport

The source of waste for the scenarios analyzed in this study (construction/demolition site) was assumed to be located northwest of Barcelona with geographical coordinates 41.3891492, 2.1148339 (latitude, longitude). Average transport distances used in related studies have been used as a reference to delimit the area of analysis based on two key installations: the construction/demolition site and the concrete mix plant. Based on these referential distances, a series of geographical radios were defined and then used to identify the number of available facilities in these areas in Catalonia. The mapping of facilities has been developed with data from regional entities of Catalonia. Final transport scenarios and specifications on additional criteria are listed in **Table 6.**

The vehicle "lorry 16-32 metric ton – EURO 6 was considered for transporting input materials to the concrete mix plant, and for transporting waste to treatment facilities or final disposal sites. A lorry >32 metric ton – EURO 6 was used to transporting the equipment required to perform on-site sorting and recycling.

Table 6. Transport scenarios

Origin	Destination	Radio - referential distances (km)	Number of facilities in Catalonia	Number of facilities in the defined radio	Distance of study (km)[1]	Source
Construction/ demolition site	Concrete mix plant	10[b]	110	14	**10**	Spanish Association of Ready-mix Concrete Manufacturers (ANEFHOP, 2020)
	Recycling plant	-	-	-	**18**[5]	Catalan Waste Agency (ARC)
	Inert landfill	-	55	-	**60**[6]	
	Municipal landfill	-	23	-	**77**[6]	
Recycling plant	Concrete mix plant	30[a]	72	2[4]	**13**	Catalan Waste Agency (ARC)
	Inert landfill	-	55	-	**60**[6]	
	Municipal landfill	-	23	-	**90**[6]	
Cement factory	Concrete mi plant	75[a]	3[2]	3	**38**	Spanish Cement Association (OFICEMEN, 2017); Catalan Cement Association (Ciment Català, 2020)
	Municipal landfill	-	23	-	**90**[7]	Catalan Waste Agency (ARC)
Natural coarse and fine aggregates factory	Concrete mix plant	40[a]	66	15[3]	**36**	Catalan Aggregates' Guild (GREMIARIDS, 2020)
	Municipal landfill	-	23	-	**80**[7]	Catalan Waste Agency (ARC)
Concrete mix plant	Inert landfill	17[c]	55	0	**64**[6]	Catalan Waste Agency (ARC)
	Municipal landfill	21[c]	23	0	**84**[6]	

a (Oliver-Solà et al., 2009)

b (Marinković et al., 2010)

c (Suárez Silgado et al., 2018)

Notes:

(1) Calculation of the average distance of facilities in the referential radio. It considers the additional criteria from the following notes.

(2) A total of 6 cement plants are located in Catalonia, but currently, only 3 produce the cement CEM I 42.5 R considered in the study.

(3) A total of 21 plants are in the radio of 40 km (from the concrete plant), however, only the plants that produce both sand and coarse aggregates were considered (15).

(4) A total of 23 plants are located in Barcelona, however, to simplify the scenarios we considered the plants that provide the service of sorting and recycling waste in the same facility (2 plants).

(5) Average distance to the two recycling facilities specified in note 4.

(6) Non-availability of facilities in the referential radio. The distance was calculated from the total available facilities for performing the corresponding disposal of waste.

(7) Consists of the disposal of residual waste derived from the production process. The average distance was calculated considering the facilities previously identified (cement plants and natural aggregates plants) and the corresponding distances to the available municipal landfills in the region.

4.2.2.3 Life cycle impact assessment

The Life Cycle Impact Assessment (LCIA) was conducted using the mid-point (problem-oriented) approach. This measurement provides a more complete picture and analysis of results, in contrast to the complexity and lack of transparency of the end-point approach (Chau et al., 2015; Lockrey et al., 2018).

The impact categories used in this study encompass the four main aspects for evaluating the environmental performance of circular economy strategies: gas emissions, energy, water, and use of resources (Bilal et al., 2020; EMF and GRANTA, 2015). The selection of the corresponding impact categories was based on their use frequency in related scientific studies (listed in **Appendix A, section II**) and their appropriateness in the assessment of the environmental performance of buildings, construction products and CDW management in a CE perspective. Moreover, the selection included the impact categories recommended by the Level(s) framework for assessing the environmental performance of buildings.

Table 7 lists the impact categories considered in this study grouped by the CE assessment aspect and the methods used to perform the LCIA. Specifications on the selection of impact methods are provided in **Appendix A, section II**. All calculations have been performed with the support of SimaPro software.

Table 7. Impact categories used in the study

CE aspect	CE category description	Impact category	Abb.	Unit	Method
Gas Emissions	Measures the negative effects on the atmosphere and stratosphere due to anthropogenic emissions.	Global warming	GWP	kg CO2-eq	CML-IA baseline
		Ozone layer depletion	ODP	kg CFC-11-eq	CML-IA baseline
		Photochemical oxidation	POP	kg C2H4-eq	CML-IA baseline
Energy	Quantifies direct and indirect energy consumption from both renewable and non-renewable resources	Cumulated energy demand	CED	MJ	Cumulative Energy Demand
Water	Assess water consumption and damage to the quality of aquatic ecosystems	Water use	W	m^3	AWARE
		Eutrophication	EP	kg PO4-eq	CML-IA baseline
		Acidification	AP	kg SO2-eq	CML-IA baseline
Use of resources	Assess the decrease of non-biological resources as a measure of the scarcity of fossil fuels, minerals, metals, etc.	Depletion of abiotic resources (elements, ultimate reserves)	ADP_E	kg Sb-eq	CML-IA baseline
		Depletion of abiotic resources (fossil fuels)	ADP_F	MJ	CML-IA baseline

4.2.3 Economic evaluation

The methodology to calculate the economic criteria is based on the necessary data for producing 1 m^3 of SC and NSC for the different alternatives presented in the system boundaries defined in **section 4.2.1.2**and considers the parameters used in the LCA for transport distances and equipment. This economic evaluation comprises a detailed analysis of the following elements: inputs to produce the concrete mixes; demolition of structures and CDW segregation activities; recycling process (transport to fixed plants, rental of equipment, material processing, waste management and transportation of residual waste); final disposal fees and taxation on recycling plants, and; the manufacturing of recycled concrete.

Equations used to perform the economic evaluation are presented in **Table 8**. The calculation method used to estimate the recycling cost in both on-site and off-site alternatives was adapted from Jung et al. (2015). The inventory data for the multiple processes and materials were obtained from the BEDEC 2020 database (ITeC, 2020) containing current economic data on products and activities regarding the construction sector for the region of Catalonia, Spain. The cost analysis developed in this study considers 10% indirect costs, 13% overhead costs and 6% company profit according to the ranges established by BEDEC for the zone of study.

Table 8. Calculation method to estimate the cost of alternatives

Concept	Equation	Variables
Cost of producing the concrete mixes ***(PC)***	$PC = C_{MAT} + C_{RCA\,(1,2)} + C_{CM}$	PC= total concrete production cost (€/m^3) C_{MAT}= cost of input materials (€/m^3) = Supply cost ***(Sc)*** + Cost of transportation ***(T$_C$)*** C_{CM}= cost of manufacturing concrete mixes (€/m^3)
Cost of RCA produced by on-site recycling ***(C$_{RCA1}$)***	$C_{RCA1} = C_E + R_{EM}$	C_E= cost of equipment and machinery required to move, crush, sieving and load of materials (€/m^3) R_{EM}= cost of renting the equipment and machinery (€/m^3)
Cost of RCA produced by off-site recycling ***(C$_{RCA2}$)***	$C_{RCA2} = R_{FP} + T_c$	R_{FP}= cost of recycling in fixed plants (€/m^3) T_c = cost of transportation (€/m^3)
Cost of the additional processes required to perform the linear and CE alternatives ***(SC$_{AP}$)***	$SC_{AP} = D_C + S_C\, C_{PR} + C_{TM} + C_{DR}$	D_C= demolition cost (€/m^3) S_C= cost of CDW segregation (only for on-site recycling alternatives) (€/m^3) T_c= Cost of transportation (waste from the construction/demolition site to fixed plants, RCA produced on-site to concrete mixing plant, internal transport for on-site recycling) (€/m^3) W= Cost of waste disposal (residual waste disposed of in inert and municipal landfills

4.2.4 Multi-criteria evaluation

The multicriteria evaluation was performed using the VIKOR method. This methodology was used as a decision-making tool to determine the best option among circular economy solutions and linear economy alternatives in terms of their economic and environmental performance. Multicriteria evaluation was performed separately for structural concrete and non-structural concrete alternatives.

The methodological steps of the VIKOR method and the specific criteria used for this study is widely detailed in **Appendix A**, **section III**.

4.3 Results and discussion

4.3.1 Alternatives for structural concrete

The impact assessment results for each scenario considered in the production of SC are listed by impact category in **Table 9** and shown in terms of relative values in **Figure 11**.

From the results for SC, it can be noticed that under the adopted system boundaries and inventories, the alternatives based on the use of RCA have lower environmental effects than conventional SC-NA in all the categories (**Figure 11**). The environmental advantage of the use of RCA over NA for concrete production was also outlined in recent research (Behera et al., 2014; Gálvez-Martos et al., 2018; Ghisellini et al., 2018b; Suárez Silgado et al., 2018). In general, alternatives based on the use of RCA provide environmental benefits from 6% to 28% among impact categories compared to conventional SC-NA, but for ODP and ADP_F this benefit is significantly higher, ranging from 28% to 35% and 24% to 30% respectively in comparison to CE alternatives. That is because of the influence of the final disposal of waste in inert landfills and the consumption of fuel during the corresponding transportation at the end-of-life stage, which represents 34.4% of the total ODP impacts of SC-NA and 29.4% of ADP_F impacts. For the remaining categories of SC-NA, this influence ranges from 8.2% to 26.3% and constitutes the second larger contribution. However, this value is especially low for the water use category, accounting for 1.76% of impacts. Furthermore, when analyzing the concrete production process, it is noticed that fuel consumption of transportation of coarse and fine natural aggregates significantly affects ODP impact category.

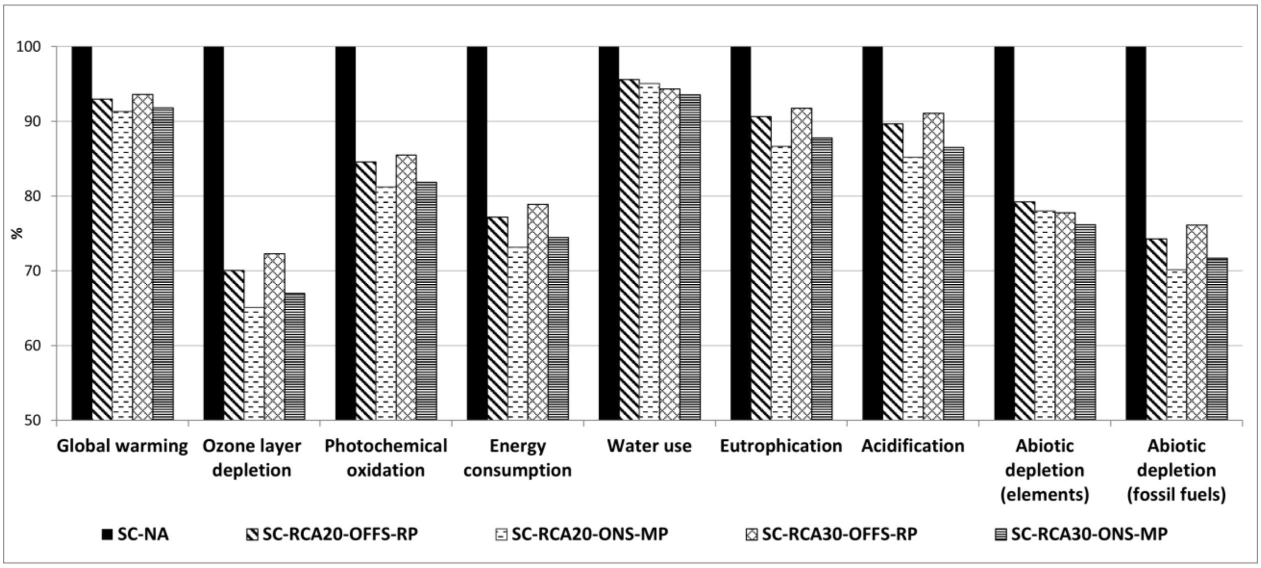


Figure 11. LCA results: contribution of SC alternatives by impact category

As shown in **Figure 11**, SC-RCA20-ONS-MP and SC-RCA30-ONS-MP have the best environmental performance compared to all the alternatives in all the categories. This advantage mainly results from the shorter distances to the concrete mix plant compared to NA and RCA produced in fixed plants and quarries. It is demonstrated when comparing the environmental performance of the production process of RCA using mobile and fixed plants **(Figure 12a**). For all the impact categories, RCA obtained from sorting and recycling on-site have lower environmental effects than RCA produced in external plants: GWP (-14.7%), ODP (-11.5%), POP (-15.5%), CED (-18.5%), W (-55.5%), E (-1%), AP (-5.2%), ADP_E (-29.4%) and ADP_F (-11.9%). As stated above, this better environmental performance is conditioned by transport distances. It was found that without considering transportation (0 km scenario, **Figure 12b**), the impacts from the production process of RCA in mobile plants are slightly higher than fixed plants for all categories except for POP (due to the higher use of fuel during the process), energy consumption (by the higher need of electricity required in fixed plants). Moreover, water use presents the highest variation between fixed and mobile plants, which is mainly attributed to its usage in the production of electricity for operating the recycling plant. The general better environmental performance of on-site recycling over recycling in fixed plants has been also shown by various authors (Hossain et al., 2017; Jung et al., 2015; Li et al., 2020; Vossberg et al., 2014).

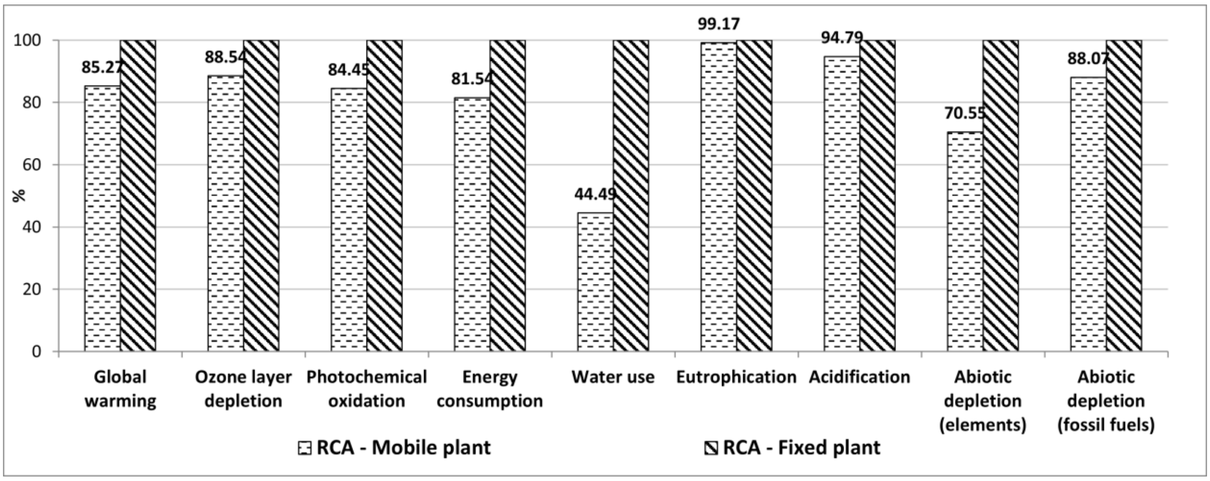
Table 9. Environmental impacts of SC and NSC alternatives

Scenario	**GWP** (kg CO_2-eq)	**ODP** (kg CFC-11-eq)	**POP** (kg C_2H_4-eq)	**CED** (MJ)	**W** (m^3)	**E** (kg PO_4-eq)	**AP** (kg SO_2-eq)	**ADP_E** (kg Sb-eq)	**ADP_F** (MJ)
Structural concrete									
SC-NA *(Linear economy)*	4.09E+02	2.43E-05	4.10E-02	2.85E+03	1.79E+02	2.54E-01	1.01E+00	4.59E-04	2.34E+03
SC-RCA20-OFFS-RP	3.80E+02	1.70E-05	3.47E-02	2.20E+03	1.71E+02	2.31E-01	9.09E-01	3.63E-04	1.74E+03
SC-RCA20-ONS-MP	3.73E+02	1.58E-05	3.33E-02	2.09E+03	1.70E+02	2.20E-01	8.64E-01	3.58E-04	1.64E+03
SC-RCA30-OFFS-RP	3.83E+02	1.75E-05	3.51E-02	2.25E+03	1.69E+02	2.33E-01	9.23E-01	3.57E-04	1.78E+03
SC-RCA30-ONS-MP	3.75E+02	1.63E-05	3.36E-02	2.13E+03	1.68E+02	2.23E-01	8.77E-01	3.50E-04	1.68E+03
Non-structural concrete									
NSC-NA *(L. economy)*	2.83E+02	2.06E-05	3.21E-02	2.30E+03	1.83E+02	1.93E-01	7.65E-01	4.09E-04	1.91E+03
NSC-RCA100-OFFS-RP	2.62E+02	1.52E-05	2.63E-02	1.82E+03	1.69E+02	1.77E-01	7.06E-01	2.51E-04	1.46E+03
NSC-RCA100-ONS-MP	2.53E+02	1.36E-05	2.45E-02	1.65E+03	1.67E+02	1.67E-01	6.58E-01	2.39E-04	1.33E+03

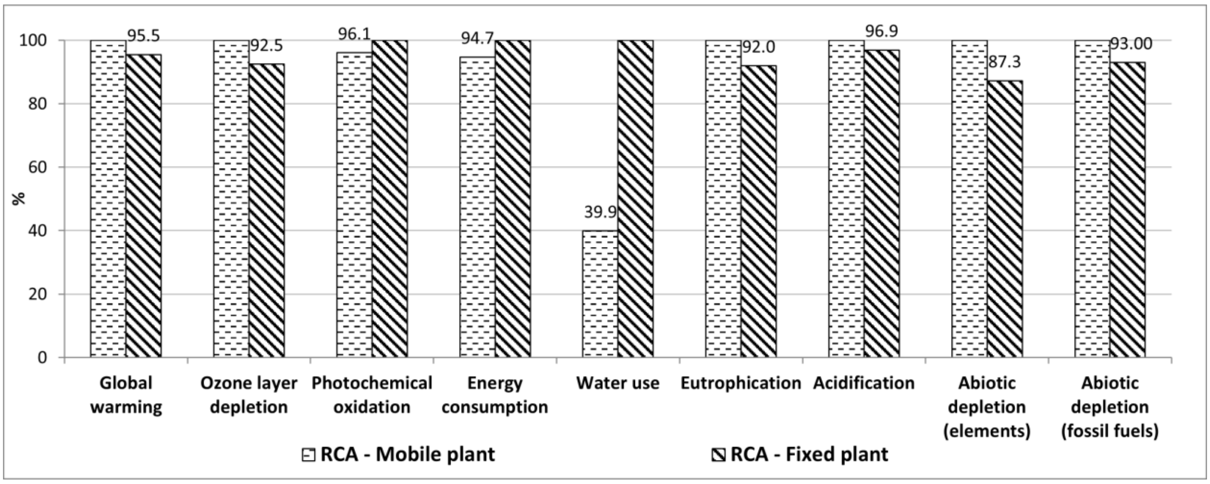
Concerning alternatives with RCA replacement, when analyzing by production stage (concrete manufacturing), the production of recycled aggregates for both mobile and fixed plants has a reduced influence on the total impacts of concrete because of the low rates of RCA used. Furthermore, it is noticed that cement is the largest contributor to all impact categories in both recycled and conventional concrete alternatives, especially for GWP (ranging from 92% to 94% among alternatives) due to the high energy consumption and CO2 emissions derived from the calcination reaction from the cement kiln. These results are consistent with previous studies (T. Ding et al., 2016; Stafford et al., 2016).

Regarding the economic analysis, **Figure 13**a presents a comparison of the total cost of performing the five SC alternatives. While **Table 10** lists the cost of producing SC and the additional cost related to waste management and the corresponding transportation by scenario. It is observed that SC-NA has the highest cost over all the alternatives, mainly due to the influence of landfilling fees and long transport distances. Therefore, CE alternatives based on the use of RCA present the lowest costs, around 22% less compared to SC-NA. However, there is a minor cost variation of 1% to 2% among circularity alternatives.

As stated above, the final disposal of waste and transportation phase at the end-of-life is the most conditioning factor in the total cost of SC alternatives. Moreover, although the cost of RCA is lower than NA, it has limited influence on the production cost of SC because of the reduced substitution of NA.



(a) **Impacts from RCA production by recycling type**

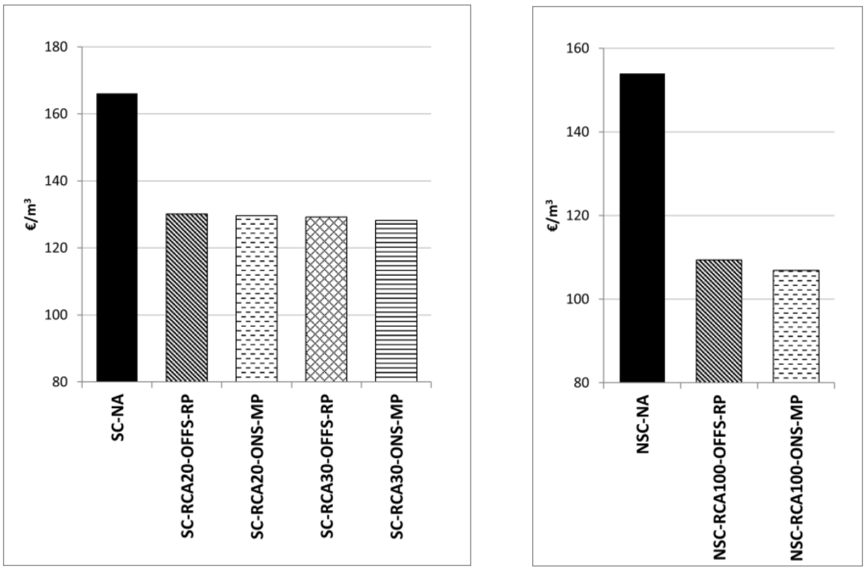


(b) **RCA production by recycling type (0 km scenario)**

Figure 12. Contribution of RCA production processes (on-site & off-site)

Table 10. Economic analysis of SC and NSC alternatives

Scenario	Concrete production cost (€/m³)	Additional costs: waste management and transportation (€/m³)	Total (€/m³)
Structural concrete			
SC-NA *(Linear economy)*	84.64	81.47	166.11
SC-RCA20-OFFS-RP	82.82	47.25	130.07
SC-RCA20-ONS-MP	81.80	47.74	129.54
SC-RCA30-OFFS-RP	81.92	47.25	129.16
SC-RCA30-ONS-MP	80.39	47.74	128.13
Non-structural concrete			
NSC-NA *(Linear economy)*	73.03	80.94	153.97
NSC-RCA100-OFFS-RP	62.46	46.86	109.31
NSC-RCA100-ONS-MP	59.34	47.52	106.87



(a) **Structural concrete** (b) **Non-structural concrete**

Figure 13. Total cost of SC and NSC alternatives (€/m3)

Results of the multicriteria analysis (S, R and Q values and ranking lists) for SC alternatives are given in **Table 11.** For all the three preference criteria the compromise solution consists of the four alternatives with RCA replacement (SC-RCA20-ONS-MP, SC-RCA30-ONS-MP, SC-RCA20-OFFS-RP, and SC-RCA30-OFFS-RP) as condition 1 is not satisfied and the advantage of the best ranked alternative over the remaining RCA-based alternatives is lower than 25% (Solution a: $Q\left(A^{(M)}\right) < 0.25$).

Although the difference among selected solutions is not significant, alternatives based on the use of RCA produced in mobile plants are ranked as the best solutions because of their environmental and economic advantage over the remaining alternatives. In all the cases, conventional SC is identified as the worst option.

Table 11. Ranking list for structural concrete alternatives (S, R and Q values)

	R value	Rank in R	S value	Rank in S	Q value	Rank in Q
Neutral importance (1:1)						
SC-RCA30-ONS-MP	0.01	1	0.01	1	0	1
SC-RCA20-ONS-MP	0.019	2	0.019	2	0.013	2
SC-RCA20-OFFS-RP	0.088	3	0.113	3	0.131	3
SC-RCA30-OFFS-RP	0.103	4	0.117	4	0.148	4
SC-NA100 (linear economy)	0.5	5	1	5	1	5
Environmental preference (2:1)						
SC-RCA20-ONS-MP	0.012	1	0.012	1	0	1
SC-RCA30-ONS-MP	0.014	2	0.014	2	0.002	2
SC-RCA20-OFFS-RP	0.117	3	0.134	3	0.142	3
SC-RCA30-OFFS-RP	0.138	4	0.147	4	0.164	4
SC-NA (linear economy)	0.67	5	1	5	1	5
Economic preference (2:1)						
SC-RCA30-ONS-MP	0.007	1	0.007	1	0	1
SC-RCA20-ONS-MP	0.025	2	0.025	2	0.023	2
SC-RCA20-OFFS-RP	0.058	3	0.092	4	0.081	3
SC-RCA30-OFFS-RP	0.068	4	0.086	3	0.086	4
SC-NA100 (linear economy)	0.67	5	1	5	1	5

4.3.2 Alternatives for non-structural concrete

Results for non-structural concrete present a similar trend to that of structural concrete. Recycled concrete alternatives have lower environmental impacts compared to NSC-NA in all the categories (**Figure 14,Table 9**). For NSC-RCA100-ONS-MP the environmental advantage over NSC-NA ranges from 8.9% to 28.4% among impact categories, but higher for ozone layer depletion (33.7%), abiotic depletion-fossil fuels (30.4%) and abiotic depletion-elements (41.6%). As stated for SC-NA, the ozone layer depletion category is significantly affected by landfilling and transportation at the end-of-life stage of conventional concrete alternatives, while transportation has the most important influence for abiotic depletion-fossil fuels. Concerning abiotic depletion-elements, the greatest environmental benefit of NSC-RCA100-ONS-MP over NSC-NA is due to the avoided extraction of minerals. For NSC-RCA100-OFFS-RP the benefit over conventional concrete varies from 7.7%-38.5% and follows the reasoning to that NSC-RCA100-ONS-MP.

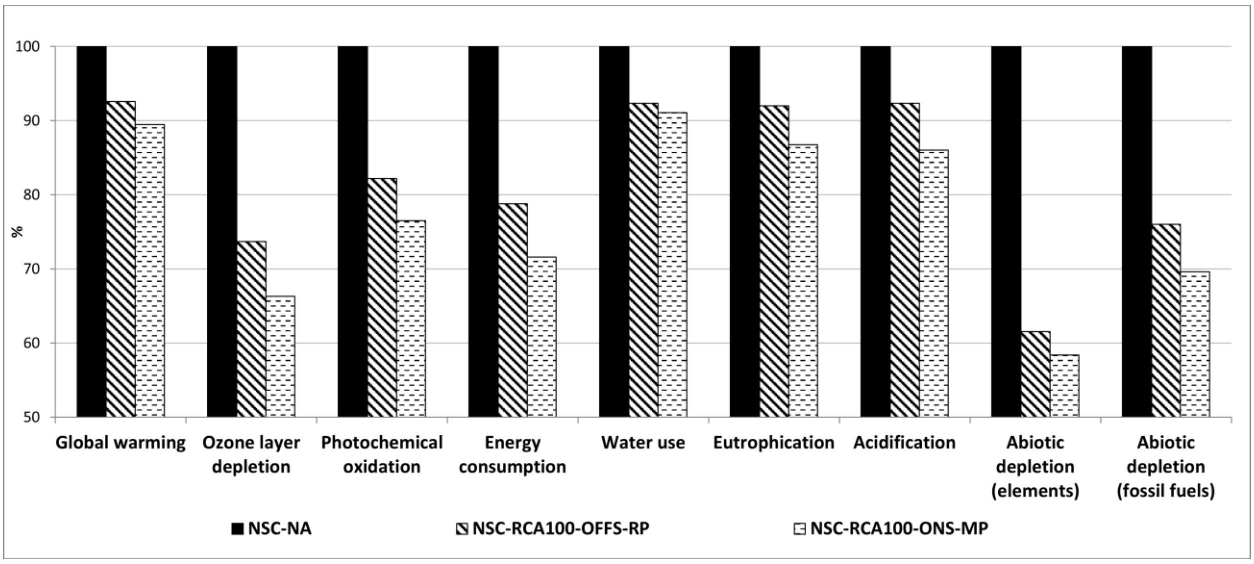


Figure 14. Contribution of NSC alternatives by impact category

Results by lifecycle stage for the NSC-NA alternative show that the production of concrete (material inputs and mixing process) acts as the major contributor to the total life cycle impacts: GWP (84.1%), ODP (49.1%), POP (70.6%), CED (59.5%), W (97.9%), E (73.8%), AP (70.9%), ADP_E (79.3%), ADP_F (55.3%). All these impacts are mainly produced by the use of cement, except for the categories of water use and abiotic depletion of minerals, in which the supply of fine and coarse aggregates has the main contribution, respectively.

The alternative NSC-RCA100-ONS-MP has lower environmental burdens in all the categories. When compared to alternatives using RCA produced in fixed plants (NSC-RCA100-OFFS-RP), the on-site recycling alternative provides better environmental performance with benefits from 1.2% to 7.4% among categories. This is due to the additional transportation required for processing the concrete waste in fixed plants.

Results from the economic analysis are similar to those from SC, in which conventional concrete (NSC-NA) presents the greatest cost, around 30% more compared to RCA-based alternatives (**Figure 13b**). Furthermore, the concrete alternative produced with RCA obtained from mobile recycling plants (NSC-RCA100-ONS-MP) present the best economic performance, although the cost advantage over NSC-RCA100-OFFS-RP is reduced (2%).

When NSC is produced with 100% RCA replacement, the additional costs related to segregation, waste management and transportation reach 44% of the total cost, and concrete production cost is decreased because of the lower cost of RCA than NA. Contrary to SC, the use of RCA has a significant influence on the concrete production cost, resulting in an economic advantage from 14% to 19% over NSC-NA.

Multicriteria analysis for NSC is presented in **Table 12**. Alternatives NSC-RCA100-ONS-MP and NSC-RCA100-OFFS-RP are identified as the final alternatives for all ranking criteria as condition 1 is not satisfied and their Q value is no greater than 0.5 as established in solution "a" ($Q\left(A^{(M)}\right) < 0.5$). Therefore, conventional concrete (NSC-NA) represents the less preferable option in all the three criteria. Lastly, like results for SC, concrete produced with RCA from mobile plants is the best-ranked alternative.

Table 12. Ranking list for non-structural concrete alternatives (S, R and Q values)

	R value	Rank in R	S value	Rank in S	Q value	Rank in Q
Neutral importance (1:1)						
NSC-RCA100-ONS-MP	0	1	0	1	0	1
NSC-RCA100-OFFS-RP	0.125	2	0.151	2	0.2	2
NSC-NA100 (Linear economy)	0.5	3	1	3	1	3
Environmental preference (2:1)						
NSC-RCA100-ONS-MP	0	1	0	1	0	1
NSC-RCA100-OFFS-RP	0.168	2	0.185	2	0.217	2
NSC-NA100 (linear economy)	0.67	3	1	3	1	3
Economic preference (2:1)						
NSC-RCA100-ONS-MP	0	1	0	1	0	1
NSC-RCA100-OFFS-RP	0.082	2	0.117	2	0.12	2
NSC-NA (linear economy)	0.67	3	1	3	1	3

4.4 Conclusions

This study proposed a set of methodological steps to identify circularity alternatives for CDW products and to assess their environmental and economic performance for supporting the decision-making process through multicriteria analysis. This study was particularly focused on the application to concrete waste. For this purpose, a circularity matrix and mapping of circular material flows were developed integrating the life cycle thinking perspective and the key influential factors for circularity of CDW. The analysis was particularly performed in terms of waste recovery for producing secondary construction products. Recovery of concrete is identified to happen throughout three main strategies: reuse of prefabricated components, recycling of concrete and downcycling. Recycling of concrete is identified as the most suitable alternative from a CE perspective, as concrete can be reintroduced multiple times in the material cycle in the form of RCA for its use in high-grade applications, particularly in the production of new structural and non-structural concrete. In this case, the type of sorting and recycling (on-site or off-site) is an influential factor when recovering the material.

A real case scenario was analyzed considering its specific site conditions to perform the evaluations and corresponded to the city of Barcelona in the region of Catalonia, Spain. Two high-grade applications were analyzed considering the availability of technology and infrastructure, as well as current technical regulations in Spain: the use of RCA in the production of structural concrete and non-structural concrete.

Five alternatives were considered for SC and three for NSC depending on the recycling type and replacement percentage of NA (structural concrete with 20% and 30% RCA replacement, and non-structural concrete with 100% RCA replacement. Each with two recycling options. For structural concrete, RCA replacement is limited to up to 20% by Spanish regulations. An additional scenario representing the current linear economy model was included to compare and to identify the potential benefits of CE alternatives. The LCA method was used to evaluate the environmental dimension comprising nine impact categories associated with the four key environmental aspects of the CE (gas emissions, energy, water, and use of resources). A cost analysis was carried out to determine the total cost of performing the selected alternatives. Finally, the VIKOR method was used to determine the best, preferable alternatives based on three different ranking criteria (neutral, environmental, and economic preference).

The proposed methodology provides comprehensive examination of processes and circularity parameters in the entire lifecycle of CDW products, allowing to obtain solid, precise estimations of the environmental and economic performance of different circularity alternatives. In addition, the application of the proposed methodology can provide a detailed diagnosis for the identification of factors influencing both environmental and economic aspects. This methodology has no geographical restrictions and can be used to evaluate all CDW typologies considering different CE factors and scenarios, and also can be extended to evaluate other materials.

Within the adopted system boundaries and assumptions, alternatives with RCA replacement are preferable over conventional concrete for both structural and non-structural concrete and all the criteria (environmental, economic and multicriteria). Moreover, concrete alternatives based on the use of RCA obtained from on-site sorting and recycling present better economic and environmental performance than off-site alternatives, mainly due to the shorter transportation needs. In this case, the environmental advantage has the greater benefits in water use and ADP_F impact categories. However, when considering a 0 km scenario the environmental burdens of RCA produced in fixed plants are slightly lower than on-site alternatives for all the impact categories except for POP, energy consumption and water use. Thus, transport distances are a conditioning factor for choosing the type of recycling. Regarding the cost analysis, the economic benefits of RCA-based alternatives obtained from mobile plants over fixed plants are not significant.

Concerning conventional concrete alternatives, the environmental burdens for SC-NA are 6% to 28% higher than recycled alternatives but particularly higher for ODP (28% to 35%) due to the influence of landfilling and fuel consumption during the transportation of concrete waste to the final disposal sites and of coarse and fine natural aggregates, and for ADP_F (24% to 30%) particularly due to transportation requirements. For NSC, the advantage of recycled alternatives is like results for SC, however, the greatest environmental benefit corresponds to ADP_E, due to the avoided extraction of minerals, accounting for 41.6% and 38.5% for on-site and off-site recycling, respectively. Regarding the economic analysis, conventional concrete for both SC and NSC presents a higher cost compared to recycled alternatives. The main reason is the influence of landfilling taxation and transport distances. This is more evident for NSC alternatives, in which a 100% RCA replacement results in economic advantages around 30% over conventional NSC-NA.

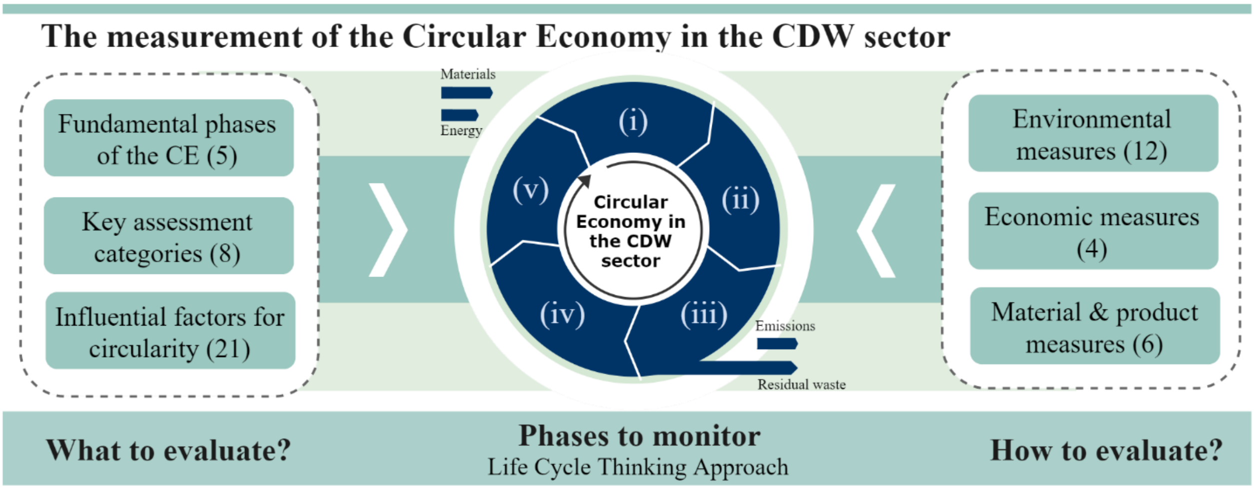
Results from the multicriteria analysis show a clear trend in all the three criteria evaluated (environmental, economic, and neutral preference), which leads to favour CE alternatives based on the use of RCA for both structural and non-structural concrete. Although alternatives containing RCA from on-site sorting and recycling are listed as the best options in all the ranking criteria, the advantage over RCA from fixed plants is not significant according to the criteria established in the VIKOR method.

Finally, it can be concluded that the environmental and economic performance of CE strategies is significantly influenced by the specific site conditions and can vary among regions. Thus, the availability of infrastructure and technology, transportation, and an adequate regulatory framework is conditioning when implementing and selecting CE strategies.

Chapter 5 An indicator framework for monitoring circularity in the construction and demolition waste sector

Abstract

Circular economy (CE) constitutes a solution to the environmental problems of the current linear economy model through the application of new production and consumption patterns. To achieve the successful transition towards this new circular system, it is essential to ensure the adequate monitoring of CE interventions, first and foremost in critical sectors such as the construction and demolition waste (CDW) sector. However, due to the recent developments in the implementation of the CE concept in the industry and policies, the availability of indicators and measuring tools focused on CE basis is still limited. The main objective of this study was to develop an integrative approach to measure circularity performance in the CDW sector. The key factors and parameters influencing the CE performance and its measurement were identified to construct a framework of measures and indicators for evaluating the progress of the CE in the CDW sector. This proposed framework adopted a systematic approach and evaluated the three CE dimensions of environment, economic and innovation/materials. These dimensions are comprised of 22 measures within eight common assessment categories for a comprehensive circularity evaluation.



(i) Preconstruction, (ii) construction & building renovation, (iii) collection & distribution, (iv) end-of-life, (v) material recovery & production

5.1 Introduction

Over the last years, Circular Economy (CE) has become increasingly important and emerged as a solution to series of environmental challenges and limitations of the current linear economic system (Lieder and Rashid, 2016). Environmental problems include climate change, biodiversity loss, water, air and soil pollution, and resource scarcity (Geissdoerfer et al., 2017). CE aims to re-design this traditional linear path "take-make-dispose" (Merli et al., 2018) by moving to more sustainable business and responsible production and consumption patterns (Riba et al., 2020; Tunn et al., 2019) while integrating economic growth with environmental quality and social development (Palafox-Alcantar et al., 2020). In addition, CE is recognized as a relevant option for achieving sustainability in the economic system, and to meet the Sustainable Development Goals (Saidani et al., 2019).

At the global level, various countries are including CE in their agendas, and particularly recognize the construction industry as a priority for immediate mitigation actions for reducing the current environmental issues (Ghaffar et al., 2020), i.e. United Kingdom (Infrastructure and Projects Authority, 2016; WRAP, 2013, 2011), the Netherlands (Government of the Netherlands, 2016), Spain (MAPAMA, 2018), and the European Union (European Commission, 2020c, 2020a, 2018a, 2016, 2014a, 2014b). Moreover, several authors highlighted that the building industry is one of the key sectors with the greatest potential for CE adoption (Akanbi et al., 2019; Brambilla et al., 2019; Nußholz et al., 2020).

The construction sector is characterized by high consumption of resources and energy, the emission of polluting gasses and especially by the high volumes of waste produced (Braga et al., 2017; Gallego-Schmid et al., 2020; Suárez Silgado et al., 2018). Thus, construction and demolition waste (CDW) is a major challenge for this sector (Ginga et al., 2020). It constitutes the largest waste stream worldwide (Akanbi et al., 2019), accounting for 30-40% of all generated wastes globally (Jin et al., 2018; Kabirifar et al., 2020). Therefore, there is an urgent need to encourage the adoption of CE focused on waste minimization, CDW management, and more sustainable production and use of materials (Bilal et al., 2020; Ghaffar et al., 2020), and to monitor its effects through the use of measuring instruments (Saidani et al., 2017).

In the scientific field, research on the CE within the construction sector has significantly increased. An emerging trend of publications is observed since 2017 with Europe leading this related research (Benachio et al., 2020; Eberhardt et al., 2020; Hossain et al., 2020; López Ruiz et al., 2020). However, because of the novelty of the concept and its application to sectors, research developments in the construction industry and particularly for the CDW sector are in their infancy stage (Hossain et al., 2020). Scientific literature is still limited (Esa et al., 2017a; Ghaffar et al., 2020; Ghisellini et al., 2018b; Ginga et al., 2020; López Ruiz et al., 2020) and tends to be focused on CE approaches to construction activities (Benachio et al., 2020; Gallego-Schmid et al., 2020; Osobajo et al., 2020b, 2020a) and the built environment (Joensuu et al., 2020; Munaro et al., 2020; Pomponi and Moncaster, 2017), CDW management strategies (Bao and Lu, 2020; Sormunen and Kärki, 2019; Wu et al., 2020), barriers and challenges (Hossain et al., 2020; Mahpour, 2018), and some individual CE principles such as design, reuse and use of prefabricated elements (Eberhardt et al., 2020; Foster, 2020; Silva et al., 2020). Moreover, developments on measuring-monitoring tools such as indicators for capturing CE progress and performance are very reduced, resulting in the lack of a comprehensive framework for CE evaluation (Hossain et al., 2020; Munaro et al., 2020). Although some research efforts about circularity indicators and measuring tools including CDW have been developed (Akinade et al., 2015; Bilal et al., 2020; Foster and Kreinin, 2020; Fregonara et al., 2017; Heisel and Rau-Oberhuber, 2020; Jiménez-Rivero and García-Navarro, 2016; Vefago and Avellaneda, 2013; Yeheyis et al., 2013), they do not consider a complete integration of CE-related principles and are mostly steered to monitor one or more circularity strategies for buildings. Therefore, specific indicators focused on tracking circularity progress in the CDW sector are currently unexplored.

Indicators are essential tools for achieving a successful transition to CE as they provide support to practitioners, decision-makers, and policymakers in the monitoring, quantification and measurement of CE performance and its implementation progress and effects (Bilal et al., 2020; Moraga et al., 2019; Rincón-Moreno et al., 2021; Saidani et al., 2017). As outlined by Moraga et al. (2019), the adoption of CE strategies can be constrained by the lack of indicators that provide an evaluation framework for sustaining these initiatives and demonstrating their potential benefits. For CDW, the absence of appropriate indicators and the lack of sufficient data on waste reduction hinders its transition towards CE (Mahpour, 2018; Nuñez-Cacho et al., 2018).

In this regard, there is a need for a specific, integrative system of indicators to measure and monitor circularity in the CDW sector, considering the direct and indirect aspects influencing its circular performance. This study aims to address such a gap by providing a basis for the assessment of CE interventions and to develop a specific referential framework of measures and indicators to enable the measurement of the CE in construction and demolition activities from a Life Cycle Thinking perspective while integrating the main focus on waste minimization, material recirculation and circularity impact.

For this purpose, this work comprises five main sections. Section 5.2 provides insights into CE performance and what are the parameters, aspects and factors required for the measurement of the CE in general applications. A comprehensive analysis of existing CE indicators is also provided. Next, section 5.3 presents the specific parameters for assessing the circularity of CDW and proposes a framework of measures. Then, section 5.4 provides a graphical conceptualization of the proposed monitoring framework including identification of indicators. Lastly, section 5.5 summarizes the main findings of the study.

5.2 The CE model: fundamental aspects for developing circularity indicators

To be able to establish a framework of indicators for measuring CE implementation to CDW, it is essential to have a clear definition of terms and concepts involved. This section gives a brief definition of the CE paradigm and its key performance elements, an overview of current measurement approaches, as well as a view of the main indicators' features to consider in the measurement of CE strategies.

5.2.1 Concepts and definitions

5.2.1.1 Circular economy concept

According to (EMF, 2021), the CE model comprises two different approaches, biological (oriented to food and biologically-based materials) and technical cycles (focused on products, components and materials). For this study, CE is approached from the technical cycle perspective.

Although there is no one single definition of CE, according to relevant scientific research (Bocken et al., 2017, 2016; Geissdoerfer et al., 2017; Kirchherr et al., 2017), the circular economy can be defined as an economic, regenerative system that is based on business models in which materials, products and components keep their value, while resource input, waste, emissions, and energy leakage are minimized.

The end-of-life is then replaced with *slowing* (prolonging use and reuse of goods through long-lasting design and product life extension), *closing* (creating circular flows of resources through recycling processes) and *narrowing* (reducing resource use and maximizing efficiency in production processes) strategies for material and energy loops in production and consumption processes. In addition, the circular model relies on the transition to renewable energy sources to ensure optimal model efficiency.

In addition, CE is strongly related to sustainable development, as it contributes to all its three dimensions by providing environmental protection, creation of economic value and opportunities, and societal benefit (EMF, 2021; Korhonen et al., 2018).

5.2.1.2 Definition of indicator

There is no global definition of an indicator. According to the guidelines for monitoring and evaluation indicators from the European Commission (2006), an indicator can be defined as “the measurement of an objective to be met, a resource mobilized, an effect obtained, a gauge of quality or a context variable. An indicator should be made up by a definition, a value and a measurement unit”. Besides that, the OECD (2014) describes an indicator as to the “quantitative or qualitative factor or variable that provides a simple, and reliable, means to measure achievement, to reflect the changes connected to an intervention, or to help assess the performance of a development actor”.

In line with the previous definitions, scientific literature argues that the main features of an indicator include its ability to summarize, simplify and communicate relevant information in complex systems or entities. Therefore, an indicator consists of a variable (parameter), or function of variables based on the measurement of quantitative and qualitative data that provides information about the system’s properties or effects. In addition, indicators provide a comparison to a reference value or baseline scenario (Foster and Kreinin, 2020; Kristensen and Mosgaard, 2020; Moraga et al., 2019; Wisse, 2016).

On the other hand, an *indicator framework* consists of a collection of indicators aimed to provide a broader, comprehensive picture of an entity or system. And in which, each indicator gives particular information about the entity (Wisse, 2016). Moreover, monitoring frameworks are based on systematic data collection on specific indicators to measure the extent of progress and achievement of objectives in interventions (OECD, 2014).

5.2.2 The measurement of the CE

5.2.2.1 Current approaches to CE measurement

Measurement tools such as indicators are essential to support the transition to a CE. All three academics, practitioners, and policymakers highlight the importance of developing monitoring frameworks to know the impact and performance of CE interventions at different levels, as well as for measuring the circularity degree of current strategies (Bilal et al., 2020; European Commission, 2018b; Saidani et al., 2017; Sánchez-Ortiz et al., 2020; Wisse, 2016). These measurement tools support reporting and decision-making processes by providing proofs and understanding of the effects of the CE implementation (EMF and GRANTA, 2015). However, due to their recent adoption and focus on the topic (mostly since 2017), there are no globally accepted indicators considering all the elements of the CE concept (Kristensen and Mosgaard, 2020; Saidani et al., 2019).

In practice, there are some world spread measuring tools such as the Material Circularity Indicator (MCI) and Circulytics from the Ellen Mac Arthur Foundation (EMF, 2020; EMF and GRANTA, 2015), which measure the restorative rate of material flows at a micro level, and the entire company's circularity (comprising the evaluation of enablers and outcomes), respectively. Other tools are the Circular Transition Indicators (CTI) framework, which asses the circularity performance of a company incorporating Life Cycle Thinking (WBCSD, 2021), and the Cradle to Cradle Certified that assess the environmental and social performance of products including the following categories: material health, product circularity, clean air & climate protection, water & soil stewardship, and social fairness (Cradle to cradle products innovation institute, 2016). Moreover, to evaluate the progress toward CE, the European Commission (EC) launched in 2018 a monitoring framework composed of four categories of macro-level indicators related to different aspects of the CE (production and consumption, waste management, secondary raw materials, and competitiveness and innovation (European Commission, 2018b). In addition, the ISO–Technical Committee (ISO/TC 323) is currently developing a series of standards on CE, including the ISO/WD 59020.2 about a measuring circularity framework, and expected to be published in 2021 as the first standardized CE indicators.

Furthermore, although contributions from practice are most widely applied by organizations, the majority of current developments on CE indicators originate from the academic area (Kristensen and Mosgaard, 2020), accounting for 60% of existing metrics (Saidani et al., 2019). A list of the most relevant circularity indicators developed from academics and the mentioned practical measuring tools is presented in **Appendix B, section I**.

5.2.2.2 Fundamental parameters to be measured

CE elements

Various authors highlighted the influence of CE in the entire system (Elia et al., 2017b; European Commission, 2021; Fregonara et al., 2017; Moraga et al., 2019; Sánchez-Ortiz et al., 2020). Thus, CE has a presence along the whole life cycle of resources, products and services. In this regard, it is necessary to adopt a Life Cycle Thinking (LCT) approach when measuring CE progress. LCT is a key element in the making-decision process and evaluation of strategies or interventions aimed at the CE concept. In addition, it provides ideas for creating closed-circular solutions and for reducing their impacts (Civancik-Uslu et al., 2019; Puig et al., 2013).

From this perspective, CE is identified to perform through five main phases or processes (Elia et al., 2017b; EMF, 2021; European Environment Agency, 2016; Kristensen and Mosgaard, 2020):

i. material inputs,
ii. eco-design,
iii. production and distribution,
iv. use/consumption and stock, and
v. end-of-life material recovery

Material inputs include material and energy flow from both primary resources and recirculated resources. *Eco-design* aims to slow and close resource loops through strategies such as design for disassembly, long-life product design, design maintenance and repair, and design for recycling. *Production* processes in a CE aim to resource efficiency, minimize primary material inputs and hazardous materials while reducing the output of waste and emissions. *Consumption* refers to citizens behavior about choices of products and services and uses patterns. Lastly, *Material recovery* corresponds to strategies steered to fed materials back into the cycle, reducing material losses through strategies such as reuse (through repair, remanufacture or refurbishment), recycling and energy recovery.

Moreover, as identified by Hossain et al. (2020) and Pomponi and Moncaster (2017), the complexity of CE systems involves interaction among seven dimensions: governmental/policy, economic, environmental, behavioural/management, societal, technological and innovation/materials. For this study, we focused on the environmental, economic, and innovation/materials dimensions. In this case, the innovation dimension refers to material and/or product characteristics and design integrating CE.

Assessment categories

The CE system is primarily focused on reducing the need for new resource inputs while reducing emissions by preserving and creating value in the loops. Hence, these core aspects must be analyzed and assessed to guarantee the effective measurement of CE implementation. Derived from the analysis of scientific publications and practical approaches, eight common assessment categories for CE evaluation indicators have been identified: use of natural resources, energy, water, emissions, waste, revenue, and cost reductions.

Table 13 lists the literature and practical approaches analyzed and their corresponding primary CE aspects assessed. Contributions that provide measurement frameworks, a set of indicators or comprehensive analysis and classification of existing circularity indicators were considered. Practical approaches include works from recognized organizations and government bodies such as the Ellen McArthur Foundation, the World Council Bank for Sustainable Development, and the European Commission.

5.2.3 Key features of circularity indicators

5.2.3.1 Type of indicators

There are three different categories of CE indicators: single quantitative indicators, analytical tools, and composite indicators.

Single quantitative indicators measure the single impact information of a product or service. These indicators translate circularity into a single number in the form of ratio or percentage and are useful for managerial decisions – i.e. the Ease of Disassembly Metric (eDiM), Longevity Indicator (LI) (Elia et al., 2017b; Kristensen and Mosgaard, 2020; Saidani et al., 2019). While *analytical indicators* consist of guidelines, tools and models that are used as a decision-making support tool for companies in the assessing of their improvement potential – i.e. the Circular Economy Toolkit, (CET), Circularity Design Guidelines (CDG) (Kristensen and Mosgaard, 2020). Finally, *composite indicators* consist of synthetic indices of multiple indicators that summarize and communicate complex or multi-dimensional issues in a simple way - i.e. the Disassembly Effort Index (DEI), Sustainability Indicators in CE (SICE) (Yeheyis et al., 2013). Regarding the current application of CE indicators, according to Kristensen and Mosgaard (2020), single quantitative and analytical indicators are preferred in practice by companies and organizations due to their ease and practical use. Furthermore, composite indicators have been only approached by academia.

Moreover, unified sets of circularity indicators such as frameworks can support researchers and policymakers in monitoring the progress of CE implementation at different levels, providing a complete vision and including multiple influential aspects for circularity (Wisse, 2016), - i.e. Circular economy monitoring framework from the EC. According to (Corona et al., 2019), these metrics can be categorized as analytical tools.

Table 13. Identification of main categories used for CE assessment

Assessment tool	**Use of resources**	**Energy**	**Water**	**Emissions**	**Waste**	**Eco-design**	**Revenue/financial aspects**	**Costs/savings**
Product Recovery Multi-Criteria Decision Tool *(Alamerew and Brissaud, 2019)*		●		●			●	●
Reference framework for CE indicators (Elia et al., 2017a)	●		●	●	●	●		
Adaptation of the CE monitoring framework from the EC into micro-level applications *(Rincón-Moreno et al., 2021)*		●	●		●	●		
Indicators framework for adaptative reuse of heritage buildings *(Foster and Kreinin, 2020)*	●	●	●	●	●			
Analysis of indicators for CE assessment *(Bilal et al., 2020)*	●	●	●	●	●	●		●
Analysis and categorization of indicators in relation to CE elements *(Parchomenko et al., 2019)*	●				●	●	●	
Measurement scale for CE in the building industry *(Nuñez-Cacho et al., 2018)*	●	●	●	●	●	●		
Report: Monitoring progress towards a circular economy *(European Environment Agency, 2016)*	●				●	●		
Circulytics (EMF, 2020)		●	●			●	●	
Material Circularity Indicator (set of metrics) *(EMF and GRANTA, 2015)*	●	●	●	●	●	●		
Product standard certification *(Cradle to cradle products innovation institute, 2016)*		●	●	●		●		
Circular Transition Indicator Framework *(WBCSD, 2021)*	●	●	●		●	●	●	
CE Monitoring Framework (European Commission, 2018b)	●				●		●	

5.2.3.2 Measurement scope

Based on the classification framework for CE indicators developed by Moraga et al. (2019), there are three measurement scopes for circularity indicators, and which incorporate the LCT approach:

- *Scope 0:* measurement of physical properties without LCT approach (e.g. Recycling rate).
- *Scope 1:* measurement of physical properties with full or partial LCT approach (e.g. the indicator Recyclability in terms of mass includes the potential rate to recycle materials)
- *Scope 2:* measurement of effects (burdens/benefits) regarding environmental, economic, and/or social concerns (e.g. Recycling benefit rate, in terms of environmental effects).

5.2.3.3 Implementation level

CE can be implemented and assessed at different spatial levels, comprising the micro-level, meso-level and macro-level (Pauliuk, 2018; Su et al., 2013).

The *micro-level* focus on companies, products, and consumers (Saidani et al., 2019). At this level, companies are centred on their improvement in processes and business development (Rincón-Moreno et al., 2021), and CE is approached through eco-design and cleaner production strategies (Geng et al., 2012; Linder et al., 2017). Therefore, micro-level indicators analyze and provide information for specific decision processes at a company level, or about specific materials or products – i.e. product policies, energy efficiency, and integrated waste management (Vercalsteren et al., 2018).

Whereas the *meso-level* acts at the inter-firm level through company networks in the form of industrial symbiosis and eco-industrial parks, which result in benefits for the regional economy and the natural environment (Geng et al., 2012). Indicators at the meso-level provide detailed information about materials or categories of materials, industries or branches of production, and consumption activity. Moreover, indicators at this level assist in the detection of waste and pollution sources, as well as efficiency opportunities in sectors or consumption categories (Vercalsteren et al., 2018).

Lastly, the *macro-level* comprises the city, province, region or national level (Linder et al., 2017; Pauliuk, 2018), with the main emphasis on materials, waste management and the interrelation of waste flows (Merli et al., 2018) for promoting sustainable production and consumption. Macro-level indicators measure the impact of CE at the territorial level (Geng et al., 2012), and are useful for decision-making processes regarding policy and regulations (on economics, trade and environment – i.e. national waste management and resource conservation policies), and in the development of sustainable strategies and action plans (Vercalsteren et al., 2018).

In the built environment, CE is approached following this same three-level scale. The micro-level encompasses manufactured components and assemblies (e.g. bricks), while the meso-level focuses on individual buildings, and the macro-level analyses cities and neighbourhoods (Pomponi and Moncaster, 2017).

5.2.4 Conceptualization of the referential evaluation parameters

Figure 15 summarizes the key parameters and features presented in this section for measuring CE interventions in technical cycles. It constitutes a referential framework that guides the development of measuring tools for specific sectors, such as the CDW. This framework distinguishes between key parameters to be measured and the main features concerning circularity indicators. Two main aspects to be measured are identified: CE phases and assessment categories. CE phases incorporate the LCT approach and represent the processes to monitor. In addition, they encompass the series of circularity strategies adopted. Furthermore, the framework outlines eight common aspects to be assessed: use of natural resources, energy, water, GHG emissions, waste, eco-design, revenue, and cost reduction. Three main features of circularity indicators are presented: implementation scale, measurement scope, and type of indicators. The measurement scale represents the level at which circularity is implemented or assessed and comprises three approaches, the micro-level (product, company), meso-level (industrial symbiosis), and macro-level (city, region, national). Moreover, two measurement scopes focused on physical properties and one measuring effects are considered. Finally, three types of indicators can be used to measure CE strategies: single quantitative indicators, analytical tools, and composite indicators.

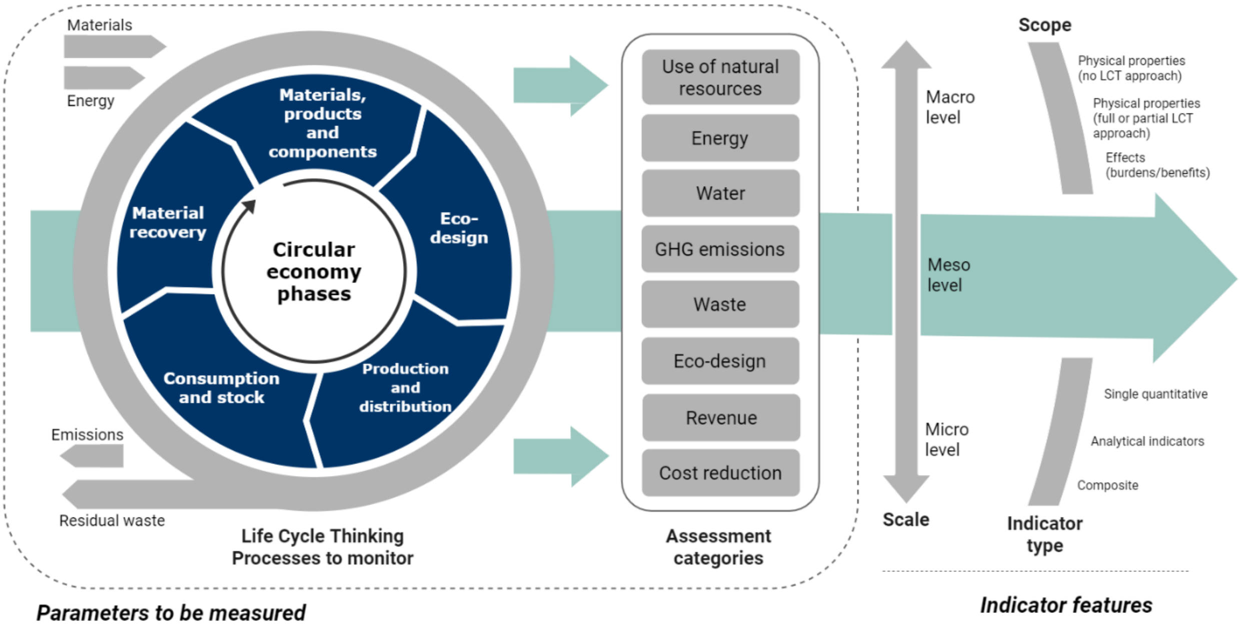


Figure 15. Key referential parameters and features for the assessment of CE progress

5.3 Establishing a CE monitoring framework for the CDW sector

This section defines the elements for constructing a monitoring framework to measure the progress of CE adoption in the construction and demolition sector. First, a brief description of the CE application in CDW is provided with a focus on the main stages and strategies involved in the circularity of the sector. Next, it presents the identification of existing measuring approaches, and the definition of circularity criteria according to the parameters defined in **section 5.2**.

5.3.1 CE in the CDW sector

The circular economy approach in the construction and demolition sector leads to the reduction of the negative environmental effects (Ghaffar et al., 2020). Furthermore, it contributes to the social and economic development of the region. For this sector, the CE system is based on the reduction of the material's environmental footprint (Díaz-López et al., 2021) by preserving the value of materials, the use of sustainable, renewable resources, and the adoption of waste prevention strategies (Mahpour, 2018; Munaro et al., 2020). Although there are some improvements in the application of CE principles in construction and demolition activities, most of the efforts have been focused on waste management strategies such as reuse and recycling (Bilal et al., 2020). However, as highlighted in section 5.2.2, integral CE interventions must act throughout the entire life cycle of products.

From a LCT perspective, CE in the CDW sector involves five main phases and 14 strategies (López Ruiz et al., 2020):

i. preconstruction aimed to waste minimization and efficient use of materials before construction, renovation and demolition activities thorough design, policies and strategic frameworks, and CDW management plans.
ii. construction and renovation, regarding best waste management practices adopted through site waste management plans (SWMP).
iii. collection and distribution, involving optimized collection and segregation of CDW and efficient transport processes.
iv. end-of-life steered to enhance material recovery by the application of selective deconstruction and pre-deconstruction/demolition audits.
v. material recovery and production, based on the recirculation of materials for their use in the manufacturing of new products through reuse, recycling, energy recovery, and low-grade recovery strategies.

5.3.2 Existing approaches

Considering CE application to sectors is a recent field of analysis, the availability of indicators and measurement approaches for circularity assessment of CDW is currently limited. A very reduced number of related approaches have been developed focused on the construction and building industry, or partially covering some aspects regarding CDW management (Hossain et al., 2020; Pauliuk, 2018). This lack of information and standard indicators leads to misunderstanding, and challenge the implementation of CE strategies (Díaz-López et al., 2021; Rincón-Moreno et al., 2021).

Table 14 lists the existing contributions for the measurement of the CE of construction and demolition activities. In addition, it includes details concerning CE categories assessed and implementation scale. Further disaggregation/composition of each indicator is presented in **Appendix B, Section II**. Even though these works show interest in evaluating CE performance of construction and demolition activities, none of the current approaches provides an integral evaluation of circularity that includes all the CE measuring aspects presented in **section 5.2.2**. Moreover, only 8 of the 12 works analyzed include CDW as part of the circularity assessment. Most of the studies have been conducted on the development of circularity indicators for buildings. Fregonara et al. (2017) proposed a methodological approach for decision-making processes considering both economic and environmental indicators at the end-of-life phase of buildings. It consists of a global synthetic economic-environmental indicator, composed of five environmental indicators and three economic indicators calculated through the Life Cycle Assessment and Life Cycle Costing methodologies, respectively. Moreover, Bilal et al. (2020) in their analysis of CE barriers for the building sector in developing countries proposed a mitigation framework that includes 24 indicators (classified and ranked by experts) used to evaluate the level of implementation of the CE in the sector. The ranking of indicators showed that energy-related indicators have received the most attention from a CE perspective, and waste indicators prevail as the most neglected aspect in the building sector. Similarly, Nuñez-Cacho et al. (2018) proposed a scale for measuring the degree of circularity implementation on buildings. This scale consists of the weighting of 21 questions and aspects to be considered in the adoption of CE interventions. Although this work covers the majority of the CE assessment aspects, it lacks calculations for indicators.

Accordingly, works on the measurement of circularity during the design stage include the proposal by Cottafava and Ritzen (2021) on the development of the Predictive Building Circularity Indicator (PBCI) to quantify the end-of-life recovery potential of materials and components resultant from the implementation of the design for disassembly in residential buildings. It consists of an improvement to the Building Circularity Indicator (BCI) and combines the Material Circularity Indicator (MCI) with embodied energy, and embodied carbon. In addition, (Akinade et al., 2015) developed an assessment score named Building Information Modelling based Deconstructability Assessment Score (BIM-DAS) to determine the extent to which a building could be disassembled and the ease of material recovery at the end-of-life of buildings. Moreover, Vefago and Avellaneda (2013) proposed a method to analyze the amount of materials that could be reused, recycled, infra-cycled and infra-used during the design of a building using two indicators: the Index of recyclability and the index of design recyclability, and which follow a weighting scale based on the material hierarchy.

Other studies have been conducted for evaluating different aspects of buildings, such as the work by Foster and Kreinin (2020) on the identification of key environmental indicators for measuring the impact of adaptative reuse of heritage buildings. Besides, Heisel and Rau-Oberhuber (2020) proposed a method to generate material passports for construction materials and products in buildings and calculates a Circularity Indicator Building Score that evaluates the use of natural resources, eco-design and CDW during the lifecycle phases of construction, use, and end-of-life. This indicator is an adaptation of the Material Circularity Indicator from the Ellen MacArthur Foundation and comprises 3 lifecycle phases-related sub-indicators. Moreover, Coenen et al. (2021) in their study developed a framework for resource efficiency in bridge projects. This framework consists of a composite indicator named Bridge Circularity Indicator and contains 9 sub-indicators classified into 4 groups (design input, resource availability, adaptability, and reusability).

Lastly, studies with the main focus on CDW are very reduced. Yeheyis et al. (2013) proposed a conceptual framework for maximizing the 3R principle in C&D waste management. And developed the Construction waste LCA-based sustainability index (CWLSI) as a tool for decision-making on material selection, waste management, and treatment options. This composite indicator is then disaggregated into 9 C&D waste management indicators and grouped into 3 sub-indicators related to the three sustainability pillars (environmental, social, economic). Furthermore, Jiménez-Rivero and García-Navarro (2016) identified 17 best performance indicators for monitoring deconstruction and processing of gypsum waste. These indicators and the associated monitoring parameters analyze technical, environmental, social, and economic aspects.

In the practical field, the European Union (EU) through the Joint Research Centre (JRC) launched in 2021 the Level(s) common framework of indicators for measuring the sustainability of office and residential buildings (European Commission, 2021). It evaluates the complete life cycle of buildings with the main focus on environmental performance and also providing relevant information about health and comfort, as well as cost, value and potential risks. This framework consists of 6 macro objectives (greenhouse gas and air pollutant emissions along a building's life cycle; resource-efficient and circular material life cycles; efficient use of water resources; healthy and comfortable spaces; adaptation and resilience to climate change, and; optimised life cycle cost and value) containing a set of 16 common indicators, which are complemented with the Life Cycle Assessment (LCA) methodology. Moreover, it is organised into three levels according to the execution stages of building projects: Level 1 – conceptual design, Level 2 – detailed design and construction performance, and Level 3 – as-built and use performance. Regarding CDW, the indicator "Construction & demolition waste and materials" provides an estimation of the overall quantity of waste and materials produced during construction, renovation and end-of-life activities, as well as a calculation of their recovery rate. Level(s) represents a useful tool with multiple benefits such as providing a standard reference language to compare progress on sustainable buildings and their multi-applicability to different life cycle phases and construction actions. However, the complexity of user guides and the dependency on external procedures and databases makes it difficult to develop a practical implementation of the monitoring framework (Díaz-López et al., 2021).

Table 14. Existing contributions for the measurement of the CE in the CDW sector

				Assessment category							
Contribution / indicator	**Type of analysis**	**Application**	**Scale**	**Use of resources**	**Energy**	**Water**	**Emissions**	**Waste**	**Eco-design**	**Revenue/financial**	**Costs/savings**
Building Information Modelling based Deconstructability Assessment Score (BIM-DAS) *Author: (Akinade et al., 2015)*	Critical analysis, development and experimentation	Buildings	Meso						●		
Mitigation framework to evaluate the level of implementation of the CE in the building sector for developing countries *Author: (Bilal et al., 2020)*	Literature review. critical analysis and classification	Building sector	Meso	●	●	●	●	●	●		
Bridge Circularity Indicator (BCI) *Author: (Coenen et al., 2021)*	Description, classification and implementation	Infrastructure projects	Meso	●					●		
Predictive Building Circularity Indicator (PBCI) *Author: (Cottafava and Ritzen, 2021)*	Development and experimentation	Design for Disassembly of residential buildings	Meso		●		●				
Level(s), European framework for sustainable buildings *Author: (European Commission, 2021)*	Governmental initiative	Office and residential buildings	Meso	●	●	●	●	●	●		●
Key environmental indicators for adaptive reuse of cultural heritage buildings *Author: (Foster and Kreinin, 2020)*	Literature review, description critical analysis and classification	Adaptative reuse of cultural heritage buildings	Meso		●	●	●	●			
Synthetic economic-environmental indicator for the end-of-life of buildings *Author: (Fregonara et al., 2017)*	Description, classification and experimentation	Buildings	Meso		●		●	●	●		●
Circularity Indicator Building Score *Author: (Heisel and Rau-Oberhuber, 2020)*	Description and experimentation	Buildings	Meso	●				●	●		
Best performance indicators to measure the management performance of end-of-life gypsum *Author: (Jiménez-Rivero and García-Navarro, 2016)*	Description, classification and experimentation	Gypsum waste	Micro	●			●	●			●
Circular Economy measurement scale for building industry *Author: (Nuñez-Cacho et al., 2018)*	Critical analysis, classification and experts' panel	Building industry	Micro	●	●	●	●	●	●		●
Index of recyclability of buildings *Author: (Vefago and Avellaneda, 2013)*	Description, development and experimentation	Buildings	Meso					●	●		
Construction waste LCA-based sustainability index (CWLSI) *Author: (Yeheyis et al., 2013)*	Description, classification and development	CD waste management	Meso				●	●			●

5.3.3 Circularity criteria

The effective implementation and assessment of the CE is a complex task involving multiple aspects and strategies with a systemic perspective. For the construction and demolition sector, it is important to ensure waste prevention and reduction of raw materials use from the early stage of design. Furthermore, efficient recovery alternatives for recirculation of materials and value creation is essential (Akanbi et al., 2018; López Ruiz et al., 2020; Munaro et al., 2020). Accordingly, **Table 15** identifies the most influential factors and criteria for circularity in the CDW sector, which represent the aspects to be considered in the evaluation of each of the eight common assessment categories identified in **section 5.2.2.2**.

Table 15. Factors influencing circularity of the CDW sector

No	CE criteria/factor	Reference
1	Design for waste prevention: accurate forecasts of CDW generation and composition, design for reuse and recycling	Benachio et al. (2020), De Wolf et al. (2020), Esa et al. (2017), Ghaffar et al. (2020), Jin et al. (2018), Minunno et al. (2018), Yeheyis et al.(2013), Yuan (2017)
2	Design for disassembly or deconstruction (DfD)	Benachio et al. (2020), European Commission (2021), Ghaffar et al. (2020), Joensuu et al. (2020), Minunno et al. (2018), Rakhshan et al. (2020), Silva et al. (2020)
3	Design and use of modular/standardised buildings and components	Akinade et al. (2017), Benachio et al. (2020), Finch et al. (2021), Ghaffar et al. (2020), Munaro et al. (2020), Silva et al. (2020)
4	Layer design approach	Akinade et al. (2017), Finch et al. (2021)
5	Minimisation of types and number of building components	Akanbi et al. (2018), Akinade et al. (2015, 2017)
6	Use of durable materials and components	Akinade et al. (2017), European Commission (2021), Finch et al. (2021)
7	Use of prefabricated elements	Akinade et al. (2017), Benachio et al. (2020), Finch et al. (2021), Ghaffar et al. (2020), Li et al. (2014), Silva et al. (2020)
8	Use of recycled and recyclable materials	Akinade et al. (2015), Finch et al. (2021), Silva et al. (2020)
9	Use mechanical, not chemical connections between different materials (e.g. nut/bolt joints instead of nails and glueing)	Akanbi et al. (2018), Akinade et al. (2015, 2017), Finch et al. (2021)
10	Avoidance of secondary finishes (e.g. chemical timber preservatives)	Akanbi et al. (2018), Akinade et al. (2015, 2017), Finch et al. (2021)
11	Avoidance of composite materials	Akinade et al. (2015, 2017)
12	Avoidance of toxic and/or hazardous materials	Akanbi et al. (2018), Akinade et al. (2015, 2017), Finch et al. (2021)
13	Energy efficiency and/or maintain embodied energy	Foster & Kreinin (2020), Fregonara et al. (2017), Nuñez-Cacho et al. (2018)
14	Selective deconstruction	Benachio et al. (2020), Chau et al. (2017), Jaillon & Poon (2014), Schultmann & Sunke (2007)
15	On-site segregation and waste collection	Bovea and Powell (2016), Dahlbo et al. (2015), Jiménez-Rivero and García-Navarro (2017), Gálvez-Martos et al. (2018), Ghisellini et al. (2018c, 2018a), Nußholz et al. (2019)
16	Material passports	Benachio et al. (2020), Heisel and Rau-Oberhuber (2020), Minunno et al. (2018)
17	Efficient transport processes	Bovea and Powell (2016), Brambilla et al. (2019), Coelho and De Brito (2012), Jung et al. (2015), Martínez et al. (2013)
18	Re-use of structures, components and materials	Akanbi et al. (2018), Akinade et al. (2015), Benachio et al. (2020), Huang et al. (2018), European Commission (2021), Gorgolewski M. (2008), Minunno et al. (2018), Nußholz et al. (2019), Rakhshan et al. (2020), Sassi (2008), Zhang et al. (2020)
19	Recycling	Akanbi et al. (2018), Bovea and Powell (2016), Chau et al. (2017), Ding et al. (2016), Rakhshan et al. (2020)
20	Energy recovery	Chau et al. (2017), Schultmann & Sunke (2007)
21	Use in low-grade applications	Coudray et al. (2017), Gálvez-Martos et al. (2018)

5.3.4 Definition and classification of CE measures

The development of the framework of indicators combines the key influential factors and parameters identified in previous sections for the effective measurement of CE in the construction and demolition sector. Intending to provide clearness of the monitoring process, the classification of indicators adopted a multilevel structure of metrics as proposed by (Kazancoglu et al., 2018). This approach consists of a three-dimensional hierarchy comprising main criteria, sub-criteria and measures/indicators. In this study, the main criteria correspond to the CE dimensions of environment, economic and innovation/materials. While sub-criteria consists of the eight common assessment categories for CE evaluation: use of natural resources, energy, water, GHG emissions, waste, revenue, and cost reductions. Lastly, measures represent the specific aspects to be measured and were deducted from the circularity criteria identified in **section 5.3.3**, and from the analysis of existing approaches measuring circularity of CDW-related strategies. **Table 16** summarizes all three levels described.

Table 16. Proposed framework structure for measuring the circularity of CDW

Main criteria	Sub-criteria	Measure	Goal
Environmental	Use of natural resources	Utilization rate of primary resources	↓
	Energy	Energy consumption	↓
		Usage of renewable energy	↑
		Embodied energy	↓
	Water	Freshwater consumption	↓
		Water quality (eutrophication)	↓
	Emissions	GHG emissions	↓
		Embodied emissions	↓
		Indirect emissions by transportation	↓
	Waste	CW & CDW generated	↓
		Recovery rate of CDW (general and per recovery option)	↑
		CDW disposed of in landfills	↓
Economic/finance	Costs/savings	Net recoverable cost	↓
		Total Product cost	↓
	Revenue	Resource efficiency	↑
		Circularity revenue	↑
Material and products	Eco-design	Level of disassembly/deconstruction	↑
		Recyclability and reusability index	↑
		Recoverability rate at the end-of life	↑
		Longevity of materials, products and components	↑
		Use of recycled and recyclable materials	↑
		Use of non-toxic and hazardless materials	↓

5.4 Conceptualization of the CE monitoring framework

Figure 16 shows the conceptual framework of measures for assessing the circularity of technical cycles in the CDW sector. As specified in **section 5.3.4** this monitoring framework incorporates a three-level approach following an up-down level. The first level represents the CE dimensions to be evaluated (environmental, economic, material and products). These three main criteria encompass eight categories or sub-criteria (level 2), which corresponds to the common assessment categories present along with the existing CE evaluation tools. Next, the third level consists of the main circularity performance criteria for CDW-related practices and represents the measures to consider in the evaluation of CE progress. Finally, the proposed framework adopted a systemic analysis, in which the five life cycle phases for circularity of CDW represents the process to be monitored individually or full evaluated.

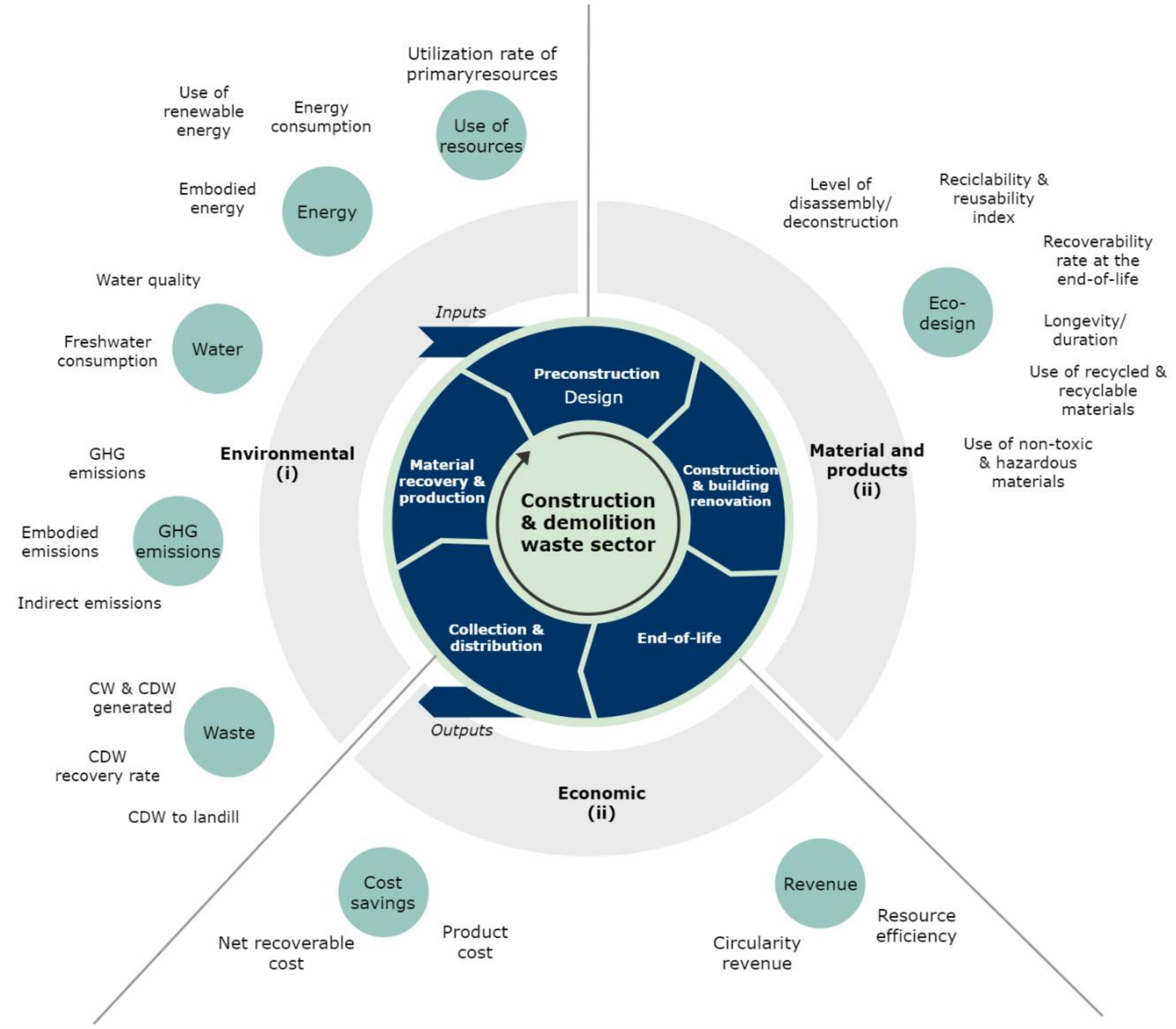


Figure 16. Conceptualization of measures and parameters for measuring circularity of CDW

Moreover, a set of circularity indicators was defined for each of the CE measures. The definition of indicators was based on the analysis of CE indicators identified in **sections 5.2.2.1** and **5.3.2** and listed in **Appendix B**. Furthermore, **Figure 17** shows the proposed framework for the evaluation of the circularity of the CDW sector. It includes a detailed classification of indicators proposed to evaluate the CE measures presented in **Figure 16**.

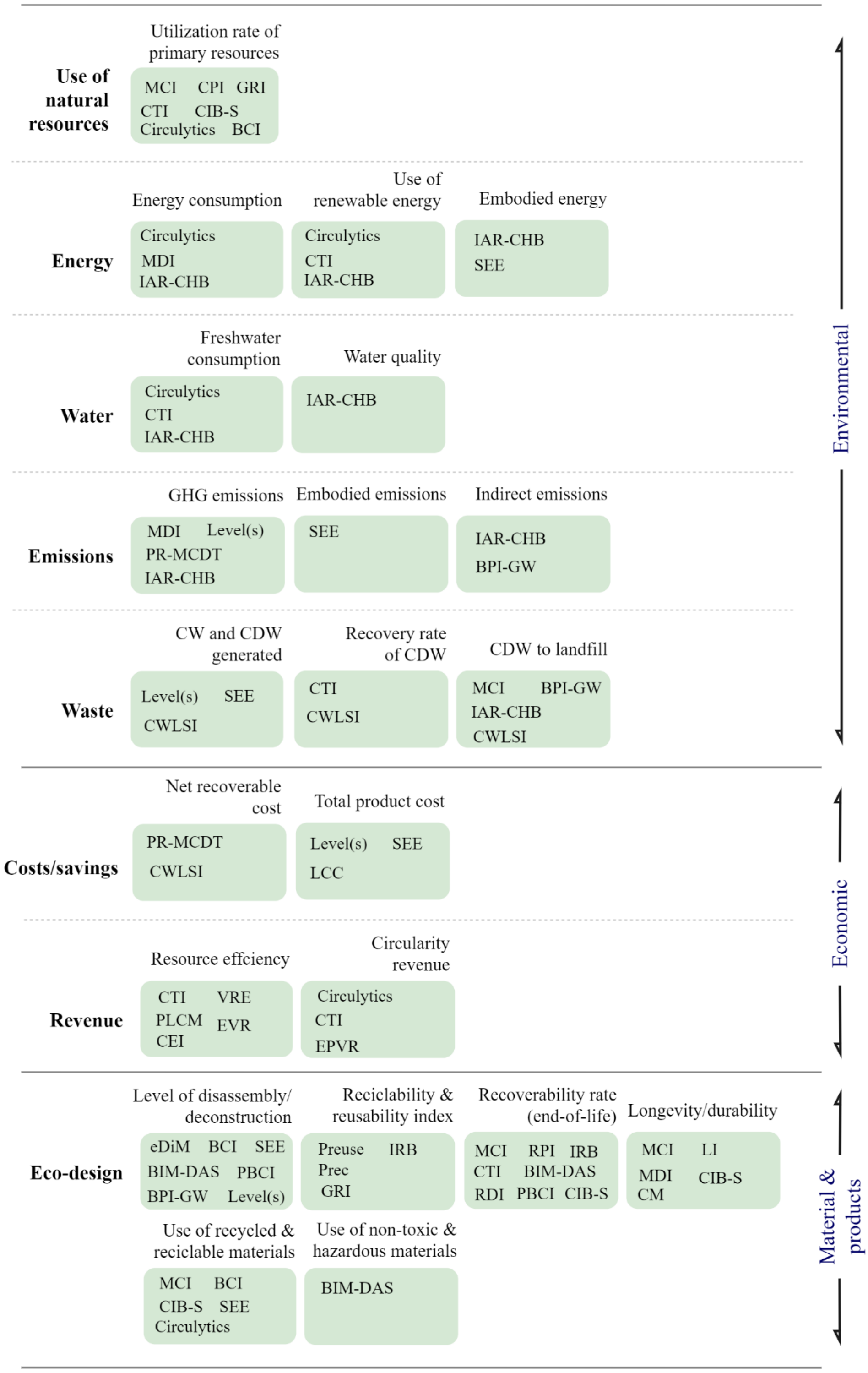


Figure 17. Proposed framework for the measurement of circularity in the CDW sector

Notes: Material Circularity Indicator (MCI); Circular Transition Indicators (CTI); Product Level Circularity Metric (PLCM); Material Durability Indicator (MDI); Potential Reuse Index (Preuse); Potential Recycle Index (Prec); Circular Economy Index (CEI); Circular Economy Performance Indicator (CPI); Value-based resource efficiency (VRE) indicator; Combination Matrix (CM); Longevity Indicator (LI); Recycling Desirability Index (RDI); Reuse Potential Indicator (RPI); Eco-costs Value Ratio Model (EVR); Product Recovery Multi-criteria Decision Tool (PR-MCDT); Design Method for End-of-use Product Value Recovery (EPVR); Ease of Disassembly Metric (eDiM); Global Resource Indicator (GRI); Building Information Modelling based Deconstructability Assessment Score (BIM-DAS); Bridge Circularity Indicator (BCI); Predictive Building Circularity Indicator (PBCI); Indicators for adaptive reuse of cultural heritage buildings (IAR-CHB); Synthetic economic-environmental indicator for the end-of-life of buildings (SEE); Circularity Indicator Building Score (CIB-S); Best performance indicators for end-of-life gypsum waste (BPI-GW); Index of recyclability of buildings (IRB); Construction waste LCA-based sustainability index (CWLSI).

5.5 Conclusions

This study proposes a framework approach steered to evaluate in a simple, practical way the progress of the CE in the construction and demolition sector. In addition, this framework provides an understanding of the functioning of the CE for CDW. In this regard, it summarizes the key, relevant factors influencing the circular performance of construction and demolition activities. Moreover, this study contributes to the scientific knowledge by providing the basis for the further development and improvement of frameworks of indicators from different sectors.

It was found that although CE has gained significant attention among academics, governments and practitioners, the developments on knowledge and practical implementation of CE strategies are still evolving. In this regard, the transition towards the circular system is hindered by the lack of metrics and indicators for measuring the progress on CE implementation, and for estimating its potential economic, environmental and social benefits. Thus, there is a need for developing comprehensive, standardized metrics to evaluate CE interventions. With this aim, frameworks of indicators provide a full perspective and monitoring of CE. Moreover, it is necessary to adopt a Life Cycle Thinking approach when evaluating CE systems.

In the CDW sector, the developments on circularity indicators are currently limited. Most of the existing contributions approach the use phase of buildings or waste management alternatives, lacking integral CE approaches. In this regard, this study identified 21 aspects or criteria for circularity of CDW and eight common assessment categories for CE measuring. These parameters were used to propose a set of 22 measures that represent the aspects to be measured for a comprehensive circularity evaluation in the CDW sector. Furthermore, a set of existing indicators were analyzed and defined for assessing the CE measures identified.

In conclusion, the proposed framework constitutes the first approach to evaluating CDW circularity. Moreover, future research could be conducted on developing a practical application of the framework. In addition, further integration and developments on new, improved circularity indicators could complement the actual approach. Finally, research should also be conducted on the CE measurement of all the four remaining CE dimensions: societal, technological, governmental and behavioural.

Chapter 6 General conclusions

6.1 Conclusions

This section condenses the overall concluding remarks of this thesis. Specific conclusions for each chapter are given in previous sections 3.6, 4.4 and 5.5.

This research work was developed to propose an approach to conceptualize the Circular Economy paradigm in the construction and demolition waste sector, as well as for evaluating its environmental and economic effects and monitor their implementation. The intention was to provide pathways to support the adoption of CE strategies for CDW products. For this purpose, the main outcomes of this thesis reside in an integrative framework of strategies involved in the implementation of CE principles in the CDW sector incorporating a life cycle thinking perspective. This, together with a methodological proposal to assess and compare different circularity alternatives from a multicriteria perspective including its validation, as well as a system of indicators measuring CE features.

The theoretical framework proposed describes how the CE performs in the CDW sector by outlining the key aspects, factors and strategies involved in the system. The exploration conducted for developing this framework denotes that CE is an emerging, not static concept still in evolution. Thus, to date, there is no single, standardized definition of the CE model and its principles that fits the specificity of all industry sectors, including the construction and demolition industry. Hence, the CE concept evolves as it is transposed to different sectors and applications. For CDW, the proposed framework approaches the CE concept from the perspective of waste minimization, waste management and recirculation of materials for their use as secondary building products in the construction industry.

Strategies from the preconstruction stage are identified as the most influential to achieve circularity. Decisions in the early stage of design play a key role in the volume and type of waste to be produced, as the selection of construction methods, materials and end-of-life scenarios are analyzed before construction and demolition works. Therefore, appropriate designing based on detailed data about the composition and technical features (e.g. type of connection, recoverability level) of building components enable the implementation of circularity strategies in further lifecycle stages. For example, the application of selective deconstruction methods, which facilitate and increase the salvaging of materials at the end-of-life phase. This endorses the fact that CE is not only intended to enhance waste management practices, but rather to prevent waste production, as well as to reduce the use of resources and their impact across the lifecycle of buildings. However, current conditions of the urban built environment restrict the application of CE strategies, as most existing buildings have not been designed and constructed adopting CE principles. All this leads to adopt recovery strategies to keep the value of materials, even though material recovery may not be the final purpose of CE. In this regard, policy and regulatory instruments such as quality standards and economic instruments are essential drivers for enhancing the application of recovery practices, and for supporting the market of secondary building products.

The methodological approach proposed for the multicriteria assessment can provide in-depth detail of the economic and environmental performance of circularity alternatives for CDW products, intending to support decision-making processes. This method incorporates a lifecycle perspective, implying a comprehensive analysis of the entire value chain of building products, in which different circularity alternatives are identified considering current legal and technical limitations on waste management and the use of CDW to produce secondary building materials. It allows evaluating different scenarios, combining different factors involved in the circularity of the system according to current conditions but also for future scenarios. The use of LCA and the proposed economic evaluation method are an adequate approach to obtain a detailed examination of processes, which enables solid estimations on the environmental and economic effects of the different alternatives, as well as the identification of parameters with high influence on the environmental and economic results.

The methodology is validated by undergoing a real case example comparing different circularity strategies for concrete waste in the region of Catalonia in Spain. In this case, the definition of alternatives showed the importance of incorporating CE principles during design. Thus, circularity alternatives were focused on segregation and recycling practices, as most of the current concrete structures in Catalonia have been constructed using traditional methods. This situation restricted the incorporation of deconstruction and reuse alternatives, nevertheless, technical regulations and the availability of technology and infrastructure allowed to consider recycling strategies (on-site and off-site) for high-grade applications.

Results show environmental and economic benefits for CE alternatives compared to linear-conventional scenarios. Within the particular conditions of the study, the environmental advantage of CE scenarios ranges from 6% to up to 41.6% among impact categories. From which, alternatives adopting on-site treatments have the largest benefits due to the shorter transportation needs. From the economic perspective, the implementation of the proposed CE scenarios could lead to average cost savings of 25%. Transportation and landfilling are the most conditioning factors for both environmental and economic criteria. In this case, transportation represents the threshold between environmental benefits and burdens. In which, linear economy scenarios are highly affected by transport requirements for the supply of materials and the transportation of concrete waste to final disposal sites. Hence, transport distances are determining when choosing the type of recycling. Besides that, landfilling fees are the most influential parameter on the total cost of alternatives.

Although the proposed methodology was successfully implemented in this case of study, this method could be hampered by difficulties to obtain all the necessary data to construct the environmental and economic inventory.

From the above, it is important to highlight that the success of CE strategies is conditioned by the specific characteristics of the context of the application. Thus, the feasibility of alternatives must be evaluated before their implementation considering the following key drivers for the circularity of CDW products: infrastructure and technology, regulatory framework, economic viability, and best environmental performance.

In the final stage of this work, the monitoring framework of indicators constitutes a first approach for measuring CE progress in the CDW sector. It identifies the key factors, criteria and influential parameters to provide a holistic integration of CE principles. The configuration of the framework allows monitoring the effects of circularity interventions through simple, structured measures that can be calculated using existing or commercialized tools. Thus, one of the main factors for the success of indicator systems is to provide simplicity and accessibility to the users. In this regard, the calculation tools for the different measures proposed in the framework should be adapted in future as soon as standardized metrics are available.

6.2 Future research

The conceptualization and application of CE models constitute a wide field of research to explore in more detail and different directions. The following ideas and perspectives are recommended for future works:

- Extend the exploration of complementary strategies and components of CE within the construction and demolition sector to provide a comprehensive basis for the application of circularity practices. The suggested elements to explore include key drivers from the preconstruction stage steered to create value and prevent waste generation. These include a broader understanding of stakeholders and collaborative networks, circular business models innovation (e.g. servitization schemes, product-to-service), analysis of current policies and regulatory frameworks, as well as guidelines for the standardization of circular building products (e.g. content of recycled materials, ease of dismantling and reuse, modularity).
- The analysis of circularity alternatives could be extended to explore cross-sectoral applications to support a more complete implementation of the CE model.
- Further evaluation of the social dimension is recommended to account for the potential negative or positive effects of circularity interventions on the conditions of society. This will complement the economic and environmental assessment proposed in this work, leading to a more comprehensive assessment within the sustainability scope of the CE concept.
- The integration of indicators or monitoring tools considering the societal, technological, governmental and behavioural dimensions is highly recommended to provide a comprehensive and detailed measurement of CE progress at the micro, meso and macro levels.

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Appendices

Appendix A: Methodological details for CE assessment

This supplementary material consists of additional details on methodological aspects to identify circularity alternatives and to perform the proposed environmental, economic, and multi-criteria assessments.

I. Considerations in the definition of circularity alternatives for concrete waste

This section comprises support information and technical specifications used to define circular economy alternatives for concrete waste and is based on the use of the proposed matrix for circularity from **section 4.2.1** of the study. These key findings are presented by lifecycle stage analyzed in the matrix.

End-of-life

CDW is generated during the phase of construction and building renovation, and in higher volumes (more to 50%) during the *end-of-life* stage (Yuan, 2013; Zheng et al., 2017). There are two general practices for the end-of-life of buildings and infrastructure: conventional demolition and selective demolition or deconstruction. Conventional demolition is the most common practice for end-of-life of buildings; however, it significantly reduces the possibilities for salvaging valuable materials (Jiménez-Rivero and García-Navarro, 2016). In contrast, deconstruction practices (selective disassembling) are generally preferred because of their greater environmental benefits and potential economic savings by maximizing and facilitating recovery of building products and components (Chau et al., 2017; Jaillon and Poon, 2014). However, its application is limited due to most of the existing buildings have not been designed for deconstruction, as this is a recent, modern construction method (Rakhshan et al., 2020).

Collection and distribution stage

CDW is collected and segregated according to their physicochemical characteristics (Jiménez-Rivero and García-Navarro, 2017; Zheng et al., 2017) to obtain better quality of waste fractions and facilitate the application of recovery strategies at more efficient rates (from 14 to 24% by volume of the overall CDW when compared with practices without sorting measures (Wang et al., 2010)). Nevertheless, even when selective demolition is implemented, special attention must be taken in the sorting process to remove the possible presence of impurities that could have a negative impact on the properties of the recovered concrete material (Schiller et al., 2017).

There are two types of sorting: on-site (in the construction/demolition site) and off-site sorting (in external facilities) (Jiménez-Rivero and García-Navarro, 2017). Because its potential for ensuring optimal preparation for production of recycled products (Bovea and Powell, 2016), on-site sorting might be preferred over off-site sorting if conditions permit it (Dahlbo et al., 2015; Ghisellini et al., 2018b). Typically, on-site sorting results in reductions of environmental impacts and lower cost by reducing transportation and disposal costs. However, its effective implementation can be hindered by different factors such as insufficient/non concerned manpower, difficulties for waste sortability, unaware management, lack of site space and lack of equipment (Wang et al., 2010).

After sorting, it is recommended to store waste of different qualities separately (e.g., separate waste from structural concrete from that obtained from non-structural concrete). It allows to obtain greater uniformity of recycled aggregates in the following stage of material recovery, as quality of the parent concrete affects the quality of the recycled aggregates (CPH, 2008).

Moreover, *transport processes* are conditioning in the environmental effects of CE strategies (Brambilla et al., 2019). Thus, environmental impacts derived from the production of recycled aggregates are affected by the transport method and distances (T. Ding et al., 2016; Ghisellini et al., 2018a).

Material recovery and production

In this stage, material recovery is steered to minimize environmental burdens and maximize economic value of concrete materials and components (Silva et al., 2020). According to the general CE framework for CDW and in correspondence to the waste hierarchy defined in the Directive 2008/98/EC on waste, there are three alternatives for recovering concrete waste (Zhang et al., 2020):

- reuse,
- recycling into aggregates for concrete production, and
- downcycling to low-grade applications.

Reuse can be applied at the level of whole building, in which the service life buildings is extended through adaptive reuse (transforming spaces for a new function), or at level of components and elements (Joensuu et al., 2020). Reuse of components and elements consists of using them again (in-situ or relocated) with the same or a different purpose limiting their need of transformation and the manufacturing of new building materials (De Wolf et al., 2020; Huang et al., 2018). Moreover, reuse can be directly applied (more beneficial, preferable alternative (Akanbi et al., 2018)) or can require little reprocessing of components throughout repair, refurbishment, or re-manufacture (Schultmann and Sunke, 2007), but involving additional processes of transport and storage (De Wolf et al., 2020).

Although reuse is preferred over recycling and other recovery alternatives because its lower environmental impacts and cost savings (Rakhshan et al., 2020), the current knowledge and experience related to construction products is still limited (Ghaffar et al., 2020). Nevertheless, there is an increasing interest in investigating new solutions of reuse in the building sector (Joensuu et al., 2020).

The potential for reuse depends on the volume and material type, as well as on the geometry and topology of components, and the assembling process of the system (De Wolf et al., 2020). For concrete, reuse is not always possible and barely applied as an alternative for recovery (Gálvez-Martos et al., 2018; Zhang et al., 2020). Some building components such as beams and blocks have the potential for being dismantled and reused, however, except for some prefabricated components, separating concrete elements may be physically impossible for many structures. Furthermore, their application in a new building or infrastructure is often restricted by the specific mechanical properties and dimensions of prefabricated components, and by the difficulties to transport bulky elements (Zhang et al., 2020).

In contrast to reuse, **recycling** is the most extended practice for concrete and other stony materials and consists of crushing to granulate for producing recycled aggregates (RA) for various applications (Di Maria et al., 2018). These can be categorized according to the material value in high-grade (recycling of concrete) and low-grade applications (downcycling of concrete) (Di Maria et al., 2018; Joensuu et al., 2020; Zhang et al., 2020). It is estimated that in the EU only 5% of aggregates produced consist of RA, with Germany and

UK as the larger producers with 65 and 50 million tons per annum respectively, while in Spain production reaches less than a million tons (Rodríguez-Robles et al., 2015).

Recycling/downcycling can be performed on-site by using mobile recycling plants or off-site by transporting the material to fixed plants. Currently, mobile plants are only used for treating the inert fraction of CDW, excluding recycling of other materials (Li et al., 2020). Moreover, depending on the material composition, two types of RA can be produced: recycled concrete aggregates (RCA) from plain and steel-reinforced concrete (primarily concrete rubble), and recycled mixed aggregates (RMA) from a combination of components with varying shares of concrete and ceramic materials, and some pollutants (plaster, plastic, glass and similar) (Rodríguez-Robles et al., 2015; Schiller et al., 2017).

In the ***recycling of concrete*** or ***high-grade applications***, RCA can be used as a substitute of natural aggregates (NA) in the production of both structural and non-structural concrete (Behera et al., 2014). Both applications are appropriate for commercialization and have been tested to meet the required mechanical properties of normal concrete (Behera et al., 2014; Joensuu et al., 2020). Nevertheless, for guaranteeing the correct performance of structural concrete, evidence from multiple studies recommends a replacement limit up to 20-30% by weight of natural coarse aggregates with RCA (Batayneh et al., 2007; Behera et al., 2014; CPH, 2008; Marie and Quiasrawi, 2012; Parekh and Modhera, 2011; Suárez et al., 2016), after this limit, strength characteristics of the concrete tend to decrease. For non-structural concrete, up to 100% of RCA can be used (CPH, 2008; Tošić et al., 2015). Moreover, the use of RCA in the production of recycled concrete (RC) is limited to coarse aggregates with a minimum size of 4-5 mm, and a maximum of 40 mm (CPH, 2008; Schiller et al., 2017). Fine recycled aggregates are not considered and leave the circular flow due to its use is not recommended because their negative effects on stability and strength of the concrete (Parekh and Modhera, 2011; Tošić et al., 2015).

Currently, the use of RCA at large-scale in structural concrete is limited by the lack of clear regulations (Di Maria et al., 2018). In Spain, the Code on structural concrete, EHE-08 (CPH, 2008) regulates the use of RCA in RC, and establishes in its Annex 15 that RA batches shall properly indicate the waste source by identifying the following aspects: nature of material (e.g., mass concrete, concrete mixture); aggregate production plant and waste carrier company; presence of impurities; details on source (type of structure), and; any other important information such as, cause of demolition, contaminants, etc. Moreover, the use of RA in concrete is limited to RCA, and RMA is excluded as it generally contains higher levels of impurities that could negatively affect concrete properties. Apart from a decrease of compressive strength, other effects such as alkali-aggregate reactions, sulphate attack, high shrinkage, and low thaw -freezing resistance may occur if these limits are exceeded. To assure the proper performance of concrete, RCA must comply with the maximum impurity content from **Table 17**.

Table 17. Limit of impurities content in RCA. Source: (CPH, 2008)

Element	Maximum impurity content % of total sample weight
Ceramics	5
Lightweight particles	1
Asphalt	1
Other materials (glass, plastic, metals, etc.)	1,0

On the other hand, ***downcycling of concrete*** refers to a recycling process or any recovery alternative where the material is reprocessed into downgraded products (RA) for their use in other applications in which the material value and quality declines (Joensuu et al., 2020; Vefago and Avellaneda, 2013). In addition, downcycling also considers the cases where pollutants or low-quality materials are mixed during the recycling process (Zhang et al., 2020). As for the final destination of the RA obtained from this process, it can be employed in low-grade applications, such as road base and subbase materials, backfilling at demolition sites, drainage layers and as final cover material at landfills (Arm et al., 2014; Beja et al., 2020; Rodríguez-Robles et al., 2015).

Because the lower purity level of RMA than RCA, the use of RMA is generally recommended for low-grade applications. Nevertheless, some studies provide insights on the viability of also using RMA in concrete but further testing and validation are needed (Rodríguez-Robles et al., 2015; Schiller et al., 2017).

Nowadays, because the lack of quality standards in the use of RA, most of the countries opt for low-grade applications (Di Maria et al., 2018), especially as unbound material in roads (Rodríguez-Robles et al., 2015; Zhang et al., 2020). In this case, RA can replace primary materials in the proportion 1:1. Nevertheless, the savings of virgin materials by weight vary depending on the particle density of the material replaced (Arm et al., 2014).

Lastly, at the end of the recovery and production cycle, residual waste from recovery processes and concrete material with no viable recovery alternatives are landfilled. Although landfilling is considered as the last preferrable alternative, it is the most common management practice for inert waste (Chau et al., 2017; Magriñá Amat, 2012), and in many EU countries, important volumes of concrete and other inert waste are still disposed of in landfills (Zhang et al., 2020).

Characteristics of selected alternatives

The manufacturing of structural concrete follows the dosages used by where concrete mixes present a cube compressive strength ($f_{ck,\ cube}$) of 41.7 MPa for concrete using 100% natural aggregates (SC-NA), 43.5 MPa for 20% RCA substitution (SC-RCA20), and 42 MPa for 30% RCA substitution (SC-RCA30). Dosages for non-structural concrete are based on Suárez Silgado et al. (2018). No additives or superplasticizers were considered in the mixes. Mix proportions for both SC and NSC alternatives are presented in Table 18.

Table 18. High-grade concrete alternatives and mix proportions per m^3

Alternatives		System	Effective w/c[a]	Cement[b] (kg)	Water (kg)	Sand (kg)	Coarse aggregate (kg)	RCA (kg)
SC-NA	Structural concrete, 100% NA	Linear economy	0.49	398	195	614	1193	
SC-RCA20	Structural concrete, 20% RCA substitution	Circular economy	0.49	398	198.2	614	954	239
SC-RCA30	Structural concrete, 30% RCA substitution	Circular economy	0.49	398	199.8	614	835	358
NSC-NA	Non-structural concrete, 100% NA	Linear economy	0.75	250	187.5	886	1,107	
NSC-RCA100	Non-structural concrete, 100% RCA substitution	Circular economy	0.75	250	206.25[c]	998		730

SC= structural concrete; NSC= non-structural concrete; NA= natural aggregates; RCA= recycled concrete aggregates

[a] water-cement ratio

[b] Ordinary Portland cement with a 28-day compressive strength of 42.5 MPa

[c] 10% additional water (pre-saturation)

II. Additional details for performing the Life Cycle Assessment (LCA)

Identification of impact categories

Table 19 lists the most frequent environmental impact categories used in LCA studies and initiatives assessing CDW management alternatives, building's performance, and building components and products with a CE perspective.

Table 19. Use frequency of impact categories

Studies	**GWP** (kg CO2-eq)	**EP** (kg PO4-eq)	**ODP** (kg CFC-11-eq)	**AP** (kg SO2-eq)	**POP** (kg C2H4-eq)	**ADP_E** kg Sb-eq	**ADP_F** MJ	**CED** MJ	**W** m^3
(Butera et al., 2015)	✓		✓			✓	✓		
(Coelho & De Brito, 2012)	✓	✓		✓		✓		✓	
(Ding et al., 2016)	✓								
(European Commission, 2021)	✓	✓	✓	✓	✓	✓	✓		✓
(Lockrey et al., 2018)	✓	✓			✓				
(López Gayarre et al., 2016)	✓	✓		✓	✓				
(Marinković et al., 2010)	✓	✓		✓	✓			✓	
(Mercante et al., 2012)	✓		✓	✓	✓				
(Rosado et al., 2019)	✓	✓	✓	✓		✓	✓		
(Song et al., 2016)	✓	✓	✓	✓	✓		✓		
(Stafford et al., 2016)	✓	✓		✓	✓		✓		
(Suárez Silgado et al., 2016, 2018)	✓	✓	✓	✓		✓			
(Tošić et al., 2015)	✓	✓		✓	✓	✓		✓	
(Vitale et al., 2017)	✓					✓			
(Wang et al., 2018)	✓	✓	✓	✓					
(Weil et al., 2006)	✓					✓		✓	

Notes: Global warming (GWP), eutrophication (EP), acidification (AP), ozone layer depletion (ODP), photochemical oxidation (POP), depletion of abiotic resources - minerals and metals (ADPM), depletion of abiotic resources - fossil fuels (ADPF), cumulated energy demand (CED), water (W).

Specifications on impact methods

All methods used to perform the Life Cycle Impact Assessment corresponded to mid-point approaches.

The method CML-IA baseline V 3.05 was used to calculate the environmental impact categories of GWP, ODP, POP, EP, AP, ADPE, and ADPF. This method is identified by Bovea and Powell (2016) as the most used method in LCA studies on CDW and has been widely applied in similar studies (López Gayarre et al., 2016; Marinković et al., 2010; Mercante et al., 2012; Rosado et al., 2019; Song et al., 2016; Stafford et al., 2016).

The method Cumulative Energy Demand (CED) V1.11 was adopted to calculate the total primary energy consumption including the direct and indirect energy, but excluding the waste used for energy purposes. This method has been proved to be adequate for this type of study by multiple authors such as Ding et al. (2016), Marinković et al. (2010), Tošić et al. (2015) and Weil et al. (2006).

Lastly, water consumption was calculated using the method AWARE V1.02. This method was developed by the international working group on water use assessment WULCA and is identified as the recommended method for assessing water consumption in LCA studies. AWARE is endorsed by the EU Joint Research Center and recommended by the Life Cycle Initiative hosted by UN Environment, the International EPD system, and the Product Environmental Footprint and Organization Environmental Footprint Program of the European Commission.

III. Methodology for multicriteria evaluation: the VIKOR method

The multicriteria method VIKOR was used in this study to determine the best alternative for SC and NSC in terms of economic and environmental aspects. The application of integrative decision-making processes helps to capture the different perspectives and priorities of stakeholder groups and integrates multiple dimensions and basis of the CE (Palafox-Alcantar et al., 2020).

The VIKOR method was developed for multicriteria optimization to obtain the best compromise solution. This method focuses on ranking and selecting from a set of alternatives with conflicting criteria. Thus, alternatives are compared based on the measure of closeness to the ideal solution (Jahan et al., 2011). This method has been proved to be appropriate for analyzing recycled concrete products (Suárez Silgado et al., 2018; Tošić et al., 2015) and for material selection in engineering (Jahan et al., 2011).

Two criterion functions are evaluated with this method: environmental and economic. The environmental criteria consist of the normalized values obtained from the LCA (**Table 9** of the study) for the nine impact categories evaluated**:** GWP, ODP, POP, CED, W, E, AP, ADP_E, ADP_F. The economic criteria values are obtained from **Table 10** of the study.

The following aggregating function was used to carry out the normalization Eq. (1):

$$f = \sum_{ic=1}^{n} w \frac{(f_{ic}^{*} - f_{icj})}{(f_{ic}^{*} - f_{ic}^{-})} \qquad \textbf{(1)}$$

where,

w = weighting factor
f_{icj} = impact category value
f_{ic}^{*} = ideal value of the impact category
f_{ic}^{-} = anti-ideal value of the impact category

Ideal and anti-ideal values correspond to the minimum and maximum values by impact category and alternatives. Based on Tošić et al. (2015), an equal weighting factor of 0.11 was assigned to each impact category. Normalized values for the environmental criterion function are listed in **Table 20**.

Table 20. Normalized values for environmental function criteria

Scenario	Normalized value
Structural concrete	
SC-NA (linear economy)	1.00
SC-RCA20-OFFS-RP	0.20
SC-RCA20-ONS-MP	0.03
SC-RCA30-OFFS-RP	0.23
SC-RCA30-ONS-MP	0.05
Non-structural concrete	
NSC-NA100 (Linear economy)	1.00
NSC-RCA100-OFFS-RP	0.25
NSC-RCA100-ONS-MP	0.00

The following step is to determine the best (f_i^*) and worst (f_i^-) benefits of each criterion by using the Eq.(2a) if the criterion is positive, and Eq.(2b) if the criterion is negative:

$$f_j^* = Max_i f_{ij} \quad , \quad f_j^- = Min_i f_{ij} \quad ; \quad j = 1,2,\dots,n \quad \textbf{(2a)}$$

$$f_j^* = Min_i f_{ij} \quad , \quad f_j^- = Max_i f_{ij} \quad ; \quad j = 1,2,\dots,n \quad \textbf{(2b)}$$

The positive ideal solution (f^*) and negative ideal solution (f^-) can be expressed as follows:

$$f^* = \{f_1^*, f_2^*, f_3^*, \dots, f_n^*\}$$

$$f^- = \{f_1^-, f_2^-, f_3^-, \dots, f_n^-\}$$

Next step is to calculate the S_i and R_i values, which represents the group utility and individual regret, respectively. Eq. (3) and Eq. (4):

$$S_i = \sum_{j=1}^{n} w_j \frac{(f_j^* - f_{ij})}{(f_j^* - f_j^-)} \qquad \textbf{(3)}$$

$$R_i = Max_j \left[w_j \frac{\left(f_j^* - f_{ij}\right)}{\left(f_j^* - f_j^-\right)} \right] \quad \textbf{(4)}$$

Where, w_j represents the weight of the criteria. Three criteria rankings were established giving emphasis to criteria functions and considering an additional neutral criterion (**Table 21**):

Table 21. Criteria characteristics

Ranking criteria	Type	W_j Environmental function	W_j Economic function
1- Neutral importance	Negative (-)	0.5	0.5
2- Environmental preference (2:1)	Negative (-)	0.67	0.33
3- Economic preference (2:1)	Negative (-)	0.33	0.67

The value Q_i is calculated by Eq. (5). This measure represents a linear interpolation of the Sj and Rj values. The value of interpolation coefficient or group utility (γ) was defined of 0.5 to give equal importance to both S_i and R_i values.

$$Q_i = \gamma \frac{(S_i - S^*)}{(S^- - S^*)} + (1-\gamma)\frac{(R_i - R^*)}{(R^- - R^*)} \quad \mathbf{(5)}$$

Where,

$S^* = Min_i\{S_i\}$ $\qquad$ $S^- = Max_i\{S_i\}$

$R^* = Min_i\{R_i\}$ $\qquad$ $R^- = Max_i\{R_i\}$

The final step is to propose as a compromise solution the alternative ($A^{(1)}$), which is the best ranked (closest alternative to 0) by the measure Q if the following two conditions are satisfied:

Condition 1: Acceptable advantage:

$$Q(A^{(2)}) - Q(A^{(1)}) \geq 1/(m-1)$$

where, $A^{(2)}$ is the second-best ranked alternative by Q and m is the number of alternatives.

Condition 2: Acceptable stability in decision making, in which $\mathrm{A}^{(1)}$ must also be the best ranked by S or/and R.

If one of the conditions is not satisfied, then a set of compromise solutions is proposed:

Solution a: Alternatives $A^{(1)}$, $A^{(2)}$, … . , $A^{(M)}$ if condition 1 is not satisfied.
where, $A^{(M)}$ is determined by $Q\left(A^{(M)}\right) - Q\left(A^{(1)}\right) < 1/(m-1)$ for maximum M

Solution b: Alternatives $A^{(1)}$ and $A^{(2)}$ if only condition 2 is not satisfied.

Solution c: Alternative with the minimum Q value is selected as the best Alternative if both conditions are satisfied.

Appendix B: Circular economy indicators

I. Existing CE-related indicators

			Main criteria			
Indicator	**Description**	**CE category/ criteria**	**Environmental**	**Value-oriented**	**Material and products**	**Author**
Circular Transition Indicators (CTI) framework	*Consists of the following set of indicators that asses the circularity performance of a company incorporating Life Cycle Thinking*	Eco-design, use of resources, recovery alternatives, value				(WBCSD, 2021)
% Circularity	Represents the weighted average between %circular inflow (non-virgin content and renewable content) and % circular outflow (recovery potential and the actual recovery)		●		●	
Water circularity	Determines the circularity of freshwater (inflow/outflow)		●			
Renewable energy	Calculates the percentage of renewable energy consumed		●			
Critical inflow	Represents the share of the inflow considered critical.				●	
Recovery type	Describes how the company recovers outflow and recirculates it into the value chain.		●			
Circular material productivity	Estimates the effectiveness of the company in decoupling financial performance and linear resource consumption			●		
CTI revenue	Consists of the company’s revenue adjusted for the percentage circularity of its product portfolio			●		
Material Circularity Indicator (MCI)	Measures the restorative rate of material flows of a product. It considers the utility of the products, the use of virgin materials, the waste recovered, and the waste disposed of in landfills	Manufacturing, recovery alternatives, resource duration	●		●	(EMF and GRANTA, 2015)

Indicator	Description	CE category/ criteria	Main criteria			Author
			Environmental	Value-oriented	Material and products	
Circulytics	Measures the entire company's circular economy performance and consisting of an overall score evaluating enablers (strategy and planning; innovation; people and skills; operations; and external engagement) and outcomes (products and materials; services; plant, property and equipment (PPE) assets; water; energy; and finance	Manufacturing, recovery alternatives	●		●	(EMF, 2020)
Product Level Circularity Metric (PLCM)	Cost-based approach to evaluate circularity of product parts and value chain activities	Recycling, remanufacturing		●		(Linder et al., 2017)
Material Durability Indicator (MDI)	Evaluates chemical and mechanical durability of materials and the environmental performance of material processing and recycling	Eco-design, manufacturing and recycling	●		●	(Mesa et al., 2020)
Potential Reuse Index (Preuse)	Measures the degree of potential reuse of components between different product variants within the product family	Reuse			●	(Mesa et al., 2018)
Potential Recycle Index (Prec)	Measures the degree of potential recycling of components within the product family	Recycling			●	(Mesa et al., 2018)
Circular Economy Index (CEI)	Calculates the ratio between the material value produced by the recycler (market value) and the intrinsic material value entering the recycling facility	Recycling		●		(Di Maio and Rem, 2015)
Circular Economy Performance Indicator (CPI)	Represents the ratio of the actual environmental benefit over the ideal environmental benefit according to quality in terms of natural resource consumption, Environmental data can be calculated by Life Cycle Assessment (LCA)	Waste management options: recycling and energy recovery	●			(Huysman et al., 2017)
Value-based resource efficiency (VRE) indicator	Focuses on the market value of non- sustainable/stressed inputs to the economy, in relation to output, which consists of the value added of the economy or the industry.	Resource efficiency		●		(Di Maio et al., 2017)
Combination Matrix (CM)	Combines circularity and longevity to assess the overall lifetime of products and materials. Circularity is expressed as the number of	Resource duration			●	(Figge et al., 2018)

Indicator	Description	CE category/ criteria	Main criteria			Author
			Environmental	Value-oriented	Material and products	
	times a resource is used, and longevity is the amount of time the resource is used. CM considers the contribution of the initial use, remanufacturing and recycling.					
Longevity Indicator (LI)	Measures the contribution to material retention based on the time a resource is kept in in the system. It includes initial lifetime, earned refurbished lifetime and earned recycled lifetime.	Resource duration			●	(Franklin-Johnson et al., 2016)
Recycling Desirability Index (RDI)	Evaluates material recycling desirability of products at the end-of-life by quantifying the simplicity of materials to be separated, a material security index, maturity of recycling technology, and the economic value of materials.	Recycling		●	●	(Mohamed Sultan et al., 2017)
Reuse Potential Indicator (RPI)	Describes how materials change from waste into a potential resource or vice versa. It determines the possibility of reuse for a material.	Reuse			●	(Park and Chertow, 2014)
Eco-costs Value Ratio (EVR) Model	Evaluates resource efficiency in terms of the ratio between eco-costs and economic value	Resource efficiency		●		**(Scheepens et al., 2016)**
Product Recovery Multi-criteria Decision Tool (PR-MCDT)	Evaluate product circularity strategies considering relevant economic (e.g. Net Recoverable Value, NRV), environmental (e.g. End of Life impact on the Environment, EOLI), and social indicators (e.g. number of employees)	Recovery options	●	●		(Alamerew and Brissaud, 2019)
Design Method for End-of-use Product Value Recovery (EPVR)	Evaluates end-of-use scenarios (recycling, reuse and disposal) based on their recovery profit	Reuse, recycling and cost-savings		●		(Cong et al., 2019)
Ease of Disassembly Metric (eDiM)	Calculates the disassembly time of products based on the Maynard operation sequence technique (MOST), and enables to analyze the contribution of each task to the total disassembly time	Eco-design and recovery			●	(Vanegas et al., 2018)
Global Resource Indicator (GRI)	Evaluates resource performance based on recyclability and criticality using multicriteria analysis and is complemented by scarcity	Recycling			●	(Adibi et al., 2017)

II. Composition of existing CE indicators for the CDW sector

Author	Indicator	Disaggregation
(Akinade et al., 2015)	Building Information Modelling based Deconstructability Assessment Score (BIM-DAS)	*Deconstruction score* – Type of elements – Number of elements – Connection type – Prefabricated elements *Recovery score* – Reusable materials – Recyclable materials – Secondary finishes – Toxicity of material
(Bilal et al., 2020)	Mitigation framework to evaluate the level of implementation of the CE in the building sector for developing countries	– Comprehensive utilization rate of industrial solid waste – Recycling rate of reclaimed wastewater – Total amount of SO_2 emissions – Total amount of CO_2 emissions – Rate of waste emissions – Design in accordance with CE principles – Total amount of wastewater discharge – Water consumption per unit product in key industrial sectors – Environmental awareness in society – Passing rate of used materials back into the supply chain – Comprehensive disposal rate of dangerous waste – Reusing rate of products/materials – Freshwater consumption – Willingness for transformation to a circular economy model – Percentage consumption of renewable or clean energy – Energy-saving amount – Redesign of products/services – Rate of carbon footprint – Availability of complete bill of materials and substances for the product – Output of main mineral resource – Energy consumption – Total amount of industrial solid waste disposal – Availability of complete bill of solid waste for the manufacturing process – Recycling rate of industrial solid waste
(Coenen et al., 2021)	Bridge Circularity Indicator (BCI)	*Design Input* – Material input – Robustness *Resource Availability* – Scarcity *Adaptability* – Extensibility – Heightenabily – Strengthenability *Reusability* – Disassembly – Transportability – Uniqueness
(Cottafava and Ritzen, 2021)	Predictive Building Circularity Indicator (PBCI)	

Author	Indicator	Disaggregation
(European Commission, 2021)	Level(s), European framework for sustainable buildings	*Greenhouse gas and air pollutant emissions along a building's life cycle* – Use stage energy performance – Life cycle Global Warming Potential *Resource efficient and circular material life cycles* – Bill of quantities, materials and lifespans – Construction & demolition waste and materials – Design for adaptability and renovation – Design for deconstruction, reuse and recycling *Efficient use of water resources* – Use stage water consumption *Healthy and comfortable spaces* – Indoor air quality – Time outside of thermal comfort range – Lighting and visual comfort – Acoustics and protection against noise *Adaptation and resilience to climate change* – Protection of occupier health and thermal comfort – Increased risk of extreme weather events – Increased risk of flood events *Optimized life cycle cost and value* – Life cycle costs – Value creation and risk exposure
(Foster and Kreinin, 2020)	Key environmental indicators for adaptive reuse of cultural heritage buildings (IAR-CHB)	*Direct reductions to new natural materials extraction* – Maintain embodied energy in reused concrete, stone, brick, steel, etc. – Water efficiency / freshwater consumption – Reduce CDW to landfill through recovery and reuse on or off-site – Increase land use efficiency *Direct reductions to energy use* – Greenhouse Gas Emissions – Increase energy efficiency / consumption – Increase amount of non-renewable vs renewable energy use *Direct environmental improvements* – Reductions to air emissions including CO2, Nitrogen oxides (NOx), Sulphur oxides (SOx), and PM – Improve water quality measured as eutrophication potential based on nutrient loads *Indirect reductions to energy use or pollution* – Maintain embodied energy in reused concrete, stone, brick, steel, etc. – Limit land use change – Indirect emission reductions e.g. reduction in vehicle use
(Fregonara et al., 2017)	Synthetic economic-environmental indicator for the end-of-life of buildings (SEE)	*Environmental Indicators* – Embodied Energy – Embodied Carbon – Level of disassembly of building systems – Amount of Recycled material – Waste generated *Economic Indicators* – Global Cost – Costs related to Embodied Energy – Costs related to Embodied Carbon
(Heisel and Rau-Oberhuber, 2020)	Circularity Indicator Building Score (CIB-S)	– Circularity construction phase: represents the ratio of virgin materials to recycled, re-used or rapidly renewable materials

Author	Indicator	Disaggregation
		– Circularity use phase: represents the expected lifespan of utilized products, compared to the average life span of status-quo products in the same application. – Circularity end-of-life phase: represents the ratio between waste materials and re-usable and/or recyclable materials generated when a building is refurbished or demolished
(Jiménez-Rivero and García-Navarro, 2016)	Best performance indicators to measure the management performance of end-of-life gypsum (BPI-GW)	*Audit* – Effectiveness of the audit *Dismantling* – Effectiveness of the deconstruction process *Traceability* – Effectiveness of the traceability – Cost comparison between routes *Transport* – GW sent to landfill – Transport of GW emissions comparison – Follow-up of the waste management *Dismantling* – Training of the deconstruction team *Reception* – Waste acceptance criteria – GW rejected – Stakeholders' satisfaction *Storage* – Warehouse space *Processing* – Output materials of the recycling process – GHG emissions processing and transport – Natural gypsum saved *RG quality* – RG rejected – RG quality criteria
(Nuñez-Cacho et al., 2018)	Circular Economy measurement scale for building industry	*General CE Indicators* – Our company design according to Circular economy principles – There is an environmental awareness in our society – Our company consider environmental issues – We dispone of a board indicator for management of materials – Our company aims the transformation to Circular economy model – Our company use the Building Information Modelling (BIM) *Material Indicators* – Are the product's materials passed back into the supply chain? – We use asphalt pavement recycled in order to reclaim bitumen – Our crude steel production is very high – We reduce the direct Material Input – Our company analyze the iron resource efficiency – Is there a complete bill of materials and substances for the product? – We dispose of a lead indicator for resource productivity – Extensive use of environmentally responsible in materials – We dispose of Indicators of Improvement of use of materials – We reduce the output of main mineral resource *Energy Indicators* – We increase the consumption of new, renewable or clean energy – We raise the energy saving amount – We are diminishing the energy used per ton of asphalt mix produced – We have a lower fuel consumption on a trial mode

Author	Indicator	Disaggregation
		– We dispose of Indicators of energy efficiency improvement – We use agro-industrial energy (sugar, ethanol biomass) *Water Indicators* – We dispose of Indicators of Improvement of Water efficiency – Environmental Chemicals is used in the process of treating water – We dispose of Indicators of Industrial water reuse ratio – Our company recycle and reused water *3R's Indicators* – Our products/services can be repaired – Our products/services can be reused – Our products/services can be redesign – We dispose of a material recovery scheme – We use efficient technologies for recovery of materials – We increase ratio use of recycled materials/production – We improve the recycling rate of solid waste *Indicators of emissions* – We reduce the energy indirect greenhouse gas emissions level – We reduce our carbon footprint – We reduce our CO2emissions level – We reduce our energy environmental Footprints *Indicators of Waste* – Does the product reduce waste through its use? – We diminish our hazardous waste (metric ton) – We use a complete bill of solid waste for the manufacturing process – We employ measures to prevent, recycle and eliminate waste – we reduce the non-hazardous waste that is recycled – We improve our recycling rate of solid waste – We manage efficiently the waste
(Vefago and Avellaneda, 2013)	Index of recyclability of buildings (IRB)	– Index of design recyclability – Index of deconstruction recyclability
(Yeheyis et al., 2013)	Construction waste LCA-based sustainability index (CWLSI)	*Environmental Indicators* – C&D waste generated – C&D waste recycled, composed, landfilled – Avoided emissions to air & water from waste management facilities, etc. *Economic Indicators* – Cost of C&D waste disposal – Net cost of operating and maintaining recycling facilities – Fuel Consumption (transport), etc. *Social Indicators* – Public acceptance of C&D waste management plans and actions – Public participation in planning and implementation – Working safety, etc.