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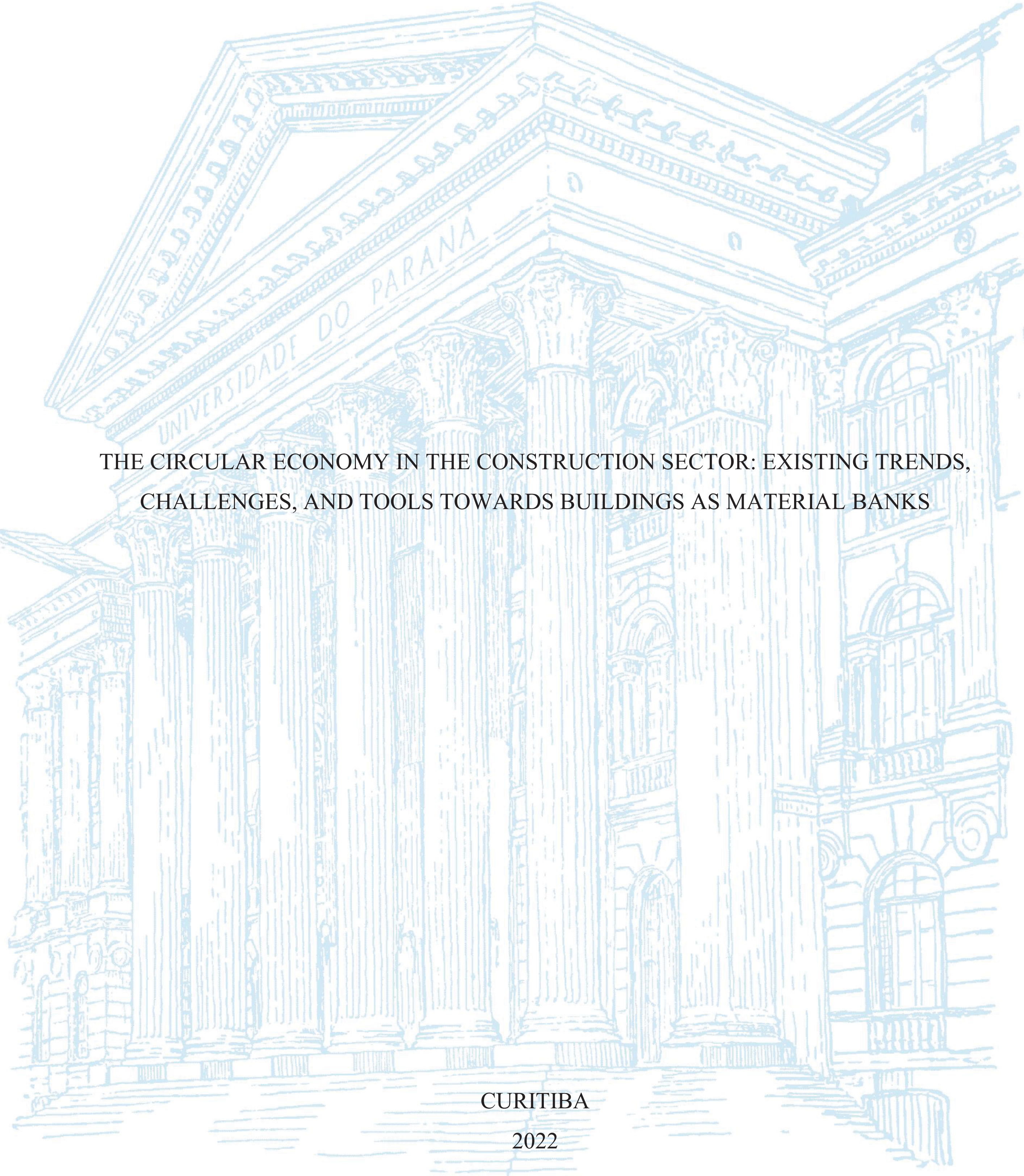

THE CIRCULAR ECONOMY IN THE CONSTRUCTION SECTOR: EXISTING TRENDS, CHALLENGES, AND TOOLS TOWARDS BUILDINGS AS MATERIAL BANKS

CURITIBA

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Orientador: Prof. Ph.D. Sérgio Fernando Tavares
Coorientador: Prof. Ph.D. Luís Bragança

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Os membros da Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação ENGENHARIA CIVIL da Universidade Federal do Paraná foram convocados para realizar a arguição da tese de Doutorado de **MAYARA REGINA MUNARO** intitulada: **THE CIRCULAR ECONOMY IN THE CONSTRUCTION SECTOR: EXISTING TRENDS, CHALLENGES, AND TOOLS TOWARDS BUILDINGS AS MATERIAL BANKS**, sob orientação do Prof. Dr. SÉRGIO FERNANDO TAVARES, que após terem inquirido a aluna e realizada a avaliação do trabalho, são de parecer pela sua APROVAÇÃO no rito de defesa.
A outorga do título de doutora está sujeita à homologação pelo colegiado, ao atendimento de todas as indicações e correções solicitadas pela banca e ao pleno atendimento das demandas regimentais do Programa de Pós-Graduação.

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When we reach the end of a journey, it is common to remember the beginning of it, and all the challenges, doubts, and setbacks that we encountered during it. Without a shadow of a doubt, in these years dedicated to this research, I had profound and significant changes in my skills as a researcher, academic, and future teacher. Above all, my character has been changed, as it is impossible not to mix personal and professional life during a long, exhausting, and rewarding project. During that time, my research was my life, my refuge, and my nightmare. And in this ambivalent relationship, I managed to observe myself and become a more resilient, empathetic person and researcher, concerned with doing and communicating science in a responsible and accessible way. I am happy to see my evolution in this process because between the beginning and the end, it was the journey that showed me that persistence and determination are omnipotent skills.

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It is not the critic who counts;
not the man who points out how the strong man stumbles,
or where the doer of deeds could have done them better.
The credit belongs to the man who is actually in the arena,
whose face is marred by dust and sweat and blood;
who strives valiantly;
who errs, who comes short again and again,
because there is no effort without error and shortcoming;
but who does actually strive to do the deeds;
who knows great enthusiasms, the great devotions;
who spends himself in a worthy cause;
who at the best knows, in the end, the triumph of high achievement,
and who at the worst, if he fails, at least fails while daring greatly,
so that his place shall never be with those cold and timid souls
who neither know victory nor defeat.

Citizenship in a Republic (or **The Man in the Arena**) is the title of a speech given by Theodore Roosevelt, former President of the United States, at the Sorbonne in Paris, France, on April 23, 1910

RESUMO

O ambiente construído exerce pressão sobre os recursos naturais e seu papel na transição para uma economia circular é fundamental. A economia circular (EC) propõe modelos de negócios circulares que substituem o conceito de fim de vida por redução, reutilização, reciclagem e recuperação de recursos nos processos de produção/distribuição e consumo, visando alcançar o desenvolvimento sustentável, criar qualidade ambiental, prosperidade econômica e equidade social. Apesar de estar ganhando cada vez mais destaque no meio acadêmico, corporativo e governamental, sua implantação no setor construtivo é limitada e a literatura carece de referências que esclareça os conceitos relacionados a EC e direcione a implantação de ferramentas e modelos de negócios circulares ao longo do ciclo de vida das edificações e aos *stakeholders* da cadeia de valor da construção civil. Este estudo buscou criar um referencial teórico baseado em conceitos e ferramentas baseadas na economia circular para entender as tendências e desafios relacionados a implementação de práticas circulares para que as edificações se tornem banco de materiais. Por meio de uma pesquisa de caráter qualitativo-exploratória, baseada em revisões de literatura e análise estruturada de dados, esse estudo buscou analisar (1) o estado da arte atual da EC no ambiente construído; (2) os desafios e as oportunidades de se implementar o passaporte de materiais nas edificações; (3) diferentes modelos de negócios circulares que podem ser implantados ao longo do ciclo de vida das edificações visando aumentar o valor residual dos materiais de construção; (4) as principais políticas públicas brasileiras que suportam os princípios circulares; (5) as metodologias de ecodesign que corroboram com o princípio de desconstrução das edificações; (6) as principais barreiras e oportunidades de implementar a EC na construção civil; e (7) as principais diretrizes de desconstrução das edificações que devem ser adotadas na fase de projeto. Esta tese é organizada por meio de um documento introdutório e artigos científicos que buscaram responder essas demandas de pesquisa e, coletivamente, fornecem um mecanismo amplo e coeso de conhecimento que fornecem direcionamento de ações voltadas a tornar as edificações como bancos temporários de materiais. Dos resultados, conclui-se que a EC ainda é incipiente no setor e voltada a mitigação e reutilização dos resíduos da construção civil. A demora do setor às mudanças, a falta de conhecimento e esclarecimento sobre as metodologias de ecodesign, modelos de negócios e os princípios da EC são barreiras críticas. Uma revisão sistêmica do modelo de produção e consumo das edificações requer arranjos entre oferta, demanda, política e governos voltadas à um mercado baseado no uso eficiente dos recursos. Além disso, é preciso elucidar os ganhos econômicos, sociais e ambientais que as práticas circulares irão proporcionar aos stakeholders da cadeia de valor da construção civil. Percebe-se que a esperada mudança de paradigma na forma como os edifícios são projetados e construídos será possível a partir de parcerias público-privadas que promovam a integração dos atores e o fechamento de ciclos dos materiais, fortalecendo a fiscalização e implementação de edifícios reversíveis, o mapeamento e compartilhamento de informações, aliadas às necessárias medidas de incentivo fiscais. Este estudo visou explicitar lacunas e descortinar novas possibilidades de pesquisa no âmbito científico e contribuir para o desempenho estratégico de tomadores de decisão para que introduzam princípios circulares nos modelos de negócios e nas cadeias de valor da construção civil, tornando as edificações e o ambiente construído mais sustentáveis.

Palavras-chave: Economia circular. Construção civil. Edificações sustentáveis. BAMB. Edificações circulares.

ABSTRACT

The built environment puts pressure on natural resources and its role in the transition to a circular economy is critical. The circular economy (CE) proposes circular business models (CBMs) that replace the end-of-life concept with reduction, reuse, recycling, and recovery of resources in production/distribution and consumption processes, aiming to achieve sustainable development, create environmental quality, economic prosperity, and social equity. Although it is gaining prominence in the academic, corporate, and governmental environments, its implementation in the construction sector is limited and the literature lacks references that elucidate the concepts related to CE and direct the implementation of tools and CBMs throughout the life cycle of buildings and stakeholders in the construction value chain. This study sought to create a theoretical framework based on concepts and tools based on the circular economy to understand trends and challenges related to the implementation of circular practices so that buildings become a bank of materials. Through qualitative-exploratory research, based on literature reviews and structured data analysis, this study sought to analyze (1) the current state of the art of CE in the built environment; (2) the challenges and opportunities of implementing the materials passport in buildings; (3) different circular business models that can be implemented throughout the life cycle of buildings to increase the residual value of building materials; (4) the main Brazilian public policies that support the circular principles; (5) ecodesign methodologies that support the principle of deconstruction of buildings; (6) the main barriers and opportunities to implement CE in the construction sector; and (7) the main guidelines for the deconstruction of buildings that must be adopted in the design phase. This thesis is organized through an introductory document and scientific papers that seek to answer these research demands and, collectively, provide a broad and cohesive framework of knowledge that provides direction for actions aimed at turning buildings into temporary banks of materials. From the results, it is concluded that CE is still incipient in the sector and focused on the mitigation and reuse of construction and demolition waste. The industry's delay in changing, the lack of knowledge and clarification on ecodesign methodologies, CBMs, and CE principles are critical barriers. A systemic review of the model of production and consumption of buildings requires arrangements between supply, demand, policy, and governments aimed at a market based on the efficient use of resources. In addition, it is necessary to elucidate the economic, social, and environmental gains that circular practices will provide to stakeholders in the construction value chains. The expected paradigm shift in the way buildings are designed and built will be possible from public-private partnerships that promote the integration of actors and the closing of material cycles, strengthening the supervision and implementation of reversible buildings, mapping, and information sharing, combined with the necessary tax incentive measures. This study aimed to clarify gaps and uncover new research possibilities in the scientific field and contribute to the strategic performance of decision-makers to introduce circular principles in business models and construction value chains, making buildings and the built environment more sustainable.

Keywords: Circular economy. Construction sector. Sustainable building. BAMB. Circular building.

LIST OF NON-TEXTUAL ELEMENTS

THESIS STRUCTURE

This thesis is structured in three main parts: characterization of the research, originated papers during the research, and final considerations of the study.

PART 1 RESEARCH CHARACTERIZATION

The introductory part contextualizes the research problem and identifies the justifications, objectives, adopted methodology, and the results of the study.

Section 1 Introduce the research context, research background, discuss the importance of the subject and identify the research question;

Section 2 Identify the conceptual background of the research and the theoretical context of the circular economy;

Section 3 Discuss the conceptual foundation and overall research design;

Section 4 Introduces the results of the research, the common themes underlying the originated articles, and how the different research are aggregated in a continuous, conceptual, and practical context.

PART 2 SCIENTIFIC PAPERS

Part 2 includes the seven scientific papers that originated as part of this study. Paper types are explained in Section 4 of Part 1.

Paper A1 Towards circular and more sustainable buildings: a systematic literature review on the circular economy in the built environment (Munaro et al., 2020)

Paper A2 Materials passport's review: challenges and opportunities toward a circular economy building sector (Munaro and Tavares, 2021)

Paper A3 Circular Business Models: Current State and Framework to Achieve Sustainable Buildings (Munaro et al., 2021)

Paper A4 Analysis of Brazilian public policies related to the implementation of circular economy in civil construction (Munaro and Tavares, 2022)

Paper A5 The ecodesign methodologies to achieve buildings' deconstruction: A review and framework (Munaro et al., 2022)

Paper A6 A review on barriers, drivers, and stakeholders towards the circular economy: the construction sector perspective

Paper A7	Design for Adaptability and Disassembly: a state-of-art review towards circular buildings
PART 3	**CONCLUSIONS** Presents the final considerations of the study. It identifies the main contributions, limitations, and future extensions for the academic development of the subject.

SUMMARY

PART 1

This document presents the justifications, questions, objectives, strategy, and results of the research. It summarizes the contribution of each paper developed during the study, explores common research themes, and provides a holistic view of the studies developed.

1 INTRODUCTION

The world population is increasing, along with the consumption of power and waste generation. In a scenario where the population of urban areas is growing by 200,000 people a day, all in need of affordable housing, social infrastructure, transport, and public services, the challenge of the construction sector is immense (WEF, 2016). The sector needs to transform and rethink the way it plans and builds the built environment. This transformation will have social effects: by rethinking the way of planning, building, and consuming, reducing construction costs; environmental: improving the use of raw materials or making buildings more sustainable; and economic: decreasing the global infrastructure deficit and stimulating economic development.

Since the Industrial Revolution, the linear growth model adopted, by assuming that resources are abundant, available, and discarding them at their end of life, has led to the continuous depletion of resources and the increase in waste (EMF, 2015a). The construction sector has effectively contributed to this scenario, being the largest consumer of resources and raw materials in the world, responsible for high levels of waste generation, greenhouse gases, and consuming more than a third of the planet's total energy (IRP, 2017; CIRCLE ECONOMY, 2018; UNEP, 2021). Construction materials and products end up being wasted when they are no longer needed for their intended function, a fact that accelerates the devastation of ecosystems, increases environmental costs and carries risks of resource scarcity. The construction sector needs to evolve towards a system based on circularity, in which buildings and construction materials are used, reused, adapted, and reconstructed, considering economic and environmental rationality at the center of decisions.

The circular economy (CE) is a model that allows us to rethink the economic practices of society and is inspired by the functioning of nature itself. It has a sustainable development approach based on the principle of "closing the life cycle" of products, allowing for a reduction in the consumption of raw materials, energy, and water. It is inseparable from innovation and the design of products and systems. Employs the principles of designing waste and pollution; keeping materials and products in use and regenerating natural systems (EMF 2015a; 2017).

The implementation of circular principles in the built environment is supported by the European project Buildings as Material Banks (BAMB), which employs information technologies, business models, and partnerships to reduce costs, and environmental impacts and make urban areas more livable, productive, and sustainable. The systemic nature of CE requires that the ecosystem and its components change. The construction sector is still at an embryonic stage and is limited to the minimization and recycling of construction and demolition waste (MUNARO et al., 2020). Systematic research, including how new circular business models (CBMs) can allow materials to maintain or increase their residual values, needs to be further explored.

This study seeks to analyze how principles based on the circular economy can be implemented in the built environment, in buildings, and construction value chains so that buildings become a bank of materials. Little research has been carried out to clarify the mechanisms based on the circular economy to make buildings more sustainable. To the author's knowledge, this is the first work that creates a theoretical framework encompassing tools, trends, and challenges towards the circular transition of the civil construction sector. It is proposed that a building, characterized as circular, be a temporary aggregation of components, elements, and materials with documented identity and records, from its origin to reuse, connected in a way that accommodates a function for a certain established period.

1.1 JUSTIFICATION

Construction is one of the largest sectors of the global economy, accounting for 13% of Gross Domestic Product (GDP) and employing 7% of the working-age population (MGI, 2017). In Europe, the sector houses more than 18 million jobs (CEN, 2017). It is also known that the urban population of the world is growing at a rapid pace. 55% of the world's population lives in urban areas, and by 2050, it is projected to increase by more than two-thirds of the world (68%) (UN, 2019). In Brazil, 85% of the population is concentrated in urban areas (UN HABITAT, 2013), a rate that is expected to reach 91% by 2050 (EMF, 2017). As a result, the dimensions of the built environment are expected to double, putting increasing pressure on urban public systems such as water, energy, and waste management networks (UNEP, 2021).

While the past few decades have seen improvements in the energy efficiency of buildings and the livability of cities, the built environment continues to be designed around the linear "take-to-make" model, in which materials are sourced, used, and then disposed of as waste. This approach results in significant structural waste and has contributed to making the construction industry one of the largest consumers of resources and raw materials in the world and a major generator of waste and carbon emissions.

The transition from the construction industry to CE requires a focus on systems thinking, which understands the building's life cycle and the construction value chain, involving the integration of all stakeholders. Buildings as Material Banks (BAMB), a project initiated in Europe with institutions from different countries, aims at systematic change in the construction sector by investigating and creating circular solutions to conserve the value and functionality of building materials and systems (BAMB, 2016). This concept is being added to the entire economic chain of construction through mechanisms such as the materials passport and the design of reversible buildings (see item 2.3).

When envisioning the BAMB project and the construction scenario, it should be noted that the implementation of guidelines and circular practices to obtain and manage information systems will facilitate stakeholder decision-making, creating opportunities for sustainable innovation in the construction industry. As a result, this study is based on the BAMB project to study initiatives and circular actions aimed at the construction sector to increase the value of materials, reduce waste, and provide more resilient and sustainable buildings.

1.1.1 Environmental justification

The construction sector consumes 42.4 billion tons of resources annually, equivalent to 40% of the total use of natural resources, 25% of water, and 36% of global energy (IRP, 2017; CIRCLE ECONOMY, 2018; UNEP, 2021). In 2020, buildings accounted for 37% of global greenhouse gas (GHG) emissions (UNEP, 2021). To limit global temperature, rise to 2°C, as set out in the Paris Agreement, it is necessary for the sector to almost reducing carbon dioxide (CO_2) emissions completely by 2050 (UNEP, 2021). This requires a three-pronged strategy: reducing energy demand and increasing energy efficiency, decarbonizing the energy system, and dealing with the embodied carbon stored in building materials (UNEP, 2021). These initiatives seek to achieve the United Nations Sustainable Development Goals (SDGs), especially with these seven SDGs: clean water and sanitation (SDG 6), affordable and clean energy (SDG 7), decent work and economic growth (SDG 8), sustainable cities and communities (SDG 11), responsible consumption and production (SDG 12), climate action (SDG 13), and life on land (SDG 15) - providing housing for all, having cleaner and more resilient cities, protecting, and improving health and support economic prosperity (UN, 2015).

The construction industry also generates a huge amount of waste. Construction and demolition waste (CDW) represent 25 to 30% of the waste generated in the European Union and about 40% of solid waste in the United States (WEF, 2016). Of the waste generated in the sector, up to 80% of the total is discarded without any possibility of recycling or reuse (WEF, 2016). In Brazil, construction waste (CW) represents a problem in many cities due to irregular disposal, generating aesthetic, environmental, and public health problems; and the overload on municipal public cleaning systems, since, in Brazil, the CW 2010 represents about 60% of the mass of solid urban waste (MUNARO; TAVARES, 2022).

Worldwide, these wastes involve a significant loss of minerals, metals, and organic materials, so there is a great opportunity to create closed material loops in a CE. Closing the building materials cycle considers that these resources can be recovered from buildings and reused by natural or industrial processes. It should be noted that most of the natural resources used in the built environment are fixed in buildings and highways for a long time. Therefore, even if the materials from demolished buildings were completely reused, large amounts of resources would still be needed to satisfy the current economic and population growth demand (CIRCLE ECONOMY, 2018).

Meeting housing, employment, and public infrastructure needs sustainably is crucial for countries facing rapid urbanization and population growth. Changes in the planning, design, commissioning, construction, maintenance, renovation, and end-of-life stage of buildings offer significant opportunities to reduce environmental impacts by providing healthy and safe living and working spaces.

1.1.2 Economic justification

Around $10 trillion a year is being spent on buildings, infrastructure, and industrial facilities, occupying more than 100 million people (WEF, 2016). By 2025, this amount is projected to total $14 trillion (MGI, 2017). In Brazil, according to the Brazilian Institute of Geography and Statistics (IBGE), in 2017 the construction activity totaled BRL 280 billion in incorporations, works, and construction services, employing about 1.9 million people. Spending on salaries and other compensation reached the amount of BRL 53.6 billion (IBGE, 2017). However, the sector could produce more for this investment if productivity were higher. Globally, labor productivity growth in construction has averaged just 1% per year over the past two decades, compared with growth of 2.8% in the total world economy and 3.6% in the case of manufacturing (MGI, 2017). In Brazil, the productivity of the construction sector has been decreasing for 20 years (MGI, 2017).

CE has enormous potential for global economic growth, accelerating society towards a more sustainable future. The total value of circular opportunities globally could reach $4.5 trillion. According to the Ellen Macarthur Foundation (EMF), material savings can result in an annual reserve of $630 billion in consumer goods (including building materials) and 20% savings on products with a short sector life. (e.g., packaging), which equates to savings of over $700 billion (WEF, 2014).

The CE market is growing, and it is estimated that in the next 10 years, economic growth will increase by up to 4% (ING, 2015). A turnover of $36 trillion in the built environment is expected, contributing 39.6% to the global GDP (ING, 2015). It is estimated that 200,000 jobs will be created in the United Kingdom (UK) by 2030, which could double with the development and implementation of circular business models (WBCSD, 2018).

The economic benefit of CE in the built environment is not just a reflection of the quantities of materials returning to use cycles but encompasses a few underlying factors throughout the industry's supply chain. It must also be defined in terms of costs avoided in resource scarcity and emerging competition for resources. The CE must be measured in terms of material, energy, water, and space resource costs saved, reduced environmental externalities, and, above all, terms of local job creation, market reuse, industrial symbioses, materials repair, and reform (KALMYKOVA; SADAGOPAN; ROSADO, 2018; WBCSD, 2018).

1.1.3 Social justification

Of the 19.4 billion tons of materials classified as waste, only 8.4 billion tons are recycled, the rest being incinerated, landfilled, or dispersed into the environment (CIRCLE ECONOMY, 2018). This current metric of circularity (9.1%) suggests that almost 90% of waste can have another destination, generating a field of opportunities for value creation.

The social benefits of implementing CE in the construction sector include the creation of new jobs, the provision of healthier buildings to users, the research and development of smarter and more sustainable materials, architectural projects with reversible characteristics, and bioclimatic principles. CE is intrinsically linked with the SDGs of the United Nations

2030 Agenda, how to ensure decent work and economic growth (SDG 8), industry, innovation, and infrastructure (SDG 9), and reducing inequalities (SDG 10). Sustainable consumption and production ensure that human beings can enjoy a full and prosperous life, ensuring that economic, social, and technological progress takes place in harmony with nature (UNEP, 2021).

The social objective of CE is the sharing economy, increased employment, participatory democratic decision-making, and the more efficient use of the physical capacity of materials (KORHONEN; HONKASALO; SEPPÄLA, 2018). New consumer culture is emphasized with user groups that share the use of the function, service, and value of products, as opposed to the culture of buying, consuming, and disposing of products. New business models will explore product leasing, service monetization, take-back strategies, reverse logistics, and concepts that enhance product function sharing among users (KORHONEN; HONKASALO; SEPPÄLA, 2018).

Resource efficiency alone is not enough. Green and sustainable buildings can reduce healthcare costs and increase people's productivity, improving indoor air quality and providing a more pleasant working environment (UNEP, 2012). Air pollution has emerged as one of the main risk factors for premature mortality in the 21st century, associated with 6.5 million premature deaths per year. Air pollution in environments, in the form of fine particles, is the dominant risk factor, responsible for 96% of health impacts (IRP, 2017). Studies show that CE strategies applied in cities can contribute to the mitigation of 15% to 36% of GHG (IRP, 2017). It is estimated that around 47,000 premature deaths are avoided annually through reduced air pollution (IRP, 2017).

Promoting sustainable development and driving the transition to greener economic growth will have a considerable impact on employment, housing, and poverty reduction. It is estimated that for every $1 million invested in energy efficiency reforms, 10 to 14 direct jobs and 3 to 4 indirect jobs are created (UNEP, 2012). To sustain and expand these gains, action in the construction sector must be accompanied by complementary actions at the city level. Integrated urban strategies, considering buildings, transport, waste, water, and infrastructure, that address overall resource and energy efficiency, will become considerably more important in achieving sustainable development goals (UNEP, 2012).

1.1.4 Technical-scientific justification

The CE theme has become increasingly important in the scientific community and various industries, such as policy making, consulting, and science. A search on the Scopus database on the term shows a 50% increase in academic publications in the last five years, a trend is even more visible for the Journal of Cleaner Production and Journal of Resources, Conservation, and Recycling. The first article on CE was registered in 2007 and more than two-thirds of the total of 101 publications listed in the term comes from the period from 2015 to 2017 (REIKE; VERMEULEN; WITJES, 2018). China and Europe lead research and practice in the field, with the support of European Union policies (MERLI; PREZIOSI; ACAMPORA, 2018).

There is a research gap in the construction industry on the more sustainable development of buildings. Pacheco-Torgal and Labrincha (2013) suggest that an explanation for this gap is the lack of university curricula adapted to incorporate sustainable development principles. The authors investigated the content of academic works on engineering and construction published by the journals Elsevier and ASCE from 2009 to 2013. Their findings showed that out of 2,500 articles, only 10% were related to environmental concerns to some degree, despite the progressive increase in regulations. environmental issues in the European Union (PACHECO-TORGAL; LABRINCHA, 2013). To the authors, evidence of resource scarcity indicates that research in the construction sector should better investigate resource efficiency solutions in buildings.

Due to the scope and socioeconomic significance of the proposed theme and the research gap in the sector, this thesis may justify the definition of a new line of research in the Graduate Program in Civil Engineering at UFPR and the creation of isolated disciplines, using the theme of CE in the built environment as a major area of research, with directions throughout the construction value chain. The proposal for a new line of research is supported by contributions and scientific recognition from Professor Ph.D. Sergio Tavares works on research projects with themes related to the sustainability of buildings.

This study has the collaboration of the University of Minho (UMinho) and the professor Ph.D. Luís Bragança, professor at the Department of Civil Engineering at UMinho since 1995. He is the coordinator of international graduate programs (Doctorate and Master) in Sustainable Built Environment and director of the Physics and Civil Construction Technology Laboratory. His main areas of interest are Sustainable Building Development, Building Physics, Acoustic Construction, and Rational Use of Energy in Buildings. He actively participates in national and international standardization work on Sustainable Construction. It is worth mentioning the coordination of the European Project “Sustainability of Buildings - Integrated Approach to Engineering at the Moment of Life” and the projects it coordinates “URBENERE - Energy Efficient Urban Communities” and “CIRES - Sustainable, Eco-efficient, Resilient and Inclusive Cities”. Professor Luís Bragança is the President of the International Initiative for a Sustainable Built Environment (iiSBE), Portugal unit, since 2011 and coordinator of the BAMB project. In 2019, he was the president of the final event of BAMB – A pathway for a circular future, held in Brussels, with the participation of the author of this thesis and Professor Sergio Tavares.

The partnership between UFPR and UMinho will contribute to expanding the research and education network of these institutions, seeking relevance in the scientific and technological development of the construction area in Brazil and Portugal. For Postgraduate Programs, it favors international support and cooperation for greater integration and relevance in the dissemination of scientific research. For universities and students, it is an opportunity to collaborate and direct future research and contribute to the strategic performance of decision-makers to introduce circular principles into strategies, business models, and value chains, making buildings and the built environment more sustainable.

1.1.5 Thesis objective and alignment with the research program

This research is linked to the research line Sustainability in the Built Environment of the Graduate Program in Civil Engineering (PPGEC). This line of research has been active mainly in research on users' thermal comfort, the energy efficiency of buildings, Life Cycle Analysis (LCA), the energy embedded in buildings and construction materials, and green roofs. This is the Program's first thesis aimed at introducing principles based on the circular economy in the built environment.

The originality of this research reiterates the creation of a new line of research in the Program, as well as isolated disciplines, as mentioned above. The exploration of circular strategies and practices for implementation in the construction sector is essential to create new business models and industrial symbioses, reduce the environmental impact of the sector, provide well-being to users, and make buildings more sustainable.

1.2 RESEARCH PROBLEM

This research intends to provide a new way of designing and building environments by considering circular principles in the construction value chain in a holistic and rational approach. It seeks to raise the main challenges and limitations of the sector to reduce waste and increase the useful life of building materials. By mapping and analyzing CE-based tools and strategies, aiming to increase the value of materials and turn buildings into a temporary material bank, this study aims to answer the following research question:

How do create a theoretical framework of the major trends, challenges, and tools based on the circular economy to the transition towards buildings as material banks in the construction sector?

1.3 RESEARCH OBJECTIVES

This study aims to generate a theoretical framework of tools and concepts to understand the trends and challenges that influence the implementation of CE practices to the transition toward buildings as material banks.

This research objective translates into several complementary objectives, some were identified at the beginning of the study, others were progressively added or refined:

a. analyze how the built environment approaches the study and actions of the circular economy;
b. identify the barriers, challenges, and propose a model of the materials passport with their respective data and information aiming at the reuse of materials at their end of life;
c. survey and analyze circular business models throughout a building's life cycle;
d. characterize the design typology of reversible and adaptive reuse buildings;
e. identify barriers and drivers needed to direct the circular transition in the construction industry.

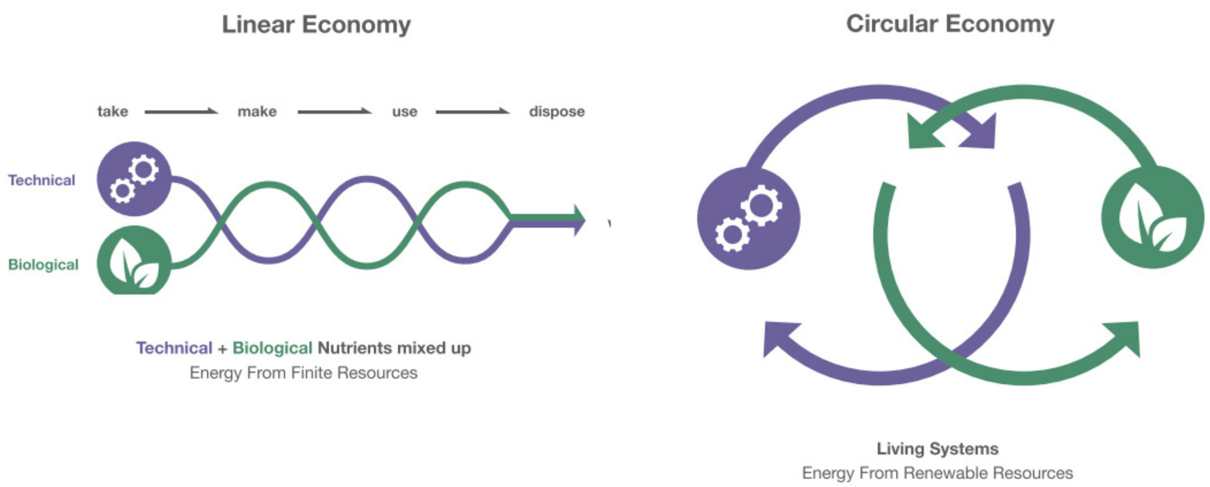
2 RESEARCH BACKGROUND

The last few years of the Industrial Revolution were dominated by a linear model of production and consumption in which goods are manufactured from raw materials, sold, used, and then discarded or incinerated as waste, as shown in FIGURE 1 (EMF 2015a,b). However, global competition, significant increases in commodity prices, increasing market volatility, and the production of negative externalities have alerted leaders to the need to rethink the use of materials and energy (EMF 2015a; 2017; ARUP 2016).

The successive sustainability conferences, which since the Brundtland Report (1987) have asked themselves when the listed recommendations will be properly adopted, put pressure on governments to act. At the recent United Nations (UN) conference, the 2021 Climate Change Conference (COP26) the consensus seemed to be that change is overdue. Indeed, the time to make changes is running out, governments seem unable to instigate change against the will of the corporate world, hidden under the perceived threat of continued economic growth (MURRAY; SKENE; HAYNES, 2017).

The view that the lack of alternative business models may constrain the transition to a sustainable future puts pressure on the need to identify and create more forward-looking alternatives. In this context, the circular economy (CE) emerges as a new economic model that seeks to decouple economic development from the consumption of finite resources. It is restorative, regenerative, and seeks to maintain products, components, and materials at their highest level of utility and value (EMF 2015a; 2017; ARUP 2016).

FIGURE 1 - LINEAR AND CIRCULAR ECONOMY MODEL



SOURCE: ARUP (2016).

By circular, an economy is considered to have no net effect on the environment; instead, it restores any damage caused in the acquisition of resources, ensuring that little waste is generated throughout the production process and during the life of the product (MURRAY; SKENE; HAYNES, 2017). This paradigm encourages new management practices and opens new opportunities adding value to the organization and customers, in harmony with the environment. For organizations, CE should be considered as a lever and motivation for growth with solid foundations and competitive advantages in the context of a highly dynamic global market (LEITÃO, 2015).

Circularity, therefore, provides a path to more sustainable and resilient buildings and cities. As sustainable development, it is expected a development that meets the needs of the present without compromising the ability of future generations, based on social, economic, and environmental pillars. For CE, the three pillars are important. The focus is on technological advances to solve the economic and environmental problem of finite resources, and on user behavior that needs to change to close the materials loop and reduce consumption. Where sustainability is the goal, CE is a roadmap to more sustainable development (ANATASIADES et al., 2020).

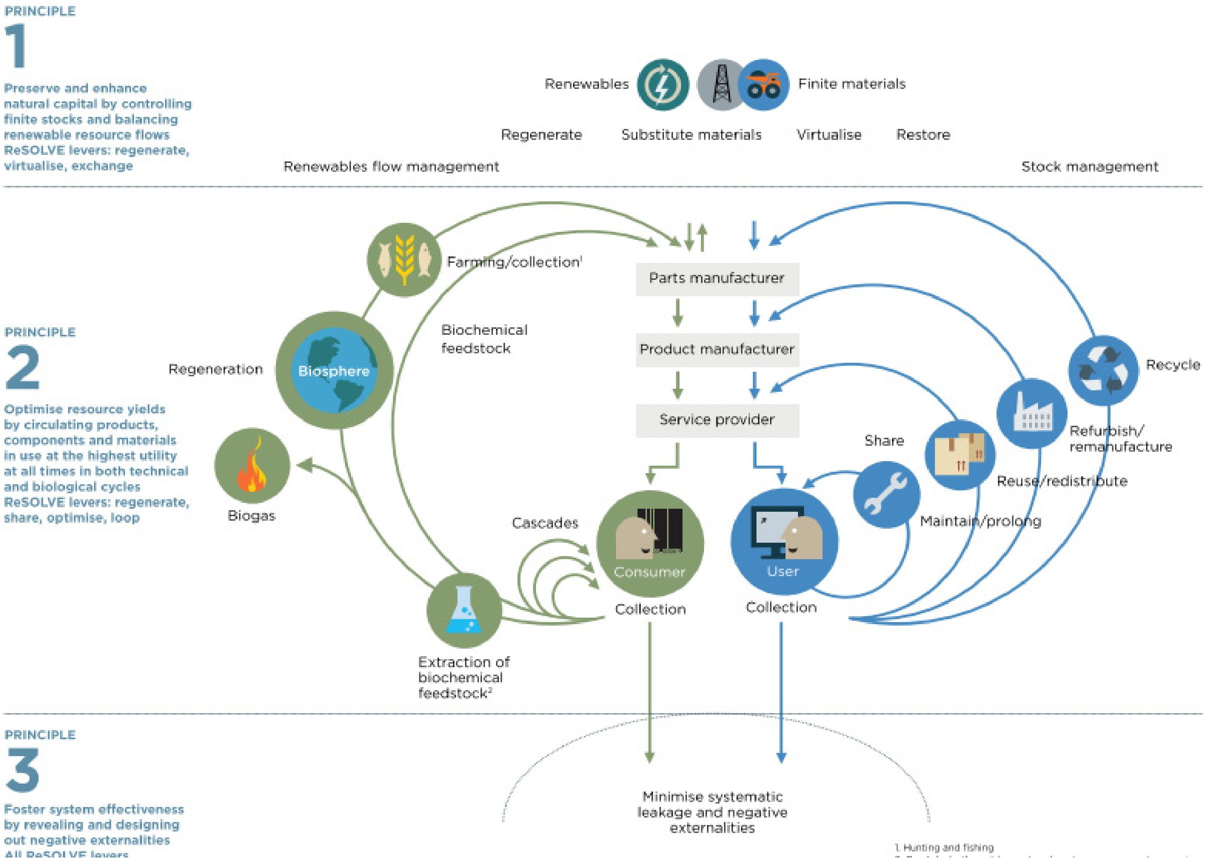
The transition to a CE is linked to public policies and the introduction CBMs, which affect all actors in the value chain, as well as substantial innovations in technology, the organization, and society (EMF, 2015a). In the construction industry, this change requires a focus on systems thinking, which allows understanding the entire building life cycle and the construction value chain, involving the integration of all stakeholders (ARUP, 2016). It instigates the need for new personal skills, for creative disciplines of design, advertising, and information, within the science, engineering, and production of materials and systems.

The CE provides value creation mechanisms based on three principles, distinguished between technical nutrient cycles, which involve the management of finite material stocks and use replaces consumption, and biological cycles, which encompasses the flows of renewable materials such as shown in FIGURE 2 (ARUP, 2016; EMF, 2015a,b):

a. preserve and enhance natural capital by controlling finite stocks and balancing the flows of renewable resources, where resources are selected sensibly and preferably from technologies and processes that use renewable resources;
b. optimizing resource yields by circulating products, components, and materials at a high level of utility, that is, encouraging remanufacturing, renewal, and recycling, to prolong the useful life of products;

c. stimulate the effectiveness of the system by revealing and excluding negative externalities, reducing damage to systems and areas such as food, mobility, housing, education, health, and entertainment.

FIGURE 2 – DIAGRAM OF THE CIRCULAR ECONOMY



SOURCE: EMF (2015a).

CE is linked to resource cycling. Some authors have divided the circular concepts into two large groups: 1) a group that assumes that the 3Rs principles (reduce, reuse, and recycle) are a way to implement CE; and 2) another group that explores sustainable design strategies as official CE principles, exploring ecological design concepts, guided by a product's Life Cycle Assessment (LCA), nature-inspired design strategies, and the principles of cradle to cradle (C2C). These strands defend the principles of diversity, the use of solar energy and that waste is equal to a resource (PRIETO-SANDOVAL; JACA; ORMAZABAL, 2018).

These principles are supported by industrial symbioses, where companies use each other's waste as resources, and in the service economy, where work is done to slow down consumption cycles and waste generation (MURRAY; SKENE; HAYNES, 2017). Murray; Skene and Haynes (2017) increased product longevity through better manufacturing and maintenance ('food waste concept') and the 3Rs have become central to the CE concept.

It is worth noting that considering the three pillars of sustainability (economic, environmental, and social), CE is even less present in the social dimension, focusing on the redesign of manufacturing and service systems to benefit the biosphere. While ecological renewal and survival and the reduction of finite resource use benefit humanity, there is no explicit recognition of the inherent social aspects, in terms of human stakeholders, well-being, and human rights (MURRAY; SKENE; HAYNES, 2017).

In Brazil, the opportunities for implementing CE practices are based on expanding access to build space with concepts of flexibility, modularity, more efficient use of resources, and waste reduction; and channeling digital technology and innovative practices to create more value (EMF, 2017). Typically, buildings are seen as finished and permanent structures, designed for an average technical and functional life of 50-75 years (DURMISEVIC, 2016). Despite their long physical life, they do not offer the flexibility to maximize functional life. Therefore, the breakdown of structural elements for adaptations, replacements, and reforms is not uncommon. Most buildings are demolished with an average lifespan of 20 years because they no longer satisfy the needs of their users, shortening the functional service life and accelerating the return on investments (DURMISEVIC, 2016).

The inability to remove and replace building systems and their components results in higher energy and material consumption, increased waste production, and a lack of spatial adaptability (DURMISEVIC, 2016). Therefore, the transition to CE will generate opportunities for innovation, integration, and value creation in the Brazilian construction chain. The market and social characteristics and the incomparable natural capital of the territory are attractive and promising scenarios for exploring the opportunities that CE can bring to the construction of economic, social, and natural capital (EMF, 2017).

2.1 THE ORIGINS OF THE CIRCULAR ECONOMY

The CE concept has deep origins and cannot be traced back to a single date or author. Its practical applications to modern economic systems and industrial processes, however, have gained traction since the late 1970s because of the efforts of academics, thought leaders, and companies. The embryonic idea was developed by Professor Kenneth E. Boulding, an environmental economist who argued that the Earth can best be understood as a spacecraft with limited reservoirs of resources, either for the extraction or for pollution (BOULDING, 1966). The concept was refined and developed by different multidisciplinary approaches that treat the economy as a living, adaptive and complex system based on ideas such as the

Regenerative Project; the Performance Economy (Walter Stahel); Cradle to Cradle (Michael Braungart and William McDonough); Industrial Ecology (Roland Clift, Thomas E. Graedel); Biomimicry (Janine Benyus); natural capitalism (Amory Lovins); the Blue Economy (Gunter Pauli), among others (ADAMS et al., 2017; EMF, 2015a, b; KALMYKOVA; SADAGOPAN; ROSADO, 2018).

Some authors consider CE as a three-phase evolution (PIETRO-SANDOVAL et al., 2018; REIKE; VERMEULEN; WITJES, 2018):

a. EC 1.0 (1960-1990): The first stage is the linear economy, which began with the industrial revolution and overexploitation of resources. This stage was interrupted in the 1960s by the interest in the environment and by the publications of ecologists such as Silent Spring, Carson, and economists such as Boulding (1966) (PRIETO-SANDOVAL; JACA; ORMAZABAL, 2018). In the 1970s, in Europe and the United States, the focus was on urban solid waste. The concept of 3Rs is gaining more and more attention (REIKE; VERMEULEN; WITJES, 2018). Waste management becomes important through the regulation of landfills and incineration, but there is still no established thinking in the systems (REIKE; VERMEULEN; WITJES, 2018);
b. EC 2.0 (1990–2010): This phase sought to connect inputs and outputs in strategies for eco-efficiency, through preventive and production measures. The first theoretical and practical industrial ecology initiatives by Ayres and Kneese (1969) explained that industrial activities can function as the metabolism of different actors integrated through their actions (PRIETO-SANDOVAL; JACA; ORMAZABAL, 2018). The idea of a win-win between the environment and commercial activity, as set out in the Brundtland Report, is promoted, and environmental problems are presented as an economic opportunity, with an interest in a greener economy (REIKE; VERMEULEN; WITJES, 2018; PRIETO-SANDOVAL; JACA; ORMAZABAL, 2018);
c. EC 3.0 (2010±): As of 2010, various elements from different schools of thought are combined to maximize or retain value in an era of resource depletion. While the rhetoric still emphasizes economic gains, threats to human survival linked to population growth and renewed attention to resource depletion and retention are emphasized. CE is celebrated for its potential to decouple economic growth from resource use (REIKE; VERMEULEN; WITJES, 2018).

However, interest in developing the concept across the world has only recently been renewed. The term CE saw little use outside China until 2010, in documents describing development in China, due to its early adoption as a national strategy (ADAMS et al., 2017; KALMYKOVA; SADAGOPAN; ROSADO, 2018). In 2010, the approach gained attention from the Ellen MacArthur Foundation (EMF), a non-profit organization dedicated to advancing the global transition to CE, emphasizing systems thinking and the need to project negative externalities. EMF argues that CE replaces the end-of-life concept with restoration, evolves towards the use of renewable energy, eliminates the use of toxic chemicals that harm reuse, and aims to eliminate waste by the design of materials, products, systems, and business models (EMF, 2015).

The evolution of the concept was directed according to the different cultural, social, and political systems. Winans; Kendall; Deng (2017) surveyed the main applications of the CE in different countries. In Germany, in the early 1990s, CE was introduced into environmental policy to address issues associated with the use of raw materials and natural resources for sustainable economic growth. In China, an eco-industrial park model was promoted, and, in the mid-2000s, the concept was implemented with an emphasis on waste recycling and the development of closed material loops. In the UK, Denmark, Switzerland, and Portugal the focus was on waste management. Some initiatives aim to increase consumer responsibility for the use and waste of material, as in Korea and Japan. In North America and Europe, companies seek to improve reduction, reuse, and recycling programs, in addition to conducting life cycle studies. life at the product level.

CE is still an emerging field, consequently, there is a need for a deeper analysis of the concept, its units of analysis, and the theoretical basis that supports it. Many articles describe several principles that underlie the transition to CE, although there is still a lack of agreement on this subject and conceptual challenges for researchers (KIRCHHERR; REIKE; HEKKERT, 2017; KORHONEN; HONKASALO; SEPPÄLA, 2018). And this can be covered in other research streams that include ecosystems and industrial symbioses, cleaner production, product-service systems, eco-efficiency, cradle-to-cradle design, biomimicry, performance economics, natural capitalism, the concept of zero emissions. and others (KORHONEN; HONKASALO; SEPPÄLA, 2018).

2.2 THE CIRCULAR ECONOMY IN THE WORLD

Regarding the reuse and recycling of resources, high-level political agendas have been implemented in Japan, the European Union (EU), and China (IRP, 2017). The European Commission launched 2014 a legislative proposal, known as the Circular Economy Package, to increase recycling and reduce landfilling, increasing resource efficiency, with a series of measures and targets aimed at moving the EU towards a CE. Among them, increase the recycling of municipal waste by 70% by 2030; ban all recyclable and biodegradable waste from landfilling by 2025 (LEITÃO, 2015).

Two main directions in CE implementation can be distinguished in the literature: i) a systemic implementation across the economy, at local, regional, national, and transnational levels, and ii) implementation focusing on a group of sectors, products, materials, and substances (KALMYKOVA; SADAGOPAN; ROSADO, 2018). A systemic implementation at three levels was envisaged in China: at the macro scale (city, province, and state), at the meso (industrial symbioses, buildings), and the micro (building materials). In the Netherlands, CE was proposed to be implemented on an economic scale, with the ambition to make the Netherlands a "circular access point". The Dutch government launched the Realization of Acceleration of a Circular Economy (RACE) project in 2014, with design work and knowledge sharing to the community. At regional and local levels, the most common example of systemic implementation is industrial parks, or eco-industrial parks, which are based on the idea of industrial symbiosis (KALMYKOVA; SADAGOPAN; ROSADO, 2018).

TABLE 1 presents initiatives and strategies employed by European countries across the supply chain in the context of a CE. Policies tend to focus on regulation or taxation of waste in landfills, or recycling targets, rather than life-cycle-based interventions (IRP, 2017). There is a growing awareness that regulatory measures are not the only ones needed for economies to become more resource-efficient; Bottom-up and collaborative approaches can be equally effective. In this sense, the government's role is to provide training, knowledge, and socioeconomic conditions that allow companies and consumers to embark on and scale up eco-innovations (IRP, 2017).

TABLE 1 – EXAMPLES OF CE STRATEGIES AND INITIATIVES IN EUROPE.

Stage of material life cycle	CE strategies and initiatives	Country
Extraction of raw materials	Reduce the use of primary raw materials	Iceland
	Reduce the impact of material extraction	United Kingdom (UK)
Design of products	Integrate environmental aspects into product design	France
	Extend the lifespan of products	Ireland

Production and distribution	Extended producer responsibility, packaging, and end-of-life vehicles	Portugal
	Industrial symbiosis and new business models	Sweden
Consumption and use	Pay-as-you-throw schemes	Belgium
	Changing consumption patterns	Italy
Reuse, repair, redistribute, refurbish, and remanufacture	Repair network initiative and the second-hand product reuse initiative	Austria
	The Scottish Institute for Remanufacture	Scotland, UK
Waste prevention	Secondary Raw Materials Policy	Czech Republic
	Strategies for prevention of waste	Denmark
Waste management	Separate collection of metal and biowaste	Croatia
	Seven goals for the National Waste Management Plan and Waste Prevention Programme	Finland
	Tailor norms or certifications to the circular economy	The Netherlands
	Transform waste into resources	Poland

SOURCE: IRP, 2017.

In Brazil, there is still no specific public policy aimed at introducing circular principles in the business models of the construction value chain (MUNARO; TAVARES, 2022). Topics related to CE are present in several laws, programs, and projects, however, in a decentralized way. The National Policy for Solid Waste (NPSW), law number 12,305/2010, is currently the most impactful policy in encouraging circular actions. However, the elaboration of a CE-oriented ISO standard (ISO/TC 323 Circular Economy) is in progress to develop frameworks, guidance, support tools, and requirements for the implementation of activities of all involved organizations (ISO, 2022).

2.3 BUILDING AS MATERIAL BANKS (BAMB)

One of the challenges for the implementation of the CE lies in the lack of adequate information about the main stakeholders, direct and indirect beneficiaries, and others involved in the business cycle (BAMB, 2016). A circular and reversible built environment can only be supported by an interconnected network of values. Due to the magnitude of information and variety of stakeholders within the building value network, a digital way of collecting, manipulating, and exchanging data is indispensable. The reuse of building components and the high-value recycling of building materials are still limited due to the lack of information about the design, composition, and use of the product during its lifetime (BAMB, 2016).

Circularity provides a path to sustainable and resilient cities. Increasing the value of materials means less waste and less consumption of resources, and this is what the concept of buildings as a material bank is creating. Building as material banks (BAMB) is a project developed in the European Union that aims to systematically change the construction sector, investigating and creating circular solutions to conserve the value and functionality of building materials and systems (BAMB, 2016). The main instruments used by BAMB are the materials passport (MP), the design of reversible buildings, and the circular assessment - supported by data management and decision making, new business models, policy propositions and standardizations, and pilot case studies (BAMB, 2016).

2.3.1 Materials passport

The materials passport (MP) is a set of data and information that describes the characteristics of materials that give them value for recovery and reuse (LUSCUERE, 2016). It is a tool for tracking value at all stages of the material lifecycle and for driving innovation by guiding in choosing more sustainable materials (BAMB, 2016; 3XN ADEPA, 2016; LUSCUERE, 2016). According to BAMB (2020), MPs involve two main strategies: closing the material cycle and resource productivity. Material loops or closing loops are flows where materials or parts are recovered, reused, recycled, or biodegraded by natural or technological processes. Resource productivity should be interpreted as a measure of the number of virgin materials extracted, about the value created from that amount. Productivity is expected to be maximized if waste is avoided and materials are reused.

2.3.2 Reversible Building Design

The concept of reversible building design is based on the repair, reuse, and recovery of materials, products, and building components. It is an approach to designing and building, where the value of buildings will be based on the ability to transform and the potential for reuse of constructive elements (BAMB, 2016; 3XN ADEPA, 2016).

The measures of reversibility of buildings are evaluated by the reuse potential and the materials transformation capacity. The reuse potential expresses the probability that parts of an assembly can be disassembled simply, quickly, and without damage and therefore reused (BAMB, 2020). It is based on aspects such as the compatibility and independence of its parts and evaluates criteria such as functional and technical autonomy, assembly sequence, connection reversibility, and component geometry (DURMISEVIC, 2016).

2.3.3 Evaluation of circular buildings

The assessment of circular buildings is an approach that aims to provide a holistic estimation and interpretation of various aspects of building sustainability. Adopting a life cycle approach includes aspects such as environmental impact, financial costs, and health consequences to promote more informed decision-making about circular alternatives (BAMB, 2020). Circular building assessment is facilitated by extracting data from building information models and materials passports. It can compare the overall impact of replacing new products with refurbished products, life extensions resulting from improved processing capacity, and future reuse of parts and materials (BAMB, 2020).

2.4 TRANSITION TO A CIRCULAR VALUE NETWORK

BAMB aims to turn buildings into material banks by integrating MPs and reversible building designs to optimize circular value chains. This transition aims to create circular business models and a circular value network. A circular business model describes how companies can generate revenue or make a profit, including the way they operate and finance their activities, within a CE (BAMB, 2020). These models describe how to offer services, rent components, and recover materials profitably. The circular value network of a building is the set of interrelated activities carried out by companies to maintain or increase the social, financial, or environmental value of that building and its parts. A circular value network includes activities that keep components in use for as long as possible and preserve their value at the end of use. A circular value network can be seen as the backbone of circular business models (BAMB, 2020).

3 RESEARCH DESIGN

Considering that scientific research is a systematic, organized, and the rational search for information, it is necessary to contextualize the type of research with the adopted problem. However, the methodological procedures are diverse, classified in different ways, and there is no dominant paradigm between strands and authors. For example, a research activity can be classified in terms of approach (qualitative, quantitative), in terms of objective (exploratory, descriptive, causal), in terms of methods (bibliographic research, case studies, etc.), in terms of the type of collection data (interviews, questionnaires, etc.) among others.

In this thesis, the methodological choice was based on the researcher's interests, premises and purposes, and the guiding question, seeking to ensure greater validity to the work. This study seeks to explore a new domain of knowledge and not to prove, disprove or compare phenomena. A qualitative approach was adopted, with positivist and interpretive influences, and an exploratory methodology with mixed data collection (FIGURE 3).

3.1 RESEARCH PARADIGMS

All research is based on philosophical premises that relate to the epistemology that guides the work. Myers (1997) suggests three categories: positivist, interpretive and critical. And while they are philosophically distinct, in practice the differences are not so clear-cut.

Positivists generally assume reality as given and described by measurable properties independent of the observer and his instruments, research is value-free (MYERS, 1997). According to Meredith et al. (1989), the positivist logical perspective assumes that the phenomenon under study can be isolated from the context in which it occurs and that facts or observations are independent of the laws and theories used to explain them.

Interpretive researchers assume that access to reality occurs through social constructions, such as language and consciousness (MYERS, 1997). Studies seek to understand phenomena through the meanings people attach to them, and investigation is largely influenced by the values of the investigator. The object of study is people, with a focus on meanings and interpretations rather than behavior (MEREDITH et al., 1989). In contrast to the absolutism of positivism, interpretivism is relativistic because the facts are not considered independent of the theory of the observer.

The critical category assumes that reality is constituted, produced, and reproduced by people, in this way, the research focuses on the oppositions, conflicts, and contradictions of contemporary society and seeks to be emancipatory (MYERS, 1997). Critical theorists transcend the contradiction between the way people behave in practice and the way they understand themselves acting (MEREDITH et al., 1989).

This study seeks to bring meaning and explore a series of phenomena through a qualitative human perspective. A qualitative approach is not synonymous with an interpretive one, as it depends on the underlying assumptions of the researcher (MYERS, 1997). Furthermore, the positivist logical strand is not restricted to quantitative and causal research. The choice of a qualitative research method is independent of the philosophical position adopted (MYERS, 1997). In this way, research paradigms are complementary, and although qualitative, this research has a mixed positivist and interpretivist philosophical predominance.

3.2 RESEARCH STRATEGY

The most common distinctions between research approaches are qualitative and quantitative. Qualitative research provides better insight and understanding of the context of the problem, is unstructured, and has reduced sampling. While quantitative research seeks to quantify data and generalize sample results to the population of interest, it is structured and applies some form of statistical analysis (MALHOTRA, 2012).

Among the basic research objectives, it can be exploratory, descriptive, or causal. For Malhotra (2012), exploratory research aims to discover ideas and information, is flexible and versatile, and uses methods such as bibliographic research and interviews with experts. The descriptive seeks to describe the characteristics or functions of a phenomenon, is planned and structured, and is based on quantitative analysis methods, such as surveys. Causal research determines cause and effect relationships by manipulating variables through experiments.

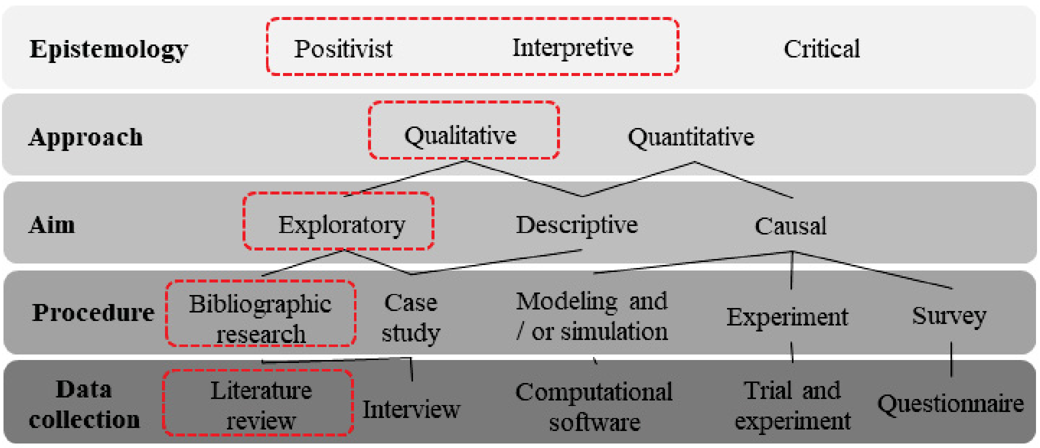
Qualitative research with an exploratory character has as its main objective the improvement of ideas or the discovery of intuitions (MALHOTRA, 2012). The research strategy clarifies that the topic of study is little addressed and there is still not much knowledge about the topic to be debated. The research has an innovative approach in the design and construction sector since the concept of buildings as a bank of materials was not widespread in Brazilian construction techniques and systems. According to Creswell (2003), this kind of inquiry supports research that honors an inductive style and focuses on the individual meaning and the importance of making a situation complex. Research planning is flexible, versatile, and unstructured to provide greater familiarity with the problem and enable a better understanding of the varied aspects related to the object of study (MALHOTRA, 2012).

Exploratory research is used in cases where it is necessary to define the problem more precisely, identify relevant courses of action, or obtain additional data before an approach can be developed (MALHOTRA, 2012). The findings of this research should be considered trials and are followed by further research. It can be used to formulate a problem or define it more precisely; identify courses of action; develop hypotheses; isolate key variables and relationships; obtain information to develop an approach to the problem; and establish priorities for further research (MALHOTRA, 2012).

Exploring a subject means adding more knowledge and incorporating new features, as well as looking for new dimensions hitherto unknown to the explored subject (CRESWELL, 2003). This study aims to deepen and/or develop concepts approached preliminarily on a certain theme and to familiarize the researcher, providing more information about the phenomenon to be studied. Once new ideas are discovered, research can change direction. Thus, the researcher's creativity and ingenuity play an important role in this research (MALHOTRA, 2012).

The methodology applied to explore the questions of this thesis was based on bibliographic research. A research method is an inquiry strategy that moves from underlying philosophical assumptions to research design and data collection (MYERS, 1997). As for the data collection process, literature reviews, and surveys of bibliographic and documentary material were addressed. FIGURE 3 illustrates the general conception of the research adopted, highlighted by red rectangles.

FIGURE 3 – GENERAL CONCEPT OF EXPLORATORY RESEARCH



SOURCE: The author (2022).

3.3 SYSTEMATIC LITERATURE REVIEW

A systematic literature review (SLR) is a rigorous methodology proposed to identify studies on a topic in question, applying explicit and systematized methods of search, critical appraisal, and synthesis of selected information. It is a method for obtaining evidence-based practice data. According to Tranfield et al. (2003), the objective of conducting an SLR is often to allow the researcher to map and assess the existing intellectual territory and specify a research question to further develop the existing body of knowledge. This methodology is essential to obtain the state-of-the-art of a given problem, identify research gaps, and future research directions, and, also, achieve the academic novelty required in a doctoral study. In this thesis, SLRs were used as methodological approaches in different papers.

To de Almeida Biolchini et al. (2007) the SLR is an initial and necessary step in any research and development process. As science is a cooperative social activity and scientific knowledge is the result of a cumulative process of this cooperation, an SLR is how the researcher can carry out a mapping of knowledge and existing and previously developed initiatives in the field. The objective of the SLR is to provide collective insights through the theoretical synthesis of fields and subfields (TRANFIELD et al., 2003). For academics, the review process increases methodological rigor, and for practitioners, it helps to develop a reliable knowledge base, accumulating knowledge from multiple studies.

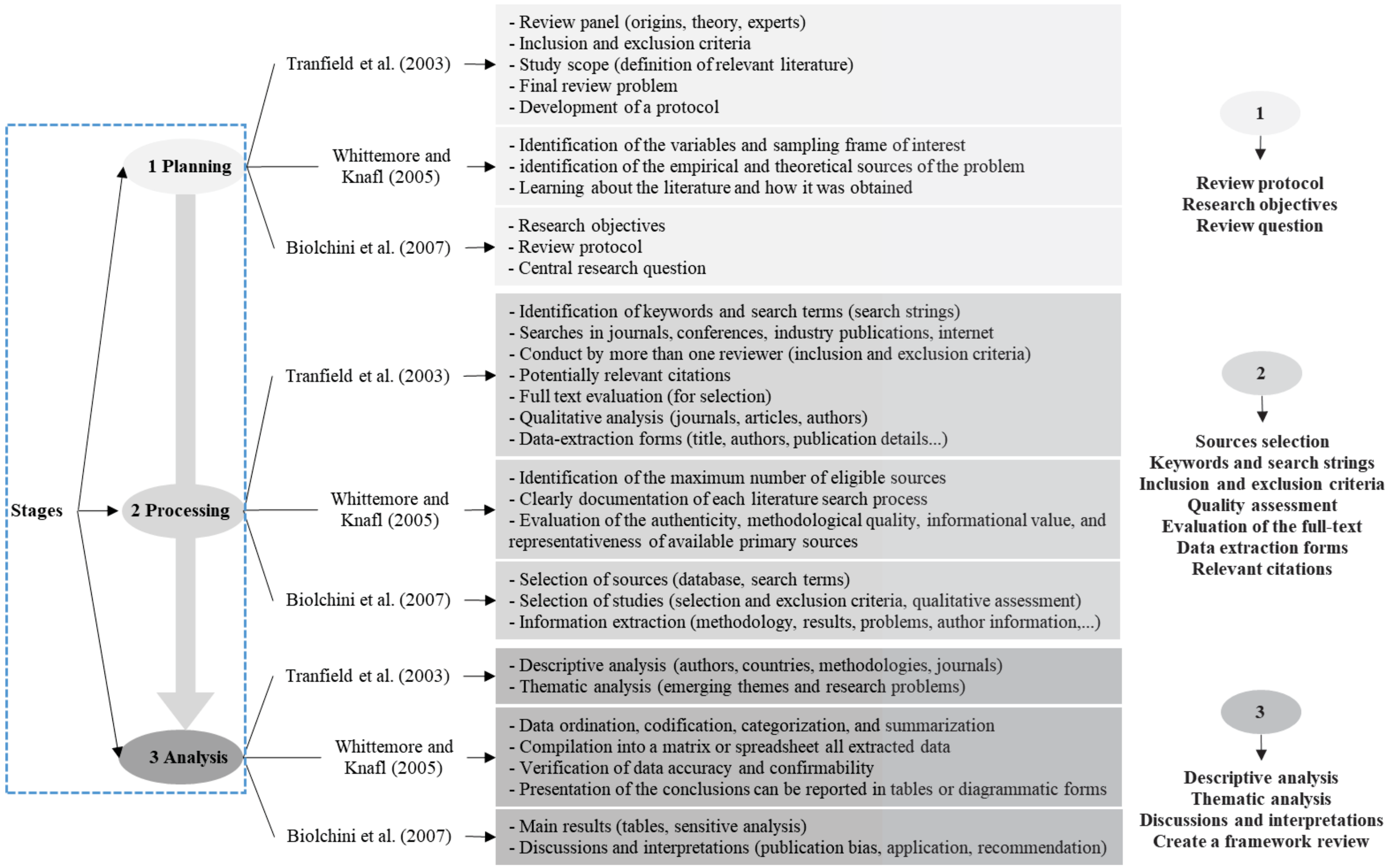
Due to its important role in the scientific community, and to minimize the risk of bias and errors, a research protocol must be developed, based on strategies to recover the evidence, the focus of the question and so that other professionals can reproduce the same protocol (TRANFIELD et al., 2003). An SLR consists of a specific scientific methodology that goes a step beyond the simple overview. It aims to integrate empirical research to create generalizations (de ALMEIDA BIOLCHINI et al., 2007). The systematic conduct of the review can be understood as a three-step approach. In this thesis, a research protocol was structured, whose collection, data processing, and analysis of results were based on management and organization studies, as illustrated in FIGURE 4.

Step 1 - Planning: A research protocol is developed from previous research to map and identify the terms and the way the subject has been inserted in the journals. The research strategy must be reported in enough detail to ensure that the research can be replicated.

Step 2 – Processing: A SLR starts with the identification of keywords and search terms, which are constructed from the scoping study, literature, and review team discussions. The data extraction process requires documentation of all steps taken. The data extraction process is flexible and depends on the nature of the study. Data extraction forms should include details of the information source (title, authors, journal, publication details) and any other study characteristics.

Step 3 – Analysis: After reading and analyzing the articles, researchers also need to report the findings of a thematic analysis, regardless of whether the results were obtained through an aggregative or interpretive approach, describing what is already known and established from the forms of extraction of data from the main contributions (TRANFIELD et al., 2003). According to Cruzes; Dyba (2011) thematic analysis is a method for identifying and analyzing reporting patterns in the data. Organizes and describes the dataset in detail and interprets aspects of the research topic. Themes reduce large amounts of code into a smaller number of analytical units and help the researcher build a more integrated framework for understanding local incidents and interactions.

FIGURE 4 – PROTOCOL ADOPTED IN THE SYSTEMATIC LITERATURE REVIEWS



SOURCE: The author (2022).

4 RESEARCH RESULTS

This thesis originated seven articles from event proceedings and seven journal articles. The proceedings papers were published at the final BAMB event, at the National Meeting of Technology in the Built Environment (ENTAC), at the Latin American and European Meeting on Sustainable Buildings and Communities (EuroELecs), and at SEE-U: Sustainable Development Goals, the global scientific conference at UFPR. However, in this document, just the seven journal articles were considered and were listed in TABLE 2.

TABLE 2 – LIST OF PAPERS CONSTITUTING THE THESIS

	Paper	Method	Research problems	Research aim	Status
A1	Towards circular and more sustainable buildings: a systematic literature review on the circular economy in the built environment	Systematic literature review	How the built environment approaches the study and the actions of the circular economy to reduce the environmental impact of buildings?	To analyze how the built environment discusses and studies the circular economy	Published
A2	Materials passport's review: challenges and opportunities toward a circular economy building sector	Systematic literature review	How the construction sector approaches the materials passport to make the buildings more circular?	To explore the state-of-the-art of MP to raise awareness about this tool and thus expand its implementation in the sector	Published
A3	Circular Business Models: Current State and Framework to Achieve Sustainable Buildings	Systematic literature review	1) How does the construction sector approach business models to achieve sustainable buildings? 2) How is the implementation of circular strategies distributed in the BMs described in the literature? and 3) How can the implementation of CBMs be facilitated?	To analyze how the construction sector approaches business models to achieve sustainable buildings	Published
A4	Analysis of Brazilian public policies related to the implementation of circular economy in civil construction	Bibliographic and documentary research	Which are the Brazilian public policies that relate to the implementation of the CE in the construction sector?	To analyze the main Brazilian public policies that support the implementation of CE in the construction sector	Published
A5	The ecodesign methodologies to achieve buildings' deconstruction: A review and framework	Integrative literature review	How does the construction sector approach the ecodesign methods to achieve buildings' deconstruction?	To study how the construction sector approaches the ecodesign methods to achieve buildings' deconstruction	Published
A6	A review on barriers, drivers, and stakeholders towards the circular economy: the construction sector perspective	Integrative literature review	What are the major barriers and drivers to a circular economy in the construction sector? What is the role of the construction stakeholders in this transition?	To understand the barriers, drivers, and stakeholders that influence current developments in the construction industry	Submitted

A7	Design for Adaptability and Disassembly: a state-of-art review towards circular buildings	Integrative literature review	How can Design for Adaptability and Disassembly and other building deconstruction-oriented ecodesign methods support the transition towards integration of circular economy within the construction sector?	To explore the state-of-art of DfAD and discuss critical criteria needed to recognize deconstruction as a strategy that must be part of the design and planning stage of the buildings	Revision

FONTE: The author (2022).

4.1 STRUCTURE OF THE STUDIES

This section presents the summary of the articles listed in TABLE 2 to meet the overall objectives of the thesis.

Paper 1: This initial article provides a comprehensive and holistic view of how the built environment approaches the study and actions of the circular economy. This study represents a contribution to the theoretical foundations of CE research and emphasizes research gaps that were addressed in the other studies of this thesis.

Paper 2: This article presents a concept of materials passport in the context of the built environment, identifying the main information, opportunities, and obstacles that this mechanism should provide to support circular practices in the construction sector. The study meets the research direction of article 1, aiming to assist decision-making in the design phase of buildings.

Paper 3: The study presents an iterative methodology for creating value in building projects and a framework that relates CBMs according to the phase of the building's life cycle. The study addresses the research gap in introducing circular principles into construction sector policies, actions, and value chains.

Paper 4: This study analyzes Brazilian public policies that support the implementation of CE in the construction sector. The study contributes to the literature on public policies to support CE and assists policymakers in creating a circular policy plan to support decision-making and the adoption of sustainable strategies in the construction sector.

Paper 5: This study analyses how the construction sector approaches ecodesign methods to achieve buildings deconstruction and established that the most inclusive and sustainable ecodesign method is Design for Adaptability and Disassembly (DfAD). The study addresses the research gap of paper 1 on buildings disassembly strategies.

Paper 6: This study analyzes the barriers, drivers, and stakeholders that influence the implementation of the CE in the sector and highlighted the need for joint action between government and construction stakeholders to the establishment of public-private partnerships and effective and segmented communication aimed at the circular transition in the sector.

Paper 7: This study understands how DfAD and other deconstruction-oriented ecodesign methods can support the sector's transition towards circularity. 71 criteria to guide the deconstruction of buildings were listed, emphasizing standardization, modularization, and prefabrication of materials and components as fundamental requirements to support building deconstruction.

4.2 A HOLISTIC AND CONTINUOUS VIEW OF RESEARCH

The results of this study are a product of several intertwined research paths, which aim to form an expansive and continuous research network. FIGURE 5 presents the connection between the articles developed as part of this thesis. The organization of the articles was based on research gaps presented in paper 1 and based on the principles and tools of the BAMB project, as presented in Section 2.3.

TABLE 3 explores the research common themes in the papers. The research methodology used, the distribution of concepts and circular tools, as well as the main results of each paper, are listed to highlight the gradual progression of the work. It should be noted that TABLE 3 highlights topics that were addressed in the articles, but it does not mean that they were subjects discussed in depth.

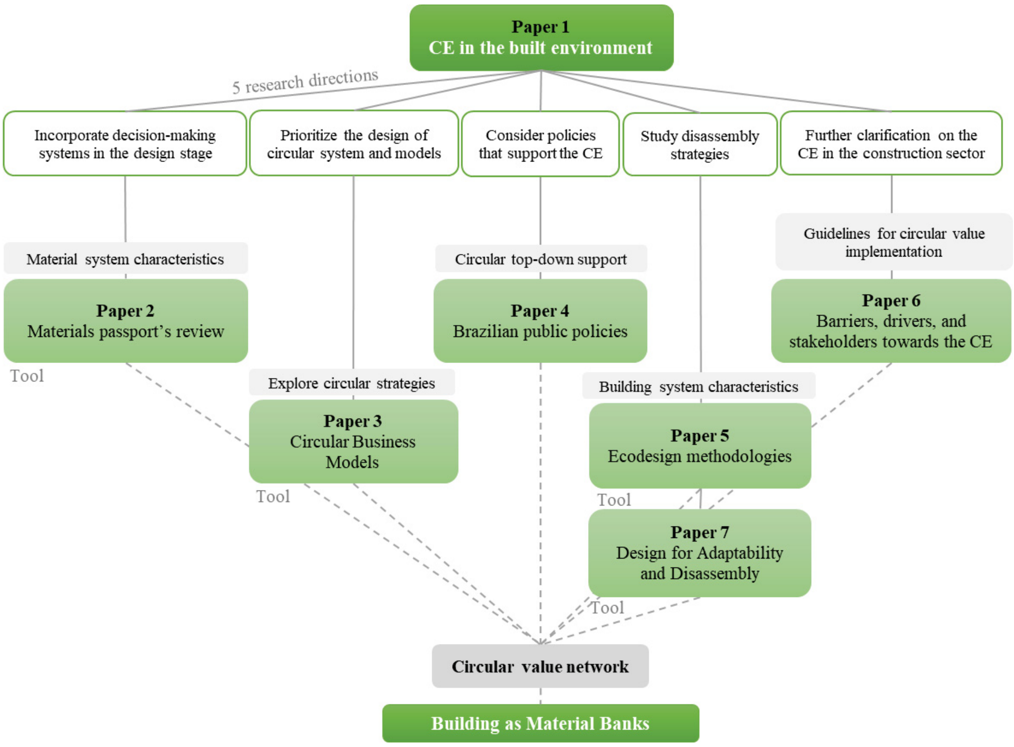
TABLE 3 – STUDY RESULTS ACROSS THE SEVEN PAPERS

	A1	A2	A3	A4	A5	A6	A7	Thesis
Background theoretical								
Origin of the circular economy	x							x
Overview global	x		x	x				x
Major schools of thought	x							x
Sustainability x CE	x		x					x
Research methodology								
Framework development methodology								x
Research design	x	x	x	x	x	x	x	x
Conceptual terms								
BAMB	x	x	x			x	x	x
Building life cycle		x	x					
Business models			x					
Circular business models			x					
Circular economy	x	x	x	x	x	x	x	x
Cradle to cradle		x						x
Design for Adaptability (DfA)					x		x	
Design for Disassembly (DfD)					x		x	x
Ecodesign					x		x	
Environmental Product Declaration (EPD)		x						
Innovation			x					
Materials passports		x						x
Public policies				x				
Reversible building					x		x	x

R-strategies				x				
Construction stakeholders						x		
Sustainability	x		x	x	x			x
Main deliverables								
State of the art on CE research	x				x	x	x	
Research concentration areas	x		x		x		x	
Research gaps	x							
Future research direction	x							
Materials passport model		x						
Main challenges and opportunities		x				x		
Conceptual model			x		x			
Review framework			x		x	x		
Circular public policies				x				
Criteria for DfAD							x	

SOURCE: The author (2022).

FIGURE 5 – INTEGRATIVE SCHEME OF RESEARCH PERFORMED IN THIS THESIS



SOURCE: The author (2022).

The analysis and discussion of the proposed articles were conducted according to the guiding questions and the specific objectives of this research. TABLE 4 lists the main research question of this thesis, the central questions of each proposed article, with the respective specific objectives analyzed at each stage of this research.

TABLE 4 - RELATIONSHIP BETWEEN RESEARCH QUESTIONS AND SPECIFIC OBJECTIVES

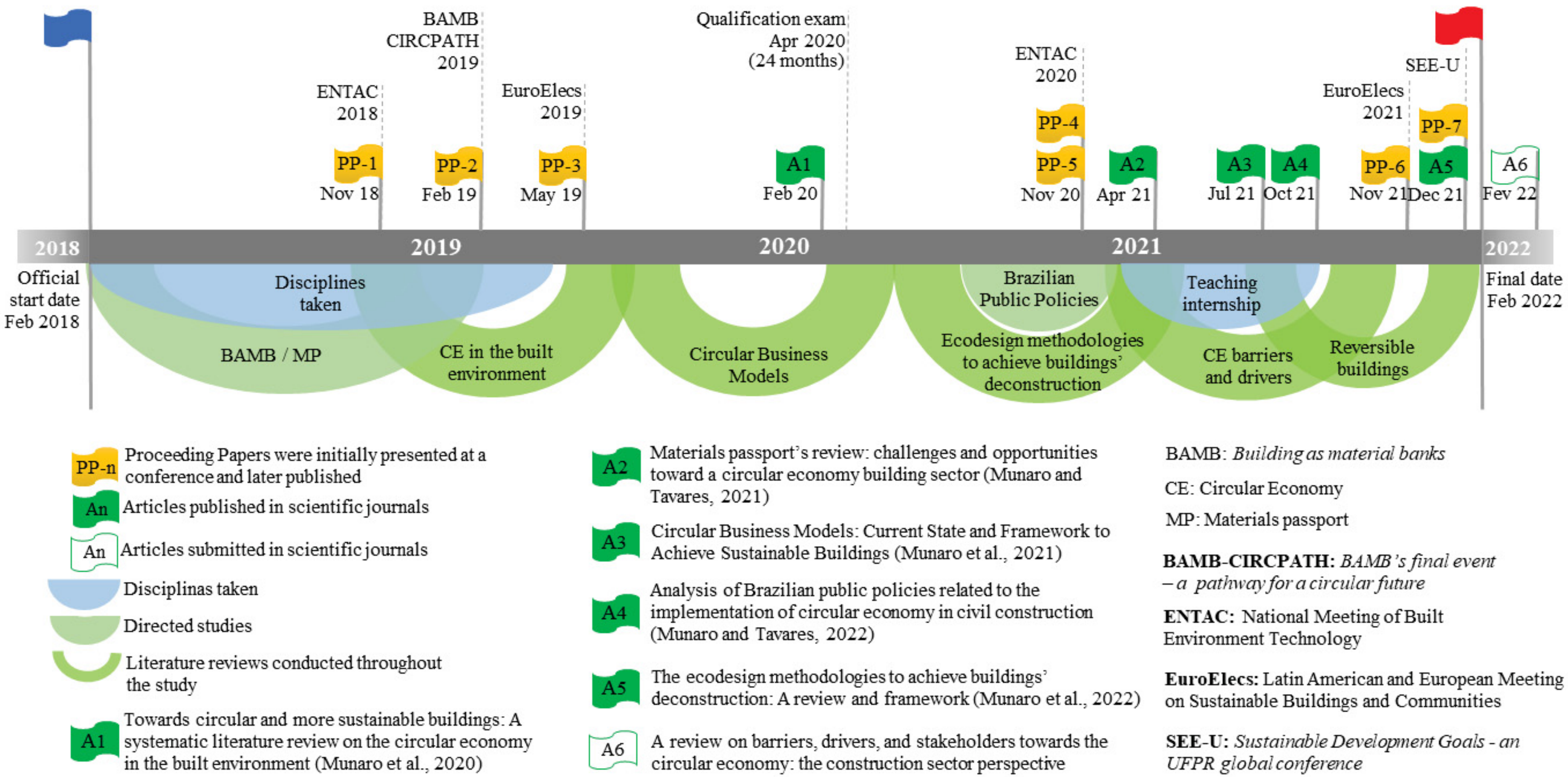
Research question	Research problems	Paper	Research objectives
How do create a theoretical framework of the major trends, challenges, and tools based on the circular economy to the transition towards buildings as material banks in the construction sector?	How the built environment approaches the study and the actions of the circular economy to reduce the environmental impact of buildings?	A1	a, e
	How the construction sector approaches the materials passport to make the buildings more circular?	A2	b, c
	1) How does the construction sector approach business models to achieve sustainable buildings? 2) How is the implementation of circular strategies distributed in the BMs described in the literature? and 3) How can the implementation of CBMs be facilitated?	A3	c
	Which are the Brazilian public policies that relate to the implementation of the CE in the construction sector?	A4	e
	How does the construction sector approach the ecodesign methods to achieve buildings deconstruction?	A5	d
	What are the major barriers and drivers to a circular economy in the construction sector? What is the role of the construction stakeholders in this transition?	A6	e
	How can Design for Adaptability and Disassembly and other building deconstruction-oriented ecodesign methods support the transition towards integration of circular economy within the construction sector?	A7	d

SOURCE: The author (2022).

FIGURE 6 illustrates the chronology of the study, identifying the main results through the studies and papers resulting from this thesis. It should be noted that the study is exploratory and new research possibilities may arise. Furthermore, the initial results obtained can be refined to solidify and continuously expand the network of this research. Thus, this study provides a continuing body of academic and empirical circular economy principles research.

Following this document, Part 2, the articles originating from this study will be presented in full in chronological order of development and publication, as shown in TABLE 2. The inclusion of papers already published in this document was verified with the publishers of academic journals, thus avoiding any violation of copyright.

FIGURE 6 – TIMELINE OF MAIN RESEARCH ACTIVITIES DEVELOPED



SOURCE: The author (2022).

PART 2

Part II aggregates all the original articles resulting from this thesis. The discussion of the articles and their contributions was carried out in Part 1, section 4.

PAPER A1

Towards circular and more sustainable buildings: a systematic literature review on the circular economy in the built environment

MUNARO, Mayara Regina; TAVARES, Sérgio Fernando; BRAGANÇA, Luís. Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment. **Journal of Cleaner Production**, v. 260, p. 121134, 2020. https://doi.org/10.1016/j.jclepro.2020.121134

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Towards Circular and more Sustainable Buildings: A Systematic Literature Review on the Circular Economy in the Built Environment

ABSTRACT

The built environment exerts great pressure on natural resources. Its role in the transition to a circular economy (CE) is critical. However, research from a holistic perspective, including how new business models can enable materials to increase their residual values, need to be deepened. This study provides a comprehensive and holistic overview of how the built environment approaches the study and the actions of the circular economy. Through a systematic literature review, 318 papers were selected and evaluated by two optics: i) a descriptive analysis and ii) a thematic analysis. The descriptive analysis highlights the relevance and incipient nature of circular thinking, the qualitative nature of the research, and the predominance of European countries and China at the forefront of circular research. In the thematic analysis, five axes were established as guiding lines of research, which evidenced the focus of research on minimizing and reusing construction and demolition waste. This study aims to provide the state of the art on CE research through a literature review. The results show research gaps, and a theoretical framework was proposed to guide future research. The need for more explanations about CE and circular business models is highlighted, as well as greater integration between stakeholders in the construction value chain. Government support, such as subsidies, laws, and tax incentives, is crucial to the strategic performance of decision-makers to introduce circular principles and make buildings and the built environment more sustainable.

Keywords: Circular economy. Construction. Built environment. Systematic literature review.

1 Introduction

With the prospects of a rising global population coupled with changes in consumption patterns, significant challenges to health, well-being, and the environment have arisen, accelerating development, the use of natural resources, and their associated environmental impacts. Since 2008 more than half of humanity lives in urban areas (Debacker and Manshoven, 2016), and by 2020 urbanization is expected to increase by almost 80% (Ellen MacArthur Foundation - EMF, 2015). In Brazil, 85% of the population is already concentrated in urban areas and this value is expected to reach 91% by 2050 (EMF, 2017).

The construction industry is important for the development of the economy. At the European level, it is one of the largest industrial sectors, corresponding to approximately 10%

of the Gross Domestic Product (GDP) and 18 million jobs (European Committee for Standardization - CEN, 2017). In addition to providing the built environment, the industry contributes to the development of national economies. However, it is the largest consumer of natural resources (Zimmann et al., 2016), representing more than a third of the total energy consumed in the world, as well as being an equally important source of carbon dioxide (International Energy Agency - IEA, 2013). Cities consume 75% of global primary energy, account for 60-80% of greenhouse gas emissions (United Nations Environment Programme - UNEP, 2016), and produce 50% of the world's waste (EMF, 2015). The role of the built environment is crucial in innovation and economic development.

The evolution of the global economy has been dominated by a linear model of production and consumption in which goods are manufactured from raw materials, sold, used, and then discarded or incinerated as waste (EMF, 2015). However, significant price rises, increased volatility in global commodity markets, and the production of negative externalities have alerted leaders to the need to rethink the use of materials and energy (p. 17). In this sense, the circular economy (CE) emerges as a new economic model that seeks to decouple economic development from the consumption of finite resources. The CE concept has gained academic, government, and organizational recognition. It is restorative, regenerative, and seeks to keep products, components, and materials at their highest level of utility and value (EMF, 2017).

The main strands of CE research in the academic literature are combined in the themes of the scarcity of resources, environmental impacts, and economic benefits (Ghisellini et al., 2016). The optimization of CE resources is linked to cleaner production, increasing the value of technical and biological cycles of materials through circular strategies such as reuse, repair, remanufacturing, and recycling of products, materials, and components. Innovative and more efficient ways of producing and consuming drive new business opportunities. It is estimated that the market for a CE in the next 10 years will boost economic growth by up to 4% (Hieminga, 2015). In Europe, technologies and business models can improve resource productivity and reduce the costs of mobility, food, and built environment sectors by almost € 1 trillion by 2030 (EMF, 2015).

In the construction industry, the change towards circularity business requires focusing on systemic thinking to understand the entire life cycle of the building and the construction value chain, involving better stakeholder integration (Zimmann et al., 2016). Consumption of resources and environmental impacts can be reduced by considering the principles of CE and adopting an eco-design approach that promotes more resource-efficient procedures for developed construction products. In this sense, CE transition opportunities are based on the adoption of flexibility and modularity concepts, more efficient resources, and reduction of waste to provide and maintain the built environment; in addition to investing in digital technology and innovative practices to create more value in the sector (EMF, 2017).

The theoretical and practical attention to the circular economy in the built environment is growing. However, the academic literature tends to be fragmented, focusing on barriers, and one phase of the supply chain, usually end-of-life. At this point, the emphasis is on reducing construction and demolition waste through recycling and reuse (Adams et al., 2017). However, quite limited research is available for the reuse of components. The secondary materials market is not yet widespread in the construction value chain. Moreover, there is still not much literature on the inherent systemic nature, integration materialization, and operation of circular value models. This is a critical gap because the role of managing and applying circular innovation in the built environment is often neglected. Implementing CE is hampered by a lack of knowledge about CE definition and how to implement it in business models. The barriers show inadequate awareness, understanding, and insight into CE in the building sector (Adams et al., 2017).

There are still few studies focused on the introduction of circular practices in the construction value chain. Developing guidelines for CE implementation and choosing CE indicators are in the early stages and should be based on the life cycle analysis (LCA) and material flow analysis (Stephan and Athanassiadis, 2018). Tools that support buildings as materials banks, will enable the direct reuse of whole components obtained during the demolition of structures, or the targeted recycling of construction materials for new uses. As such, there is a need to improve the current Building Information Modeling (BIM) systems to integrate the construction supply chains and ensure material waste minimization.

Considering the evolutionary path that CE is undergoing, a deeper knowledge of the circular practices introduced in the sector is essential to identify which practices are currently being performed and which still need to be implemented or improved. A holistic review is valuable of CE implications on buildings by analyzing the studies and the needs related to the development of this research field. In addition, there is a lack of clarification and guidance on how CBMs can leverage sustainable building development and cleaner production in the sector's supply chains.

This study aims to analyze how the built environment discusses and studies the circular economy. A study exclusively dealing with the CE practices in the built environment has not yet been published and exploring the research state-of-the-art will serve as a driving force in identifying academic gaps to support new value creation opportunities, facilitating stakeholder decision-making and greater integration between them. As a result, this study aims (i) to provide a comprehensive and systematically analyze of the CE state-of-the-art in the built environment; (ii) to highlight the trend of research and different considerations through a thematic analysis of the selected papers; and (iii) to identify the knowledge gaps to guide future studies.

This aim was achieved by conducting a systematic literature review (SLR) based on a deeply qualitative analysis, divided into a descriptive and thematic analysis of the data. Figure 1 shows the sequence of this article. The SLR is a transparent, reliable, and replicable manner serving to consolidate research findings in a specific area and identify research gaps that can guide future research (Tranfield et al., 2003). Framework and future research directions proposed in this study should support a paradigm shift towards circular buildings and, will contribute to the implementation of CE actions for enhancing sustainability in the construction sector as a whole.

The paper is structured in six sections. After this introduction (Section 1) a theoretical background (Sections 2) on the circular economy and buildings is presented. Section 3 introduces the methodological approach, followed by Section 4, which presents the results that were obtained. Section 5 presents a discussion of the findings, and Section 6 presents the most important conclusions and contributions to the research.

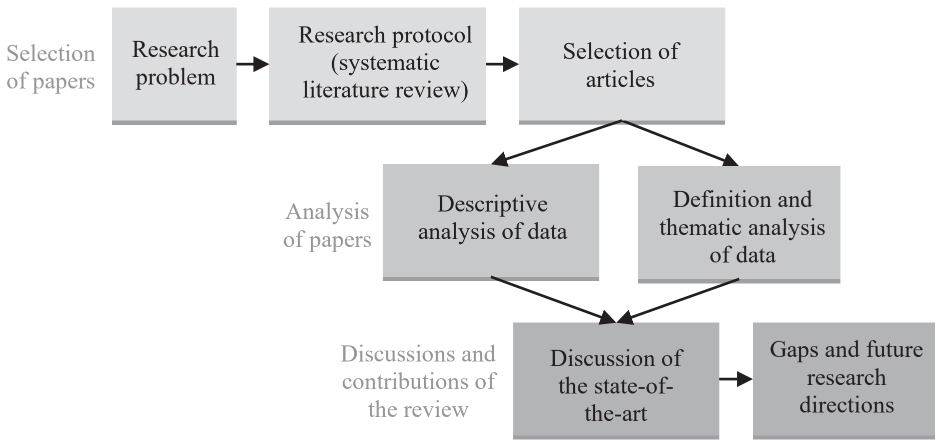

Figure 1. Sequence of article organization.

2 Circular perspectives in buildings

The major CE-related schools of thought emerged in the 1970s and gained prominence in the 1990s (EMF, 2015). The term had little use outside of China until 2010 but has been gaining popularity (Merli et al., 2018). Countries like China itself and Germany used the term within their legislation. Waste prevention and recycling are the main components of German legislation, whereas in Chinese politics the term is addressed to parks and eco-design networks (Adams et al., 2017). Common elements include eliminating the concept of waste and maximizing the value of materials. The circular economy approach gained attention from the Ellen MacArthur Foundation (EMF), emphasizing systemic thinking and the need to design out negative externalities (EMF, 2015).

The increasing need for sustainability in the construction industry and the movement of the CE are driving the research of recycling and reusing waste streams, such as recycled aggregates. Building materials and components are considered waste when they are no longer needed for the planned function, which accelerates the devastation of ecosystems, increases environmental costs, and entails risks of resource scarcity. Considering that Construction and Demolition (C&D) waste has been identified by the European Union as a priority stream and that raw materials resources are limited, the circular economy has gained interest in the construction sector.

Typically, buildings are seen as finished and permanent structures, designed for an average technical and functional life span of 50-75 years (Debacker and Manshoven, 2016). Despite the long physical life, they do not offer the flexibility to maximize lifespan. The disaggregation of structural and sealing elements for adaptations, substitutions, and refurbishment is common. Currently, most of the buildings are demolished with an average lifespan of 20 years because they no longer meet the needs of their users, reducing the service life of the facility, and this forces the return on investments to come more quickly (Debacker and Manshoven, 2016). Failure to remove and replace building systems and components results in increased energy and material consumption, enlarged waste production, and a lack of spatial and technical adaptability of the building (Debacker and Manshoven, 2016).

Circularity, therefore, provides a pathway to more sustainable and resilient buildings and cities. Like sustainable development, it is expected a development that meets the needs of the present without compromising the ability of future generations, based on social, economic, and environmental pillars. For the CE the three pillars are important. The focus is on technological advances to solve the economic and environmental problem of finite resources and is on the user behavior needs to change to close the cycle, and reduce consumption. Where sustainability is the goal, the CE is a road map to a more sustainable economy (Anastasiades et al., 2020).

Increasing the value of materials reduces waste and resource consumption, as explores the Building as Material Banks (BAMB) project in Europe, which investigates and seeks circular solutions to preserve the value and functionality of building materials and systems through methods and tools such as the material passports and the reversible building design (Debacker and Manshoven, 2016). In buildings, industrial and modular processes could reduce construction costs by 50% compared to traditional on-site construction; and passive houses could reduce energy consumption by 90% (EMF, 2015).

For the building sector, recycling natural, local waste is essential for circular business models by considering the impact on stakeholders. In this respect, the circular economy in the building sector requires a business model with a clear definition and adaptability in terms of the value creation process, and regeneration of natural waste through aligning managerial practices, sociocultural, and sustainable behaviors among supply chain actors (Ünal et al., 2019).

3 Methodology

The methodological approach of this study consists of a qualitative and descriptive systematic literature review, as summarized in Figure 2. A descriptive and thematic analysis of the data examining how the CE has been understood and explored by the stakeholders of the construction value chain, to make the urban environment more sustainable. The analysis of CE practices shows the main business models explored in the sector and the focus of this implementation on the built environment. Systematic literature reviews are appropriate for mapping, assessing, and synthesizing literature to develop knowledge in a field (Tranfield et al., 2003). In addition, the method allows the identification of research gaps and serves for developing new research agendas.

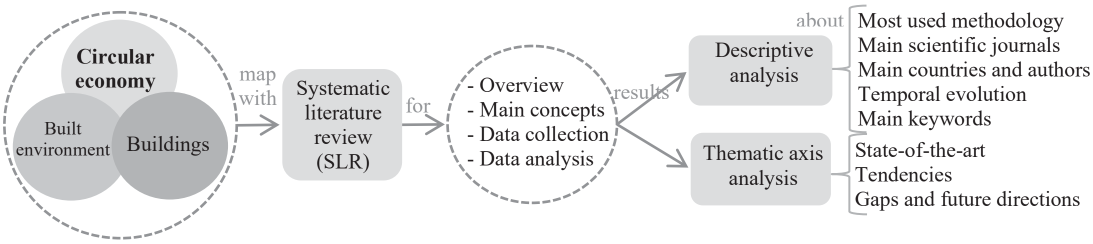

Figure 2. Summary of the systematic literature review process.

Following methodological and systematic rigor, a research protocol was structured whose data collection, processing, and results in analysis were based on management and organization studies, as shown in Figure 3, and described in the sequence (de Almeida Biolchini et al., 2007; Tranfield et al., 2003). The authors would like to highlight that this study does not claim to be exempt from any limitations or exhaustive, as it was based on the search strings, databases, and exclusion criteria. However, the authors believe it to be representative of the addressed body of literature.

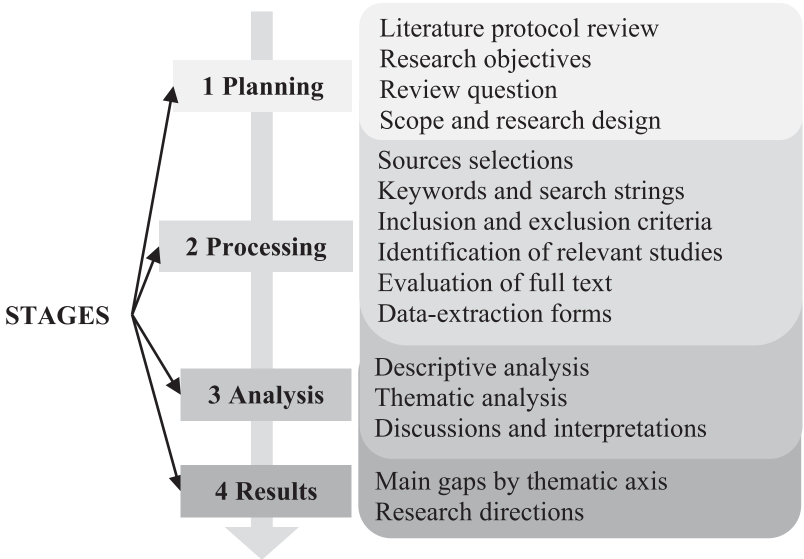

Figure 3. The main steps taken in the systematic literature review.

Step 1: Planning

From previous research to map and identify the terms and the procedure that the subject CE has been included in the journals, a research protocol was developed. The protocol reduces the risk of bias and promotes transparency of the methods and processes employed (de Almeida Biolchini et al., 2007). Applying specific principles of the SLR methodology enhances the legitimacy and authority of the resultant evidence, although the results depend on the choice of the search strings, the selection of study criteria, and the study quality assessment made by the authors. This review aims to give a comprehensive overview of the academic studies on CE, identify trends and research gaps, and provide potential future research directions on the topic. Therefore, the study addresses the following research question: "How the built environment approaches the study and the actions of the circular economy to reduce the environmental impact of buildings?"

Step 2: Processing

The sources of information were the academic databases Web of Science of Clarivate Analytics, ScienceDirect, and Scopus of Elsevier. Web of Science was selected because it can reach all indexed journals with a calculated impact factor in the Journal Citation Report (JCR) (Carvalho et al., 2013); ScienceDirect due to the multidisciplinarity of studies and references in the international scope, and Scopus was selected because it is the largest database of peer-reviewed articles (Morioka and de Carvalho, 2016). The only filter applied in the Web of Science was “type of documents”, choosing articles, reviews, and proceedings papers. In the other databases, the research criterion was “Title, Keywords, and Abstract”. The following keywords were used as search terms: built environment*, build*, construct*, and building design associated with circular* econom*. It was sought to capture the publications containing terms and expressions semantically different, but with the same meaning of the proposed problem.

A requirement for conducting the SLR is a concise description of the criteria for the inclusion and exclusion of papers (Tranfield et al., 2003). As article inclusion criteria were adopted: articles; without defined time frame; English language and full-text availability; resulting in 318 scientific articles, as shown in Table 1 and Figure 4 (review articles are marked listed in Appendix A). Articles that are not related to CE in the built environment/building were excluded.

Table 1. Selection criteria for the systematic review.

Criterion	Inclusion	Exclusion
Publication type	Available online as full-text articles, reviews, and proceedings paper	Any other publication (e.g., books, contributions to edited volumes, working papers...)
Language	English	Any other language
Time	Every year	-
Research discipline	Any area	-

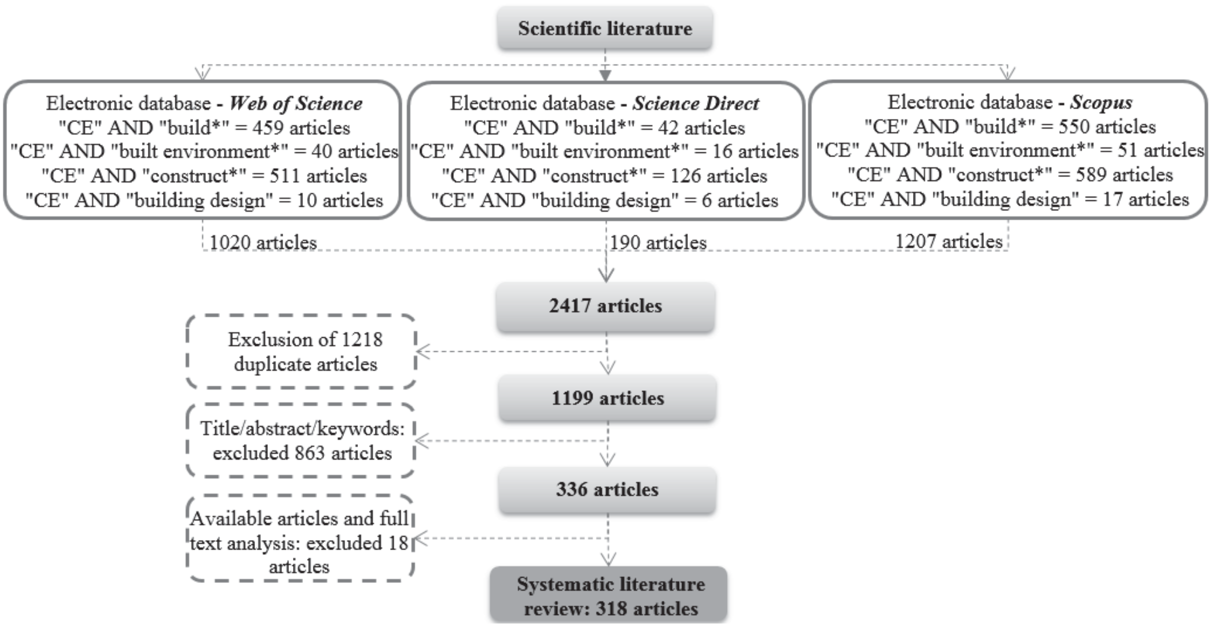

Figure 4. Processing of SLR in the scientific literature (review date: December 01, 2019).

Step 3: Analysis

A total of 18 criteria of analysis were developed for general mapping of literature, classified in three structural dimensions, as shown in Table 2. The criteria include the article title, year, database, authors, first author's country, journal, Journal Citation Reports (JCR), number of article citations, research methodologies (approach, procedure, data collection, and source), keywords, research aim, research justification, main gaps, and thematic axis. The criteria provided significant insights for identifying the research topics and driving the descriptive and thematic analysis, as well as understanding the importance and need of research in this area. Themes pull together a lot of material into more meaningful and harnessed units; it is a way of grouping the papers into a smaller number of sets, and helps the researcher understand the problem proposed. After reading and analyzing the articles, the perspectives and contexts of the studies were identified through descriptive and thematic analysis.

Table 2. Criteria of analysis of the articles selected in the systematic literature review.

Structural dimensions	Criteria of analysis		Analysis/discussion of results
Bibliometric data	1	Article title	Descriptive analysis (Sections 3.1; 4.1)
	2	Year	
	3	Database	
	4	Authors	
	5	First author's country	
	6	Journal	
	7	Journal Citation Reports (JCR)	
	8	Number of article citations	
	9	Keywords	
Research methodologies	10	Research approach (qualitative/quantitative)	
	11	Research aim (exploratory, descriptive, causal)	
	12	Research procedure (case study, experiment, modeling, qualitative research, survey)	
	13	Data source (primary/secondary)	
	14	Data collection (bibliographic, interviews and other sources, questionnaires, software/computer simulation, trials, and experiments)	
Thematic axis	15	Search aim	Thematic analysis (Sections 3.2; 4.2)
	16	Research justification	
	17	Definition of the thematic axis	
	18	Research gaps by thematic axis	

Step 4: Results

Research gaps were determined after reading the articles of the SLR and grouped according to the thematic axis of the article. The most relevant gaps, due to the number of times found in the review articles, and the authors' perception of the importance of the circular transition of the built environment, were described in Figure 11 for future research directions. It is emphasized that many gaps were observed in different articles and may be associated with more than one thematic axis. However, the gaps were grouped according to the main characteristics of each axis.

4 Analysis of results

The analysis of the results was divided into two sections: i) a descriptive analysis and ii) a thematic analysis. The results of the descriptive analysis present bibliographic data and help to contextualize the results of the thematic identification and material evaluation steps. The thematic analysis comprises the organization of the studies in research guiding axes, according to the similarities and tendencies found.

4.1 Descriptive analysis

The articles were analyzed according to the research methodology adopted considering management and organization studies (Malhotra, 2012). Figure 5 shows the methodological approach of the searches. The papers presented a qualitative (60%, 190 articles) and quantitative approach (40%, 128 articles), with the predominance of descriptive research (53%, 170 articles), followed by the exploratory type (28%, 88 papers) and causal type (19%, 60 papers). Bibliographic research was the most adopted procedure, with 110 articles (35%), followed by case studies (25%, 80 articles), experiments (19%, 60 papers), modeling (19%, 60 articles), and surveys (3%, 8 articles). Most data collection was secondary (67%, 213 papers), and 68 articles used primary data (21%) and 37 mixed data (12%).

Regarding the analysis and data collection, the literature review was the most representative (48%, 153 articles) following the qualitative procedure and the use of secondary data. The use of software simulations corresponded for 19% of the research (60 articles), trials and experiments 19% (60 articles), literature review and interviews 12% (37 papers), and 3% questionnaires (8 papers). It is worth noting that most of the articles did not make clear the methodological procedure used, being the authors responsible for the methodological classification according to the main character of the articles selected.

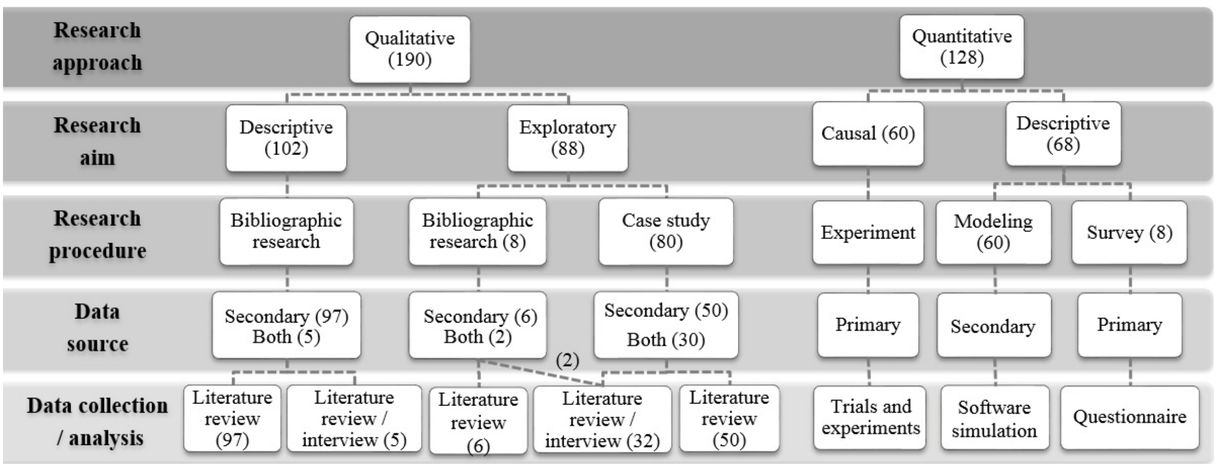

Figure 5. Research methodological procedure (number of articles, n = 318).

Exploratory research focused mainly on the current scenario and mechanisms to introduce the circular economy into the built environment, highlighting integrated policies (Pomponi and Moncaster, 2017), the development of China and Europe (Türkeli et al., 2018), and circular business models (Wong et al., 2018). The case studies explored, for instance, circular cities (Prendeville et al., 2018), the application of circular tools (Leising et al., 2018), and the role of design in creating sustainable value (De los Rios and Charnley, 2017). Bibliographic research has described CE principles on construction and demolition (C&D) waste management (Ghisellini et al., 2018b), the concepts of sustainable development in cities (Ness and Xing, 2017), as well as the consumption of natural resources and the environmental impacts of construction (Fernández, 2007).

Research with a causal approach focused on the reuse of C&D waste in the replacement of materials to reduce the waste and consumption of natural resources in the construction industry. The modeling research explored mathematical models to estimate anthropogenic stocks and flows of civil construction materials (Ortlepp et al., 2016); propose circular evaluation indicators (Nuñez-Cacho et al., 2018); assess the environmental impacts of materials and building systems (Deviatkin et al., 2016); and explore flexible building methodologies (Sanchez and Haas, 2018a). The surveys sought to investigate best practices for the management of C&D waste (Jiménez-Rivero and García-Navarro, 2017a).

The analysis of the systematic literature review points out the relevance and timeliness of the theme. The articles were published between 2006 and 2020, which proves that the research was boosted in recent years. Considering the incomplete data for 2019 (until 1 December 2019) the number of publications has increased in the last 4 years, from 7 articles published in 2015 to 21 and 44 in 2016 and 2017, respectively. The last three years account for 82% of the research (260 articles), and 2019 corresponds to 48% of the articles. This indicates the growing interest of the scientific community in the adoption of circular practices in the design, construction, and management of the built environment. The evolutionary development of publications is illustrated in Figure 6.

*Six articles from the systematic review to be published in 2020 are not represented in the chart above.

Figure 6. Yearly publications from 2006 to 2019.

Most of the scientific journals involved have environmental issues as a focus of interest and are relevant to the CE theme in the built environment. Table 3 lists the 15 first indexed scientific journals with more than three publications. The 318 articles are distributed in 86 journals (67%, 212 articles) and 43 proceedings papers (33%, 106 articles), emphasizing the extent of the subject. The three most representative journals were the Journal of Cleaner Production (13%, 42 articles), Sustainability (6%, 19 articles), and Resources, Conservation & Recycling (6%, 18 articles). The journals present notable JCR impact factors and have related research interests, designed to ensure progress toward more sustainable consumption and societies. The fifteen journals with the largest number of articles (134 articles) represented 42% of the articles in the systematic review.

Table 3. Quantitative measurements of journals in the systematic review.

Source	JCR	SJR	Number of publications	Total citations	Average citations
Journal of Cleaner Production (JCP)	6.395	1.62	42	847	20.2
Sustainability	2.592	0.549	19	97	5.1
Resources, Conservation and Recycling	7.044	1.541	18	404	22.4
Materials	2.972	0.686	9	54	6.0
Construction and Building Materials	4.046	1.522	9	69	7.7
Buildings	-	0.456	6	36	6.0
Journal of Industrial Ecology	4.826	1.486	4	178	44.5
Waste Management	5.431	1.523	4	40	10.0
Proceedings of the Institution of Civil Engineers - Engineering Sustainability	1.302	0.398	4	28	7.0
Procedia CIRP	-	0.725	4	17	4.3
Energy Procedia	-	0.468	3	40	13.3
Journal of Material Cycles and Waste Management	2.004	0.487	3	35	11.7
Building Research and Information	3.744	1.283	3	61	20.3
Proceedings of the Institution of Civil Engineers - Waste and Resource Management	-	-	3	95	31.7
World Journal of Science, Technology and Sustainable Development	-	-	3	19	6.3

Table 3 also lists the total number of citations and the average number of citations per publication. The citation is one of the main measures of the influence of academic papers and its use identifies influential studies in a field. Consistent results are observed in the most productive journal (JCP), which also receives the highest number of citations, indicating influence in terms of production and research. In terms of average citations, it is possible to note periodicals with significant contributions in the area, such as the Journal of Industrial Ecology, Proceedings of the Institution of Civil Engineers - Waste and Resource Management, and Building Research & Information.

The most prolific authors on the subject, who contributed with three or more articles, are listed in Table 4. The most productive author was Jiménez-Rivero, A., of Spain, with 7 articles on the management of construction and demolition waste. Sanchez, B., presents 5 articles focusing on selective planning disassembly of buildings. Eberhardt, L., presents research considering Life Cycle Assessments to support designers in choosing environmentally viable solutions. Pomponi, F. was the author with the highest number of citations, demonstrating his influence in research on sustainable production and consumption. It is important to note that the average annual publication is very recent, which may interfere with the total of research citations. Among the most productive researchers, the predominance of research is in European countries and the focus on tools and assessment to support the transition to circular buildings.

Table 4. Quantitative measurements of authors in the systematic review.

Authors	Number of papers	Country	Total citations	Average publication year	Average citations	Research focus
Jiménez-Rivero, Ana	7	Spain	89	2016	12.7	Recycled / reusable materials
Sanchez, Benjamin	5	Canada	48	2019	9.6	Tools and assessment to support circular buildings
Eberhardt, Leonora	4	Denmark	14	2019	3.5	Circular transition / Tools and assessment to support circular buildings
Geldermans, Bob	4	The Netherlands	36	2018	9.0	Product and building design
Akanbi, Lukman	3	UK	43	2019	14.3	Tools and assessment to support circular buildings
Heisel, Felix	3	Germany	4	2019	1.3	Product and building design
Pomponi, Francesco	3	UK	170	2018	56.7	Circular transition
Saeli, Manfredi	3	Portugal	14	2018	4.7	Recycled / reusable materials
Schiller, Georg	3	Germany	53	2018	17.7	Stock and flow analysis of resources and materials

*Total citations of the articles were obtained on December 09, 2019.

The most cited articles are listed in Table 5. Smol et al. (2015) were the authors with the most cited article, which explores the use of sewage sludge ash in the production of building materials, emphasizing many articles on C&D waste reuse. Then, Pomponi and Moncaster (2017) present a frame with fundamental defining dimensions of a CE for the built environment. Krausmann et al. (2017), the third most cited article, analyze the flow and stock of materials in search of more intensive use of existing stocks. Fernández (2007) examines the consumption of natural resources used in construction in China, analyzing the efficient use of resources and the life cycle of the built environment. This article was written more than 10 years ago, underlining the fact that the Chinese government was a forerunner in the CE expansion (Türkeli et al., 2018). Among the most cited publications, the highlight for the Journal of Cleaner production, stresses its influence on the subject.

Table 5. List of publications with the highest number of citations.

Authors	Title	Number of citations	Journal
Smol et al. (2015)	The possible use of sewage sludge ash (SSA) in the construction industry as a way toward a circular economy	172	Journal of Cleaner Production
Pomponi and Moncaster (2017)	Circular economy for the built environment: A research framework	162	Journal of Cleaner Production
Krausmanna et al. (2017)	Global socioeconomic material stocks rise 23-fold over the 20th century and require half of the annual resource use	142	Proceedings of the National Academy of Sciences
Fernández (2007)	Resource Consumption of New Urban Construction in China	125	Journal of Industrial Ecology
De los Rios and Charnley (2017)	Skills and capabilities for a sustainable and circular economy: The changing role of design	117	Journal of Cleaner Production
Nasir et al. (2017)	Comparing linear and circular supply chains: A case study from the construction industry	84	International Journal of Production Economics
Adams et al. (2017)	Circular economy in construction: current awareness, challenges, and enablers	71	Proceedings of the Institution of Civil Engineers - Waste and Resource Management
Huang et al. (2018)	Construction and demolition waste management in China through the 3R principle	70	Resources, Conservation and Recycling
Supino et al. (2016)	Sustainability in the EU cement industry: The Italian and German experiences	64	Journal of Cleaner Production
Prendeville et al. (2018)	Circular Cities: Mapping Six Cities in Transition	61	Environmental Innovation and Societal Transitions
Gálvez-Martos et al. (2018)	Construction and demolition waste best management practice in Europe	60	Resources, Conservation and Recycling
Zhou et al. (2012)	Energy consumption patterns in the process of China's urbanization	53	Population and Environment

*Total citations of the articles were obtained on December 09, 2019.

Figure 7 shows the geographical distribution of the studies analyzed according to the first author's country. Europe accounted for 74% of the research (235 articles) covering 22 countries, followed by Asia with 17% (54 articles). Both continents accounted for more than 90% of the review articles and lead the research community in the circular economy (Türkeli et al., 2018). Table 6 lists the countries with more than one publication. Among the 37 countries, the United Kingdom (UK) is the leading country in terms of volume of publications, followed by China, Italy, Spain, and The Netherlands. The predominance of England and Chinese studies are related to the adoption of public policies and regulatory institutional support for CE. UK is a member of the European Union – EU-28, in which the CE package has been part of a heated policy debate. On the other hand, China has developed the Circular Economy Promotion Law adopted in 2009 (Türkeli et al., 2018).

In addition, Table 6 lists the total number of citations of articles in each country and the average annual publications. In terms of the number of citations, the UK is the research influence, followed by Spain and Italy. China presented the lowest average publication year, showing itself as the country that earlier began publishing on the subject. Other countries present their publications mainly concentrated in 2018 and 2019.

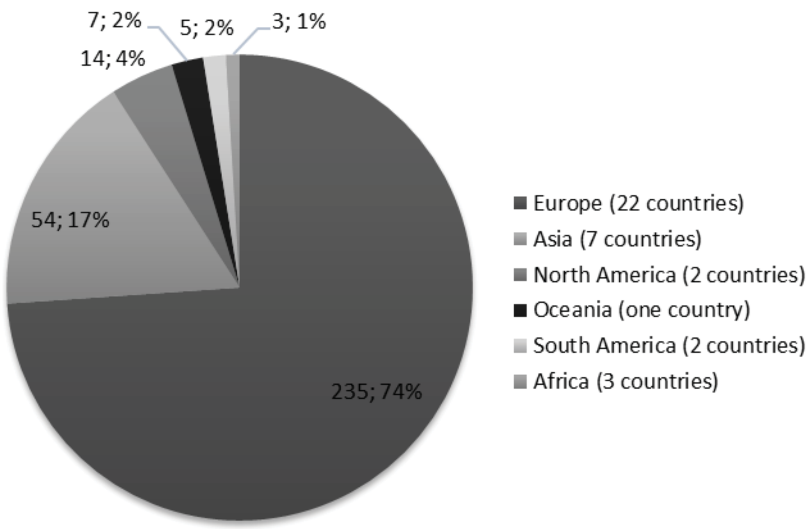

Figure 7. Geographic distribution of publications (number of articles, n = 318).

Table 6. Measurement of the countries active in the systematic review.

Country	Number of publications	Number of citations	Average citations	Average publication year
UK	42	695	16.5	2018
China	40	201	5.0	2015
Italy	33	207	6.3	2018
Spain	33	247	7.5	2018
The Netherlands	26	147	5.7	2018
Germany	16	116	7.3	2018
Portugal	13	32	2.5	2019
Denmark	10	20	2.0	2019
Belgium	8	29	3.6	2019
Canada	8	54	6.8	2018
Finland	8	41	5.1	2019
Australia	7	167	23.9	2018
France	7	12	1.7	2018
Greece	7	60	8.6	2017
Austria	6	178	29.7	2019
Romania	6	4	0.7	2018
USA	6	145	24.2	2017

Sweden	5	71	14.2	2018
Taiwan	5	22	4.4	2019
Brazil	4	8	2.0	2018
Czech Republic	3	5	1.7	2018
Hong Kong	3	22	7.3	2019
Poland	3	176	58.7	2018
Switzerland	3	7	2.3	2019
Japan	2	17	8.5	2018
Luxembourg	2	4	2.0	2019
Malaysia	2	7	3.5	2018

The keywords represent the main content of existing studies and depict topics that have been focused on a particular domain (Jin et al., 2019). Table 7 summarizes the main group of keywords found according to their occurrence. The keywords were grouped according to the similarities of the meanings of the expressions. Among 1512 expressions, "circular economy" leads the number of citations, followed by the group of expressions sustainability and recycling, demonstrating that CE in the built environment is strongly related to these two terms. Expressions such as recycling, waste management, construction and demolition waste, reuse, end-of-life, reiterate the concentration of research on C&D waste management. The terms design for deconstruction, Building Information Modeling (BIM), and adaptive reuse occurred mostly in 2019, indicating emerging issues and the attention of researchers in this field.

Table 7. Main group of keywords identified in the systematic literature review.

Group of keywords	Occurrence	Average Year Published
circular economy - CE	162	2017
sustainability or sustainable construction/development/materials	55	2018
recycling aggregate/material/concrete	45	2017
building or construction sector/industry/design	44	2017
waste management/disposal/treatment/minimization	36	2017
construction and demolition (C&D) waste	34	2016
reuse or recycle and reuse or reuse of material	32	2018
cement or concrete structures/composite	29	2018
life cycle assessment/analysis - LCA	28	2018
resource efficiency/recovery	15	2018
urban mining	14	2018
design for deconstruction or deconstruction planning/programing	13	2019
building materials/components	12	2018
end-of-life	10	2018
building information modeling (BIM)	10	2019
built environment	10	2017
China	8	2018
adaptive reuse or heritage buildings	7	2019
durable or durability	7	2017
industrial ecology	6	2016

4.2 Thematic analysis

In the qualitative analysis of the systematic review articles, five thematic axes were categorized by the number of incidence and affinity in the themes: Recycled/Reusable materials (39%, 123 papers); Circular transition (22%, 69 papers), Tools and assessment to support circular buildings (17%, 54 papers), Product and building design (46%, 14 papers), and Stock and flow analysis of resources and materials (8%, 26 papers) presented in Figure 8. The main themes of the research that support the definition of thematic axes are indicated in the graph (outer circle), with the respective number of articles in the identified axis. Table 8 indicates the theme of each axis and its respective authors.

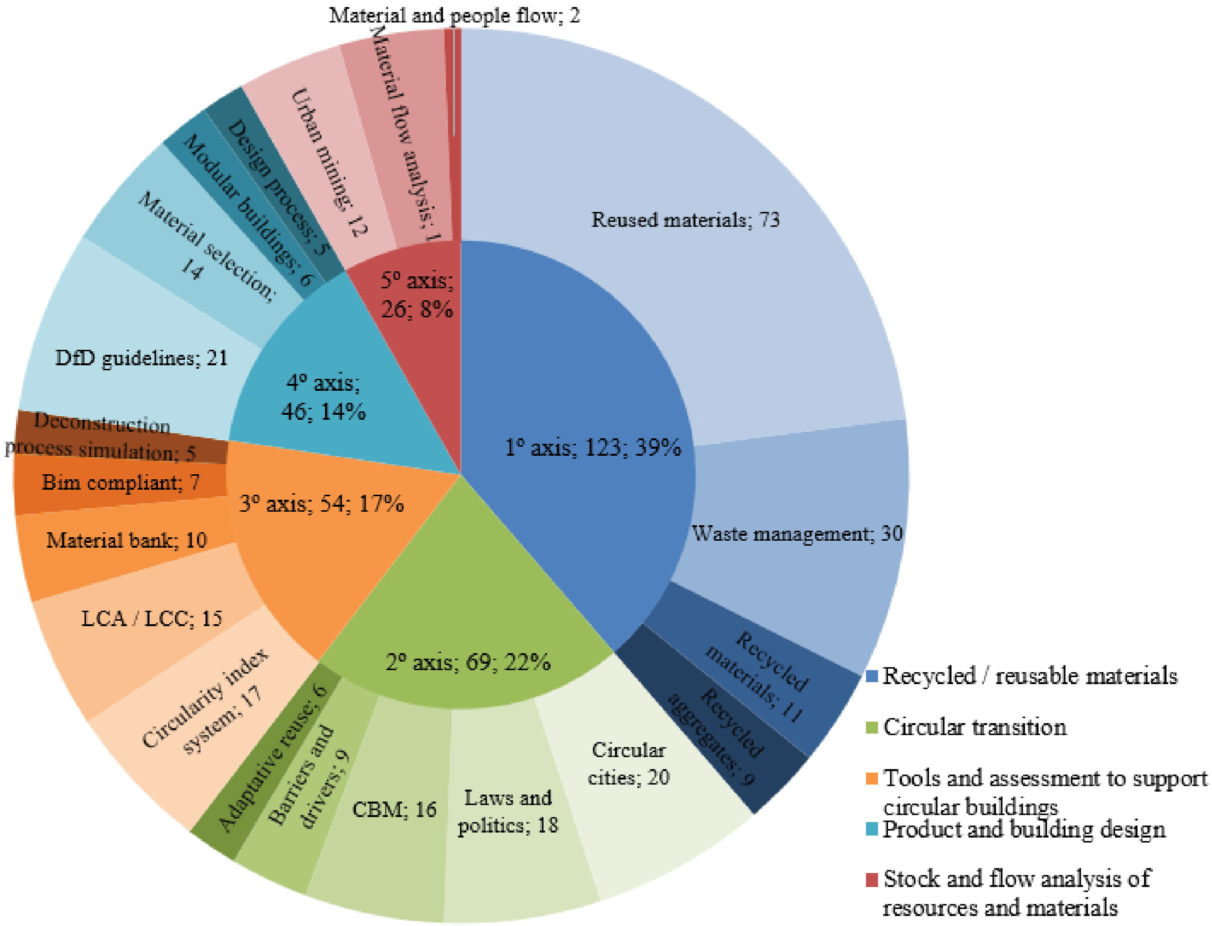

Figure 8. Organization of the systematic review articles in thematic axes with the associated research areas (number of articles; n = 318).

Table 8. Classification of the thematic axes and authors of the studies related to the systematic review.

Ranking (nº, %)	**Thematic axis**	**Topic covered**	**Authors***

1º (123, 39%)	Recycled/ reusable materials	Principles and practices for C&D waste management throughout the construction value chain to improve resource efficiency and reduce environmental impact	Ajayabi et al. (2019); Ali et al. (2019); Aneke and Awuzie (2018); Antunes et al. (2019); Araújo et al. (2019); Aversa et al. (2019); Ayati et al. (2018); Baiani and Altamura (2018); Balletto et al. (2019); Basti (2018); Bedekovic et al. (2019); Bertin et al. (2019); Bevilacqua et al. (2016); Bigolin et al. (2016); Bilba et al. (2016); Blanc et al. (2019); Brütting et al. (2019a,b); Buratti et al. (2018); Cantero et al. (2019); Carpenter et al. (2018); Chen et al. (2014); Chen et al. (2019); Cifrian et al. (2019); Cosentino et al. (2019); Costa and Marques (2018); Coudray et al. (2017); Cross (2017); Cusenza et al. (2019); Deng et al. (2010); Deviakin et al. (2016); Díaz-García et al. (2017); Esa et al. (2017a,b); Esquinas et al. (2018); Ferraz et al. (2018); Fraile-Garcia et al. (2016); Gálvez-Martos et al. (2018); Ghaffar et al. (2020); Ghisellini et al. (2018 a,b); Ho et al. (2018); Hopkinson et al. (2019); Huang et al. (2018); Husgafvel et al. (2018); Jiménez-Rivero and García-Navarro (2016; 2017 a,b,c); Jiménez-Rivero et al. (2015; 2016; 2017); Jin et al. (2019); Joseph et al. (2018); Karayannis (2016); Karayannis et al. (2017); Kemp et al. (2017); Lederer et al. (2017); Liu et al. (2017); Lozano-Lunar et al. (2018; 2019a,b); Lozano-Miralles et al. (2018); Lyubenova et al. (2018); Magro et al. (2019); Mahpour (2018); Manelius et al. (2019); Martínez-Martínez et al. (2019); Martinho et al. (2018); Martín-Morales et al. (2017); Merino et al. (2019); Merli et al. (2019); Migliore et al. (2018); Mihai (2019); Missaoui et al. (2015); Modolo et al. (2018); Noll et al. (2019); Nußholz et al. (2019); Parron-Rubio et al. (2018; 2019); Pavlíková et al. (2019); Perez-Garcia et al. (2019); Pimentel-Rodrigues and Siva-Afonso (2019); Pöykiö et al. (2019); Rebischung et al. (2017); Rios et al. (2019); Rodríguez-Quijano et al. (2015); Romnée et al. (2019); Rose et al. (2018); Ruiz et al. (2019); Saeli et al. (2017; 2019a,b); Sáez et al. (2019); Sansom and Avery (2014); Sargent et al. (2020); Seifi et al. (2019); Silva et al. (2019); Smical et al. (2015); Smol et al. (2015); Soultana et al. (2019); Spiliotis et al. (2019); Suescum-Morales et al. (2019); Tallini and Cedola (2018); Tingley et al. (2017); Vaitkus et al. (2019); Vinciguerra et al. (2018); Vladimirov and Bica (2019); Xu and He (2017); Wang et al. (2011); Wang et al. (2013); Wang et al. (2017); Wang et al. (2019); Wei et al. (2010); Wong et al. (2018); Wu et al. (2016); Wu and Deng (2013); You and Wang (2017); Zaharaki et al. (2016); Zanni et al. (2018); Zhang et al. (2019); Zhou et al. (2014); Zhu et al. (2013)
2º (69, 22%)	Circular transition	Explores how the concept of CE can be integrated into urban planning and the development of sustainable services and production systems in the construction	Adams et al. (2017); Awuah and Booth (2014); Bao et al. (2019); Bartalucci et al. (2018); Bertino et al. (2019); Bolger and Doyon (2019); Bourke and Kyle (2019); Bueren et al. (2019); Campbell-Johnston et al. (2019); Chang and Hsieh (2019); Crețu et al. (2019); Diemel and Fennis (2018); Du (2016); Eberhardt et al. (2019a,b); Foster et al. (2020); Fratini et al. (2019); Futas et al. (2019); Geldermans et al. (2019); Gervasio (2019); Giorgi et al. (2019); Gorecki (2019); Gorecki et al. (2019); Gravagnuolo et al. (2019); Hart et al. (2019); He et al. (2006); Huovila et al. (2019); Johansson et al. (2016); Kang et al. (2019); Karhu and Linkola (2019); Kennedy et al. (2016); Leising et al. (2018); Lemiatre et al. (2019); Li and Li (2013); Lu and Li (2015); Lu and Yu (2012); Maerckx et al. (2019); Mangialardo and Micelli (2017); Marin and De Meulder (2018); Milios (2018); Moropoulou et al. (2018); Nasir et al. (2017); Nazareth (2019); Ness and Xing (2017); Nordby (2019); Oyinlolaa et al. (2018); Ploeger et al. (2019); Pomponi and Moncaster (2017; 2019); Prendeville et al. (2018); Rahla et al. (2019); Rohan (2016); Sanchez et al. (2019); Sauter et al. (2019); Sfakianaki (2015); Sivo et al. (2019); Supino et al. (2016); Torrieri et al. (2019); Turkeli et al. (2018); Ünal et al. (2019); Valenzuela et al. (2018); van der Leer et al. (2018); Wang et al. (2011); Williams (2019); Wu et al. (2019); Wuyts et al. (2019); Yuan et al. (2011); Zairul et al. (2018); Zhang (2014)
3º (54, 17%)	Tools and assessment to support circular buildings	Use of tools, metrics, technologies, and management policies for the quantification, measurement, or comparison of materials and systems as a support for the circular transition	Aguiar et al. (2019); Ajayi et al. (2019); Akanbi et al. (2018); Akanbi et al. (2019a,b); Akinade and Oyedele (2019); Andersen et al. (2019); Anderson et al. (2019); Biccari et al. (2019); Buyle et al. (2019); Castro and Pasanen (2019); Charef et al. (2019); Corcelli et al. (2019); Cuenca-Moyano et al. (2019); Dong et al. (2017); Eberhardt et al. (2018; 2019); Elmaraghy et al. (2018); Eray et al. (2019); Fargnoli et al. (2019); Geldermans et al. (2019); Gepts et al. (2019); Geraedts (2016); Giorgi et al. (2019); Heisel and Rau-Oberhuber (2020); Honic et al. (2019); Hossain and Ng (2018; 2019); Kakkos et al. (2019); Luscuere (2016); Mohamed Abdul Ghani et al. (2017); Munaro et al. (2019); Nuñez-Cacho et al. (2018); Pelorosso et al. (2017); Pomponi and D'Amico (2018); Rønholt et al. (2019); Ros-dosdá et al. (2019); Sanchez and Haas (2018); Sanchez et al. (2019a,b); Shengguo and

			Xiaodong (2013); Shojaei (2019); Stijn and Gruis (2019); Su and Wang (2014); Teplý et al. (2018 a,b); Trinius and Goerke (2019); Verstraeten-Jochemsen et al. (2018); Wang and Liang (2010); Wang et al. (2018); Yi and Liu (2016; 2017); Zaman et al. (2018); Zhou et al. (2013)
4º (46, 14%)	Product and building design	Better understanding of the role of design in the construction value chain	Akinade et al. (2019); Ali (2019); Anastasiades et al. (2020); Andrade et al. (2019); Azcárate-Aguerre et al. (2017); Brambilla et al. (2019); Buyle et al. (2019); Campbell (2019); Campioli et al. (2018); Cheeseman (2019); Dannapfel et al. (2019); De los Rios and Charnley (2017); Farrar (2019a,b); Finkbeiner et al. (2019); Fregonara et al. (2017); Geldermans (2016); Geldermans et al. (2019); Gorgolewski (2019); Heisel et al. (2019a,b); Iuorio et al. (2019); Kozma et al. (2019); Kreilis and Zeltins (2017); Kyrö et al. (2019); Lazarevic et al. (2020); Leendertse et al. (2018); Liu et al. (2019); Minunno et al. (2018); Molina-Moreno et al. (2017); Morel and Charef (2019); Nijgh and Veljkovic (2019a,b); Odenbreit and Kozma (2019); Orsini and Marrone (2019); Ortlepp et al. (2017); Pavlovic and Veljkovic (2017); Rasmussen et al. (2019); Ritzen et al. (2019); Rossetti and Bin (2018); Sanchez and Haas (2018); Sencu et al. (2019); Sierra-Pérez et al. (2018); Vasile et al. (2019); Xu and Sun (2019); Zheng and Qin (2013)
5º (26, 8%)	Stock and flow analysis of resources and materials	Classify and quantify the material stock and flow in buildings to improve their use in the construction industry	Arora et al. (2019); Cai and Waldmann (2019); Casas-Arredondo et al. (2017; 2018); Cheng et al. (2018; 2019); Deetman et al. (2019); Fernández (2007); Guo et al. (2017); Heinrich and Lang (2019); Hu and Poustie (2018); Krausmann et al. (2017); Lanau et al. (2019); Lee et al. (2016); Long et al. (2010); Marinova et al. (2019); Miatto et al. (2017); Oezdemir et al. (2017); Ortlepp et al. (2016; 2018); Schiller et al. (2017a,b; 2019); Stephan and Athanassiadis (2017); Volk et al. (2019); Zhou et al. (2012)

*Review articles are in Appendix A.

5 Discussion

The discussion of SLR results was treated in two sections: i) the descriptive analysis and ii) the thematic analysis. In addition, Section 6 presents a framework with the main gaps and research trends identified through the thematic analysis.

5.1 Descriptive analysis discussion

The results of the descriptive analysis demonstrated that the CE in the built environment is still in its infancy. The exploratory nature of some research and the predominance of the qualitative method corroborate this statement, along with data collection techniques based on bibliographic research, interviews, and questionnaires, which are flexible and adaptable ways of detecting subjects (Robson, 2002). The concentration of publications in the last 3 years shows the exploratory and current relevance of the revised subject.

Journal of Cleaner Production was highlighted both in the concentration of studies and in terms of the scientific relevance of the research. Among the conference papers, had highlighted the proceeding IOP Conference Series: Earth and Environmental Science, with 49 articles published in the final event of BAMB-CIRCPATH: The Building Material Banks - A Pathway for the Future Circular occurred in February 2019. The dispersion of the articles reviewed in journals and proceedings papers emphasized the extent of the subject in engineering, sustainability, technology, and economics journals.

The variety of research areas involved, from urban planning (Prendeville et al., 2018), waste recycling (Lederer et al., 2017), circular metrics (Nuñez-Cacho et al., 2018) to business models (Johansson et al., 2016) emphasizes business opportunities to create holistic and integrated thinking of the flows and value chains of the construction industry. Although there is specific research on, for example, gypsum waste (Jiménez-Rivero et al., 2017) or the possible use of sewage sludge ash (Smol et al., 2015) that shows the lack of holistic and integrated thinking. Pomponi and Moncaster (2017) highlight the need to increase interdisciplinary research on the role of buildings in a CE transition. It is important to consider the CE as an umbrella concept that acts in all phases of the building life cycle, involving requirements of materials/products/processes, waste management, environmental impacts, and management systems.

The geographical distribution of the main authors of the papers evidences the centralization of research in European countries and China. China is a leading country in the number of CE publications, partly because of political engagement. In addition, China has the world's largest population and accelerated economic growth, requiring strong resource and energy demands, hence the need for circular initiatives in its cities and industrial parks. Both in Europe and China, researchers are attuned to the development of public policy (Merli et al., 2018). Large countries in terms of geographical area and economy, such as Brazil, the United States of America (USA), India, and Russia, still have no relevance in the academic field, only four and six publications were found in Brazil and USA, respectively. This may indicate that more scientific studies need to be conducted and applied in those countries. In Brazil, as in the rest of the world, the transition to the CE will create opportunities for more innovation and value creation. Nations that adopt this model will not only occupy leadership positions but will also have a competitive advantage through the use of resources, money, and people.

The keywords highlighted the expressions of circular economy, sustainability, and C&D waste. The authors with the most productive metrics also highlight the leadership and the current relevance of the research on waste management and tools and assessment to support circular buildings, pointing out future directions in these areas.

5.2 Thematic analysis discussion

The thematic axis "recycled / reusable materials" represented 39% of the papers (123 articles) and the leadership in the topics considered. The focus was on waste reuse from different origins, both from C&D (Gálvez-Martos et al., 2018) and from other industries (Deviatkin et al., 2016), or even from natural sources (Ferraz et al., 2018), to their reuse in the construction value chain, as an additive or replacement of materials, for the manufacture of new products, reaching the same or even better performance. Recycling was mainly addressed with the use of C&D waste in concrete manufacturing and the reduction of natural aggregates. In addition to the reuse of waste in construction materials, the axis presents research on waste management at the construction site, the quality of secondary materials, and the best waste management practices to reduce environmental impacts.

In the "circular transition" thematic axis, accounting for 22% of the surveys (69 articles), CE was treated as an innovative business model in the search for more sustainable and economically efficient buildings and cities. This axis identified fundamental dimensions for CE research in the built environment (Pomponi and Moncaster, 2017). The axis presented examples of circular city initiatives, adaptive reuse of buildings, and circular business models adopted in the construction value chain. In addition to highlighting the key barriers and drivers, laws and policies are being developed to accelerate the circular transition in the built environment.

Case studies have analyzed how circular practices are addressed in different situations, such as in cement industries (Supino et al., 2016), in the reuse of materials (Wong et al., 2018), in Product-Service Systems (PSS) (Azcárate-Aguerre et al., 2018), as well as in social projects (Oyinlolaa et al., 2018). Leising et al. (2018) focused on the need for greater incorporation of the sector and developed a collaborative tool based on the supply chain to contribute to the circular transition. It should be noted that the current scenario lacks clarification and knowledge about the circular economy focused on the built environment and construction value chain. The proposed case studies and business models have sought to illustrate existing applications and initiatives to broaden research and application in the field; provide scientific information to improve the circular performance of systems; and highlight missing connections to projects, helping to make more sustainable project decisions.

In the "tools and assessment to support circular buildings", 54 articles were selected which corresponded to 17% of the total papers, occupying third place in the ranking of the thematic axes. The axis demonstrated how CE has been introduced into the built environment. The research focus highlighted in this axis was deconstruction process simulation, circularity index system, BIM compliant, tools to support buildings as a material bank, and life cycle assessment (LCA), and a life cycle costing (LCC) to compare the environmental performance of different constructive systems. Instruments, models, systems, and policies were analyzed in the transition to more sustainable production models. In general, axis surveys focus on flexible buildings and adaptive reuse; indices and metrics to measure circular development; and urban policies and actions for sustainable development.

The fourth place in the ranking of the axes corresponds to the theme "product and building design", with 14% of the research (46 articles) approaching design aspects of products and materials to reduce the environmental impacts of the construction sector. Since the final disposal of a product is dictated by its design and manufacturing, it is essential to better understand how environmental problems are considered in product development practices. Guidelines for Design for Disassembly (DfD), choice of materials, and construction technique planning were addressed so that the construction industry develops products that fulfill functional requirements. At the same time, promoting safety and durability during all the building life cycle phases, promoting reversible buildings to avoid construction obsolescence and recourses' waste. Product aspects influence how the entire value chain will be created and managed, so the design is crucial in resource flow approaches and the creation of sustainable business models. The implementation of a holistic sustainability strategy involves changes inherent in the creation of a product or service. The design of a product is a determining factor in its reinstatement at the end of life or reuse.

The fifth place in the ranking of the thematic axes "stock and flow analysis of resources and materials" (8%, 26 papers) showed that the transition to environmentally sustainable patterns of resource consumption requires a more complete understanding of material flow relationships and stock. The axis addressed research on urban mining and approaches to quantify the flow of materials and people involved in the composition of stock anthropogenic. Reducing increases in energy demand and greenhouse gas emissions will require the decoupling of services from stocks and material flows through the intensive use of existing stocks, longer service life, and more efficient designs. Stocks not only affect the demand for material and energy inputs over time due to their longevity but also determine the amount of solid waste produced and the availability of materials for recycling in terms of quantity, quality, and time. Promoting a transition to environmentally sustainable standards of resource use requires a more complete understanding of stock-flow relationships (Krausmann et al., 2017).

6 Main gaps and future research directions

The systematic literature review led to the proposition of new studies as a continuity of knowledge production in the area. These propositions are pointed out from the reading and analysis of the studies and the respective identification of the main research gaps, which are explained according to the thematic axes in Figure 9.

Current research areas	Thematic axis	Main gaps identified
Best practices for C&DW management; waste reuse in building materials; recycled aggregates	**Recycled / reusable materials**	1. To raise the awareness of construction workers in the reduction of waste; 2. Establish acceptance criteria for C & D waste; 3. Reinforce reverse logistics policies; 4. Routes and requirements to be followed in the reuse of deconstruction materials; 5. Strategies for disassembling and storing secondary materials; 6. Clarify the relationship between producers, suppliers, researchers and public policies in the reuse of waste.
Main barriers and drivers, laws and politics to achieve CE, examples of circular cities, including circular business models and buildings adaptive reuse	**Circular transition**	7. Understand the public, academic, industrial and governmental participation in the CE in the built environment; 8. Define the stakeholder's responsibilities in the material chains and flows; 9. Identification of infrastructure bottlenecks for the construction of a circular city; 10. Define regulatory measures and taxation; 11. Raise organizations' initiatives that have circular actions; 12. Policies for the rehabilitation and maintenance of materials / systems / products; 13. Investigate collaborations between different industries to reuse materials at the end of their useful life.
Circulatory index system; deconstruction process planning; BIM compliant; material passport; LCA / LCC to environmental performance	**Tools and assessment to support circular buildings**	14. Comparison of LCAs of monolithic and flexible structures; 15. BIM-based planning methods for product and building disassembly; 16. Study on the environmental impacts and costs of dismantling, selective demolition and renovation of buildings; 17. Definition and implications of eco-design requirements for durability and reparability of materials, how they can be developed, and consumer preferences; 18. Review of the buildings' deconstruction aiming at a closed cycle and economically viable chain; 19. Establish building flexibility criteria and its socioeconomic impacts; 20. Applications and challenges of material passports and flexible buildings.
DfD guidelines; material selection; construction features; design process	**Product and building design**	21. Design strategies to introduce circularity into business models; 22. Understand the needs and preconditions of materials, products and systems to be circular and how to integrate this into buildings; 23. Check the main design requirements and economic and environmental influence on buildings.
Material and people flow analysis; urban mining	**Stock and flow analysis of resources and materials**	24. Define the role of producers and operators in relation to product liability; 25. Socio-economic study on the mapping and (re) use of anthropogenic stocks; 26. Investigate the relationship between inventories and flows and the effect of local or regional capacity on materials supply and on waste transport / recycling capacity; 27. Strategies to extend the useful life and efficiency of materials;

Figure 9. Framework linking current research topics to the main gaps and future research directions.

Figure 9 presents 27 research directions to guide the introduction of circular practices in the construction scenario to uncover new research possibilities, contribute to the strategic performance of decision-makers, and promote an approach between the subject and the market reality. Considering the current research scenario and the proposed framework, new research directions can be grouped in:

- Better clarification on the CE concepts and purposes in the built environment by raising the awareness of stakeholders about the importance of closed value cycles, waste reduction, and their responsibilities in chains and material flows;
- Prioritize the design of circular systems and materials to extend the value and useful life of the resources used;

- Incorporate a more comprehensive decision-making system in project planning considering the LCA, Material flow analysis (MFA), material passports, and end-of-life reuse potential;
- Study disassembly strategies and acceptance criteria for the use of secondary materials, as well as C&D waste;
- Consider policies around consumption taxation, legal frameworks, specific recycling targets, business responsibility for products throughout the life cycle, implementation of tax rewards for the use of regenerated resources, and regulation of the building code.

One of the major problems is the lack of awareness and clarification about CE among the stakeholders in the construction value chain. The fragmentation of the chain and the lack of information hinder the introduction of practices and awareness of circular thinking. A change of mentality motivated by environmental awareness is required of these professionals. It is also suggested to map and develop training plans on the new skills and abilities needed to execute the technical and strategic changes in the design and construction of flexible projects and materials, which could generate new business and work opportunities in the sector.

The lack of incentives to design products and buildings for dismantling and reuse at the end of their lives is a significant challenge. To encourage further implementation of the principles of the CE throughout the supply chain, metrics, tools, and guidance need to be established and support from public agencies and legislation is paramount. Another issue to be observed is the lack of knowledge and metrics about the potential for reuse of products at the end of life. The reuse of secondary materials in the construction value chain must overcome challenges related to insurance, guarantee, quality, and performance, especially its structural capacity. Technical challenges, including the lack of recovery routes and the complex design of buildings, hinder material recovery strategies.

Most of the papers focus on strategies to preserve materials. This was expected because recycling is the most frequent strategy across different CE concepts (Kirchherr et al., 2017). Resource productivity will be the key focus in the construction industry soon. In this relation, circular business models are a solution to add value to products to prolong the useful time and eliminate waste. Several changes are required, from product design to new business and consumption models. In addition, waste management at the design, construction, and renovation stages was not considered in most of the studies, just at the end of the life of the building. New ways of turning waste into a resource, at every stage of the building must be considered, as well as new modes of consumer behavior for the CE transition.

CE adoption in the construction industry is still in the beginning stage, although few frameworks and guidelines were proposed by some studies. The focus still is on the maximum reuse/recycling of materials and components to reduce the waste generation in the construction sites. Cleaner production and CE are intimately linked in the optimization of resources use by circulating products, components, and materials at the highest utility always in both technical and biological cycles, through the design of the product as a crucial pattern. However, there is the need for further clarification regarding the CE concept towards environmental sustainability in the built environment, including the definition of CE system boundaries, challenges in the governance and management, inter-organizational and inter-sectoral material and energy flows, new business models, etc.

In addition, the numerous value chains involving the supply, distribution, construction, maintenance, and end-of-life of materials and products need to be more engaged in the closed material loops. CE needs a systemic shift due to the different concepts and understanding of their influence in each segment of the construction value chain, by integrating the three pillars of sustainability.

7 Conclusions

Through the 318 articles from the SLR, the descriptive analysis verified the relevance and the qualitative nature of the subject in the scientific community. Despite the growing research in the CE field, it was still in the exploratory phase, without a confirmatory approach and empirical validation. Principles involved in the CE literature still need to be adapted to the construction and more standardized nomenclature should be applied. The centralization of work in European countries and China demonstrates the result of the implementation of public policies and underlines that the expansion of research requires political and governmental support.

Thematic axis analysis showed that the main trend in the area is the reuse of C&D waste. The most exploited practices are related to cleaner production, aiming to reduce the extraction of natural resources, the environmental impact, and waste throughout the building life cycle, in addition to optimizing the performance and efficiency of the processes. The axes also highlight the need to elucidate the link between CE and the literature on business models foreseeing the economic and sustainable development of the built environment, through evaluations of circular practices in reducing the environmental impacts.

The main contribution of this article was exclusive to analyzing what has already been done regarding circular practices in the construction value chain. The practical implication of this study is direct actions to improve or implement new business opportunities in the sector, seeking cleaner productions and more sustainable constructions.

This review recommends that best practices for the theory of CE and their implementations in supply chains become necessary. It is a trend to study new business models that encompass circular practices in the built environment. However, it needs to elucidate the link between CE and the literature on business models foreseeing the economic and sustainable development of the built environment, through evaluations of circular practices in reducing the environmental impacts and energy efficiency of buildings. For the effective CE implementation in the whole construction value chain, greater clarity is suggested on how circular actions can influence sustainability, supply chains, business models, and innovation and communication technology systems. CE should be adopted to select the best strategies and tools during the early stages of design, as this phase is decisive in the overall performance of buildings.

The gaps raised the need to develop a more consolidated theory on CE in construction. It is important for the incorporation in the planning stage mechanisms to assist decision-making (such as principles of flexible design, LCA, and reuse potential of materials) and, comprehensive legislation on the reuse of secondary materials in the supply chain. Above all, government support, such as laws and tax incentives, is crucial in the transition to a circular economy. The dissemination of a CE strategy through the whole supply chain, transforming it into a circular one, requires a systematic regulation and policy system, with better interactions among governmental institutions, policymakers, communities, and manufacturing industries.

This study shows that much remains to be done to achieve a more circular and sustainable sector. The framework proposed is a useful starting point for researchers, practitioners, and stakeholders with an interest in CE and to introduce circular practices in the built environment. In addition to the economic gains described by EMF, the CE is critical to minimizing environmental damage, providing cleaner, competitive, and more integrated production chains, energy-efficient, and more sustainable buildings, promoting thermal comfort and well-being to users.

The propositions of this research do not exhaust the subject and seek to promote new discussions and evolutions of the field being discussed. Further works are suggested to develop the discussion about the five thematic axes and the possibilities to introduce the CE in each one. This study has limitations that must be considered. First, it selected papers from journals and was more focused on academic research in the construction industry. There would be an additional need to identify the evolution of the latest industry practices and academic research. Secondly, the review was based on a keyword search, which limits the results to combinations of keywords. In addition, although the criteria for article selection were explicit, the selection of articles for review might be subject to researcher biases. Furthermore, the literature sample includes only articles published in English. Research or practical results in other languages have not been reported in this study.

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Appendix A. Reference of the systematic review articles organized by thematic axis

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PAPER A2

Materials passport's review: challenges and opportunities toward a circular economy building sector

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Materials Passport's review: challenges and opportunities towards a circular economy building sector

Abstract

Purpose: Reusing and recycling building materials depend on an efficient set of information and tracking, which can be obtained by the materials passport (MP) tool. Although MP introduces principles of circular economy (CE) and brings environmental, social, and economic benefits it is little-explored in the construction sector. This study aims to explore the adoption of the MP in the sector to raise awareness about this tool. This analysis leads to the conception of a model and identifies the main challenges and opportunities to increase MP implementation in the sector.

Design/methodology/approach: Through a systematic literature review, based on descriptive and thematic analysis, articles were selected, and analyzed to (i) review the MP state-of-the-art in the construction sector; (ii) propose a materials passport model, and; (iii) list the main challenges and opportunities to MP adoption.

Findings: The studies about MP were concentrated on strategies to implement, general concepts, and business opportunities. The MP model was proposed to overcome the lack of studies and understanding shown in the review. The model aimed to improve the recovery and reuse of materials across a building's life cycle. Challenges and opportunities were raised to direct decision-makers and support the development of this tool. A systematic regulation in the construction value chain and policy systems is crucial for creating digital platforms for data management of buildings' material.

Originality/value: This study developed an MP model to enable the management of building materials at different stages of the building's lifecycle and contributes to future developments of the studies on this knowledge domain.

Keywords: Materials passport. Circular economy. Reuse and recycle. Construction sector

1 Introduction

The last years of industrial evolution were dominated by a linear model of production and consumption, based on extract, manufacture, and disposal. However, significant price increases, volatility, and the production of negative externalities have warned of the need to rethink the use of materials and energy (EMF, 2015). Further, due to the population growth of up to 9 billion in 2050 (IRP, 2017), the demand for natural resources will increase continuously in the next years. In this scenario, the construction sector is the world's largest consumer of resources, represents over one-third of the total energy consumed in the world, and is responsible for 25-40% of global carbon emissions, where only 20-30% of construction and demolition waste is recovered (WEF, 2016).

The European Union's (EU) action plan for the circular economy (CE) is a key strategy to minimize the environmental impacts and energy consumption, as well as to reduce the imminent waste, maximizing the reuse and recycling rates (Honic *et al.*, 2019c). The circular economy emerges as a new restorative and regenerative economic model that seeks to decouple economic development from the consumption of finite resources (EMF, 2015). CE represents a change of paradigm in the way that human society is interrelated with nature and requires innovations in legislation, production, and consumption, based on preventing the depletion of resources, renewable energy, and materials closed-loops (Prieto-Sandoval *et al.*, 2018).

The transition from a linear to a circular economy in the construction sector requires a focus on systemic thinking that encompasses the building lifecycle and the construction value chain. The availability of structured information on material composition, building stock, and material flow is critical for supporting this change. Currently, many strategies make the CE a subject of discussion, such as the Building as Material Banks (BAMB) project of the European Union's Horizon 2020. BAMB is a project initiated by partners from 8 European countries that aims to systematically change the construction sector by investigating and creating circular solutions to conserve the value and functionality of building materials and systems (BAMB, 2016). The concept is being added to the sector through mechanisms such as the materials passport (MP) and reversible building design.

Materials Passport is a tool to document and track the circular potential of materials, products, and systems by providing accurate information for recovery and reuse (BAMB, 2016). The MP, with information technologies and flexible building design, aims to provide the required elements to promote the construction of more circular and resilient cities, where materials are identified in a database, removed, and reused numerous times (BAMB, 2016; Luscuere, 2017).

Currently, there are different initiatives like the MP, such as the Environmental Protection Encouragement Agency (EPEA), the Building Information Modeling (BIMobject), the Environmental Product Declaration (EPD), and the mindful Materials Library (Mindful Materials, 2020). However, they do not cover the full requirements of the MP, which mainly emphasizes the potential for the material's end-of-life reuse.

Recent studies have used the materials passport as a design optimization tool (Honic *et al.*, 2019c); as support in reducing fiscal barriers (Smeets *et al.*, 2019); as an indicator of the potential for reuse and recycling of materials (Heisel *et al.*, 2020). Although in previous studies, MP is not mainstream in the construction sector. There are few studies focused on the introduction of circular practices in the sector (Munaro *et al*. 2020). One of the reasons is the lack of information about the existing building stock for the effective management of end-of-life materials (Rose and Stegemann, 2019). Besides, information is often incomplete or inaccessible full-time to professionals (Cai and Waldmann, 2019). These are critical gaps because the role of managing and applying circular innovation in buildings is often overlooked.

To understand the underlying reasons, this study reviews the current adoption of materials passports in the construction sector. The first aim of this study is to explore the state-of-the-art of MP to raise awareness about this tool and thus expand its implementation in the sector. To enable a consensus on developments of the studies in this knowledge domain, the conception of an MP model leads to the second focus of this study. Thereby to corroborate the implantation of the passport in the construction sector challenges and opportunities regarding data and stakeholders were listed leading the third focus of the study.

Through a systematic literature review (SLR), based on a descriptive and qualitative analysis of the data, this work sought to (i) provide an analysis of the MP state-of-the-art in the construction sector; (ii) propose a materials passport model highlighting the required information, and (iii) list the main challenges and opportunities to introduce the materials passport. The model, main challenges, and opportunities were illustrated to support and enhance the improvement of buildings as material banks.

After this introduction (Section 1), a brief overview (Section 2) on MP information management is presented. Section 3 introduces the research methodology, followed by the results (Section 4). Section 5 presents the discussion. Section 6 presents an MP proposal, followed by Sections 6.1 and 6.2, which present the challenges and opportunities for the MP adoption. Section 7 presents the conclusions, followed by the implications, limitations, and future research (Section 8).

2 Information in the building sector

Information is crucial to the transition from a linear to a circular economy (Heisel and Rau-Oberhuber, 2020). The construction sector is seen as heterogeneous and conservative and is still behind in the use of information technology and technology sharing (Ganter and

Lützkendorf, 2019). The information asymmetry in building quality, due to the number of project participants and contract relations, will result in design and execution errors and under-investment in building maintenance (Sesana and Salvalai, 2018). Standardized information exchange is one of the means for a more circular and sustainable sector (Heinrich and Lang, 2019).

The sustainability of materials, systems and buildings is often assessed using labeling tools such as Leadership in Energy and Environmental Design (LEED) or Building Research Establishment Environmental Assessment Method (BREEAM) (Sesana and Salvalai, 2018). Though, one of the limitations of these tools is that they evaluate the different sustainability areas with few rating levels and do not make visible the actual measures of building performance (Sesana and Salvalai, 2018). Besides, often an analysis criterion does not meet the required sustainable performance but is obscured by the other criteria that are meeting labeling measures.

Increasing the sustainability of the construction industry depends on the reuse and recycling of materials and components (Cai and Waldmann, 2019). However, the reuse of secondary materials is limited due to the lack of data and methods to exhibit the material composition (Honic *et al*., 2019c). A challenge for the building sector is the generation of knowledge and data on the material composition of buildings (Honic *et al*., 2019c). The challenge is emphasized because people spend about 90% of their time inside buildings (Heinrich and Lang, 2019). Ecological building material choices play an important role in people's comfort, well-being, and health. The benefits also include the optimization of resource extraction, increase in dismantling and recycling potentials, energy efficiency, and sustainability of the built environment (Heinrich and Lang, 2019).

The identification and documentation of components, materials, products, and systems used in buildings is a crucial factor in attracting customers. Through this set of information, the user may be able to decide whether the building can provide safety and well-being. Also, data on the performance of materials and systems, the efficiency of water and energy, the Life Cycle Assessment (LCA) of materials, and information on the end of life of the materials will be able to determine the levels of sustainability of the building, considering the environmental impacts generated during the construction and use of the building. The materials passport seeks to be an indicator of the CE and the sustainability of the construction sector.

2.1 *Materials passport to increase the sustainability of buildings*

A materials passport, which is also known as a product passport, resource passport, or circularity passport, is a tool to evaluate the sustainability and communicate the performance of the building (Sesana and Salvalai, 2018). Is a set of digital data and information that can describe defined characteristics of materials to give them value for recovery and reuse. The concept of MP was first described as a new dimension of value to material quality in Resource Repletion, Role of buildings using the term "nutrient certificate" is based on the cradle to cradle (C2C) protocol (Hansen *et al*., 2013).

MP is a necessary methodology for collecting and handling relevant and standardized information, where data has an accessible format and compatibility with different software (Heinrich and Lang, 2019). The thoughts and principles of the C2C protocol and the Sundahus data system were used as inspiration for the BAMB materials passport and online platform (EPEA and SundaHus, 2019). Materials Passports Platform features over 300 online MP for different products, buildings, and instances that have been developed in conjunction with a software solution to facilitate access to information for different stakeholders (EPEA and SundaHus, 2019). These digital datasets can overpass the information gap and promote exchange between the stakeholders in the construction sector (Heinrich and Lang, 2019).

The information systems available for implementing BAMB are not effectively organized for enabling component reuse and recycling (Rose and Stegemann, 2019). A well-established model of MP in the construction value chain must be able to promote a fast, reliable, standardized, and structured information flow, promoting the increase in the value of building materials and the sustainability of buildings.

MP gives a more comprehensive image of the building, and every building should have an MP available to connect the stakeholders and set sustainable targets in the project based on lifetime use (Honic *et al*., 2019c). However, mechanisms that address the complete supply and demand interface of building materials are still lacking, and the information needs to be organized in a set to form an effective information system (Rose and Stegemann, 2019).

The achievement of satisfactory management of the buildings is due to a clear flow of data between the stakeholders of the construction value chain (Sesana and Salvalai, 2018). Technological and regulatory developments alone will not be enough, and a change is needed in business models and the behaviors and attitudes of stakeholders. Likewise, the information in different formats and structures hinders the flow of information. It is necessary to establish a format standard, and a document model containing the necessary information that can be accepted and followed by the stakeholders.

3 Methodology

The methodological approach of this study consists of a systematic literature review (SLR), based on four stages, as summarized in Figure 1. Systematic literature reviews are appropriate for mapping, assessing, and synthesizing literature to develop knowledge in a field (Tranfield *et al*., 2003). This procedure was chosen because it allows the synthesis and analysis of scientific knowledge already produced on the investigated topic.

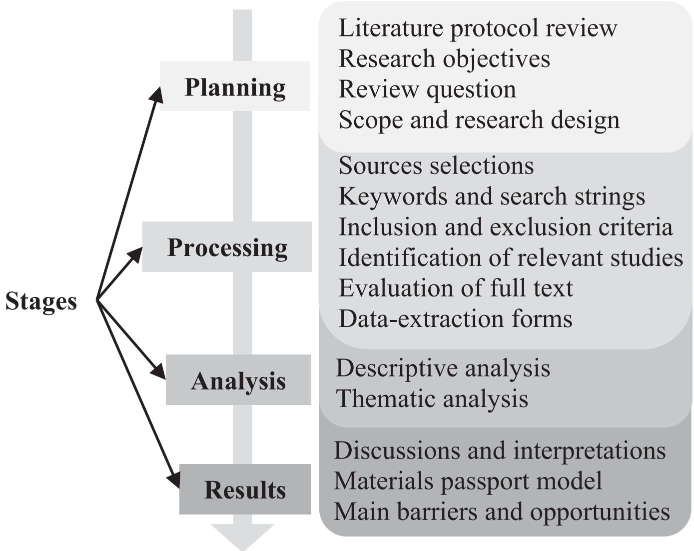

Figure 1. The protocol of the systematic literature review adopted.

3.1 Stage 1: Planning

Following methodological and systematic rigor, a research protocol was developed to identify the subject in the academic literature. The protocol, based on Figure 1, reduces the risk of bias and promotes transparency of the methods and processes employed (Tranfield *et al*. 2003). The study addresses the research question: How the construction sector approaches the materials passport to make the buildings more circular?

3.2 Stage 2: Processing the material passport review

The sources of information were the academic databases Web of Science, ScienceDirect, and Scopus. The filter applied was “type of documents”, choosing articles, reviews, and proceedings papers. In the Science Direct and Scopus the research criterion “Title, Keywords, and Abstract” was just used for the search strings “building information and CE”, and “information technology and CE”. The keywords used as search terms are identified in Figure 2. The inclusion criteria in the search for articles were documents with no research domain, without time cut, and the English language. The review resulted in 143 articles, which after excluding articles from other research areas or that did not present the MP as the object of study, resulting in 15 articles for the review.

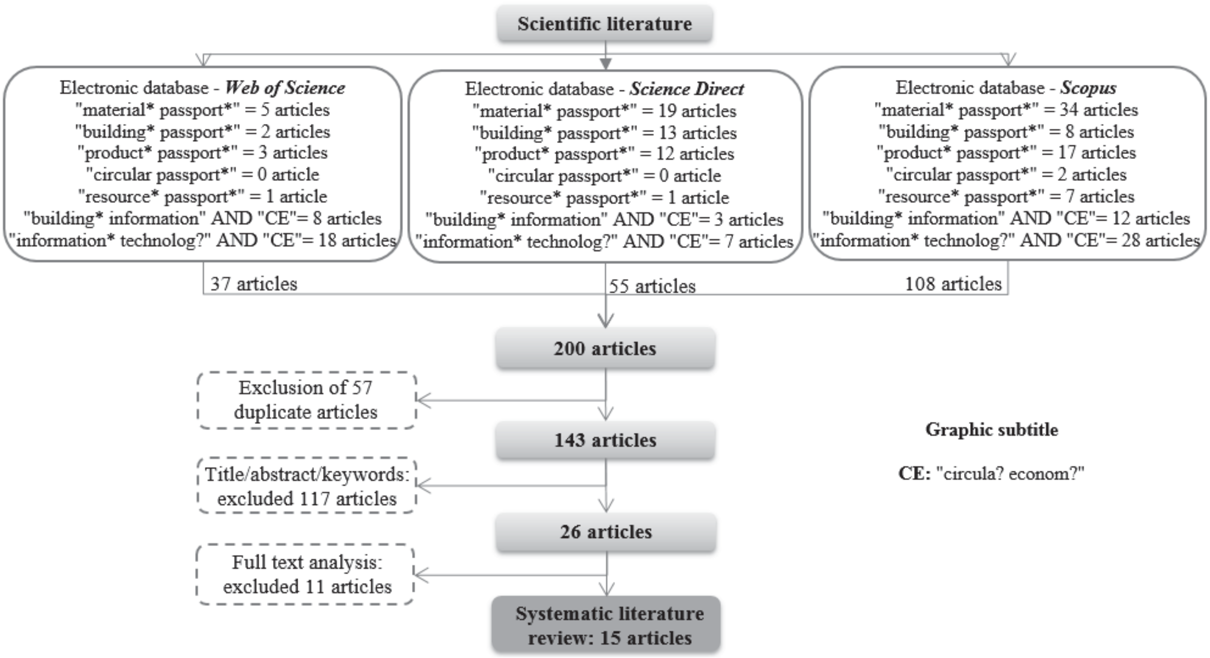

Figure 2. Processing of the review in the scientific literature (review date: January 2020).

3.3 Stage 3: Analysis

The analysis was developed based on the article's year, first author's country, research methodologies, research aim, and thematic axis. The criteria provided significant insights for identifying the research topics and driving the descriptive and thematic analysis. Themes pull together a lot of material into more meaningful and harnessed units and help the researcher understand the problem proposed.

3.4 Stage 4: Results

The results were analyzed from a descriptive and thematic perspective. The results of the descriptive analysis include the methodology, yearly, and geographic distribution of the publications. The thematic analysis comprises the organization of the studies in research guiding axes, according to the similarities and tendencies found. An MP model was developed to comprehensively portray the information needed in this tool and expand the knowledge on the topic. The main challenges and opportunities were identified to insert the MP in the construction sector.

4 Results

The analysis of the results was divided into two sections: 1) a descriptive analysis and 2) a thematic analysis.

4.1 *Descriptive analysis*

The articles were analyzed according to the research methodology adopted, considering the research approach, aim, and procedure (Malhotra, 2012). The publications presented a qualitative (73%, 11 articles) and a quantitative approach (27%, 4 articles). Descriptive research (53%, 8 articles) was the principal research aim, followed by the exploratory type (40%, 6 papers) and causal (7%, 1 article). Bibliographic research (47%, 7 articles) was the most adopted procedure, followed by case studies (27%, 4 articles), modeling (20%, 3 papers), and experiments (6%, 1 article). It is worth noting that most of the articles did not make clear the methodological procedure used, being the authors responsible for the methodological classification according to the main character of the publications selected. Besides, the scarce studies, the exploratory nature of some research, and the predominance of the qualitative method demonstrated that the adoption of the MP in the construction sector is still in the early stages.

The analysis of the review points out the relevance and timeliness of the theme. Figure 3 shows the evolution of the number of publications and geographical distribution. The research started appearing in 2017, and the number of publications increased considerably in 2019, representing 80% of the articles in the review. This proves that the research was boosted in the last year. Partly because the CE policies are still being developed, such as the BAMB project that emerged in 2015 in Europe. Besides, it indicates the growing interest of the scientific community in MP adoption in the sector.

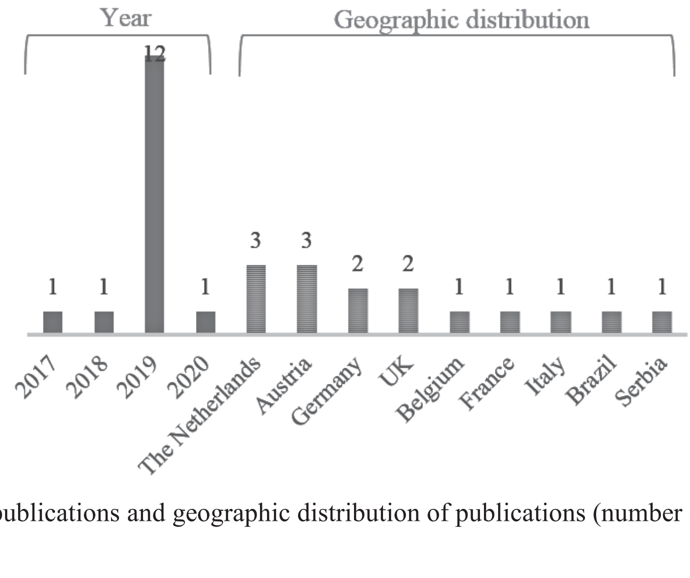

Figure 3. Yearly publications and geographic distribution of publications (number of articles, n = 15).

Europe accounted for 93% of the research (14 publications). This predominance is related to the adoption of public policies and regulatory institutional support for CE. Among the 9 countries shown in the review, The Netherlands and Austria are leaders in terms of volume of publications, followed by Germany and the United Kingdom (UK) (Figure). These countries are members of the European Union – EU-28, in which the CE package has been part of a heated policy debate. The centralization of research in European countries is attuned to the development of public policy (Merli et al. 2018). Large countries in terms of geographical area and economy, such as Brazil, India, and Russia, still have no relevance in the field. This indicates the need to develop plans and public policies to support the transition to a more circular construction sector.

4.2 *Thematic analysis*

In the qualitative analysis of the review, the number of incidence and affinity in the themes were categorized into three thematic axes: Tools and strategies to implement an MP (40%, 6 papers); General concepts and guidelines (33%, 5 papers), and Business opportunities (27%, 4 papers). Table 1 indicates the theme of each axis and the respective authors.

Table 1. Classification of the thematic axes and authors of the studies related to the SLR.

Ranking (nº; %)	**Thematic axis**	**Main axis issue**	**Topic covered**	**Authors**
1º (6 pap. 40%)	Tools and strategies to implement an MP	How to implement it?	Technological and data management resources to implement an MP	Aguiar et al. (2019); Cai and Waldmann (2019); Heisel and Rau-Oberhuber (2020); Honic et al. (2019a, b); Gligoric et al. (2019)
2º (5 pap. 33%)	General concepts and guidelines	What is?	Explaining what an MP is and some of the general concepts	Ganter and Lützkendorf (2019); Luscuere (2017); Munaro et al. (2019); Sauter et al. (2019); Sesana and Salvalai (2018)
3º (4 pap. 27%)	Business opportunities	For what?	Existing examples and business models for the building industry	Futas and Rajput (2019); Honic et al. (2019); Rose and Stegemann (2019); Smeets et al. (2019)

The first place in the thematic ranking was the "Tools and strategies to implement an MP" axis, which represented 6 articles and 40% of the review. Digital information management was the focus of this axis and is crucial for MP adoption. In this sense, the authors explored the concept of the Building Information Modeling (BIM)-based materials passport for the optimization of construction projects (Honic *et al.*, 2019a), for the compilation of the semi-automated MP (Honic *et al.*, 2019b), and the processing of information on the different phases of the building lifecycle (Aguiar *et al*., 2019). Gigoric *et al*. (2019) presented how the Internet of Things (IoT), based on printed sensors, can facilitate the exclusive identification of objects. The documentation of materials and MP can be carried out on online platforms such as Madaster (Heisel and Rau-Oberhuber, 2020). Cai and Waldmann (2019) proposed the use of material and component banks to facilitate information management, reuse, and recycling of materials.

The "General concepts and guidelines" axis represented 33% of the publications and second place in the thematic ranking. The axis presents the role that the MP can provide in increasing the availability of information to improve the efficiency of buildings, and of the construction value chain. Luscuere (2017) explores the MP's importance, objectives, and functions. Munaro et al. (2019) presented a proposal and application of the MP based on guidelines that favor the reuse of the material. Sesana and Salvalai (2018) provide an analysis of the building renovation passport to overcome the information imbalance among market stakeholders that impact the overall quality of buildings. Sauter et al. (2019) evaluated the potential of ontologies and semantics to enable building material circulation in the CE context. This corroborates the use of new information technologies such as BIM and blockchain, important mechanisms for ensuring access, and security data (Ganter and Lützkendorf, 2019).

The third place in the ranking of the thematic axes was the "Business opportunities" axis. Examples of MP implementation have been demonstrated as a design optimization tool. The materials passport can incentivize the reuse of structural steel by decreasing the financial barriers they are facing in the UK (Smeets et al., 2019). Rose and Stegeman (2019) developed a framework for the collection and application of the existing buildings as material bank information. The purpose was to check the potential to reuse, repurpose, and upcycle components before they are consigned as waste. Honic et al. (2019c) evaluated the MP as a decision support tool in the choice of materials, and as an inventory of the building. Materials passport can achieve greater transparency and lead to a circular construction sector, considering all aspects of the lifecycle of materials, and reversible construction projects (Futas et al., 2019).

5 Discussion

The review articles, grouped into three thematic axes, emphasized the incipient introduction of the materials passport in the construction sector. The first axis stressed the use of MP in the design process through BIM. BIM is seen as one of the main tools in the prevention of waste however, none of the existing BIM software products yet offers waste forecasting and support for the MP. The integration of material passports in BIM enables design operations for deconstruction. The design of buildings for deconstruction, or material banks, such as the Urban Mining and Recycling (UMAR) project (Heisel and Rau-Oberhuber, 2020), depends on the documentation and tracking of the materials during all building lifecycles. Materials passport in combination with BIM addresses the requisite for information from different stakeholders and the need to share information about the potential for reuse of materials during all building lifecycles.

The second axis 'General concepts and guidelines' highlighted the need to introduce new information technologies (IT) as a requirement to achieve sustainability in the construction sector, such as BIM and blockchain. The IT would improve approaches to documentation and accessibility of information and facilitate the use of materials passport. Besides, the need to elucidate the ontology and terminologies about the system of the circular economy and the MP in the sector was emphasized. The fragmentation of the construction value chain and the lack of information make it difficult to introduce practices and raise awareness of circular thinking.

On the third axis, few studies have explored the opportunities for creating value with the materials passport. Notwithstanding being limited, different business models explored the MP in reducing financial barriers in the reuse of steel, in analyzing carbon incorporated in materials, in choosing materials with greater potential for recyclability, and as a prerequisite in buildings as a material bank. Studies have shown the applicability potential of this tool in generating value and competitive advantage between the stakeholders of the construction industry.

The revised literature demonstrated some efforts in the implementation of the MP in the sector. Despite being an efficient tool in the optimization of projects and facilitating the reuse of materials, it is still not widespread in the sector. There is a lack of research and awareness on the opportunities that the MP will provide to stakeholders in the construction sector, as well as the challenges to adopting this tool. It is not yet clear what data and essential information the MP must provide during the lifecycle of the building, supporting the BIM, information technologies, and new business model development. Therefore, exploring these issues is essential for the incorporation of circular principles in the construction sector.

6 Materials passport model to improve material recovery and reuse

Figure 4 presents a materials passport model with requirements and information needed for buildings. A unique model of materials passport presenting the necessary information for the recovery and reuse of materials, for the construction sector, has yet to be found in the scientific community. The proposed model is planned into 9 sections and may cover building materials, products, and systems. The model sought to gather information from other documents cited in the literature, such as EPDs and the BAMB online platform, in a categorized way in different sections. Each section presents specific information that may interest different stakeholders in the sector.

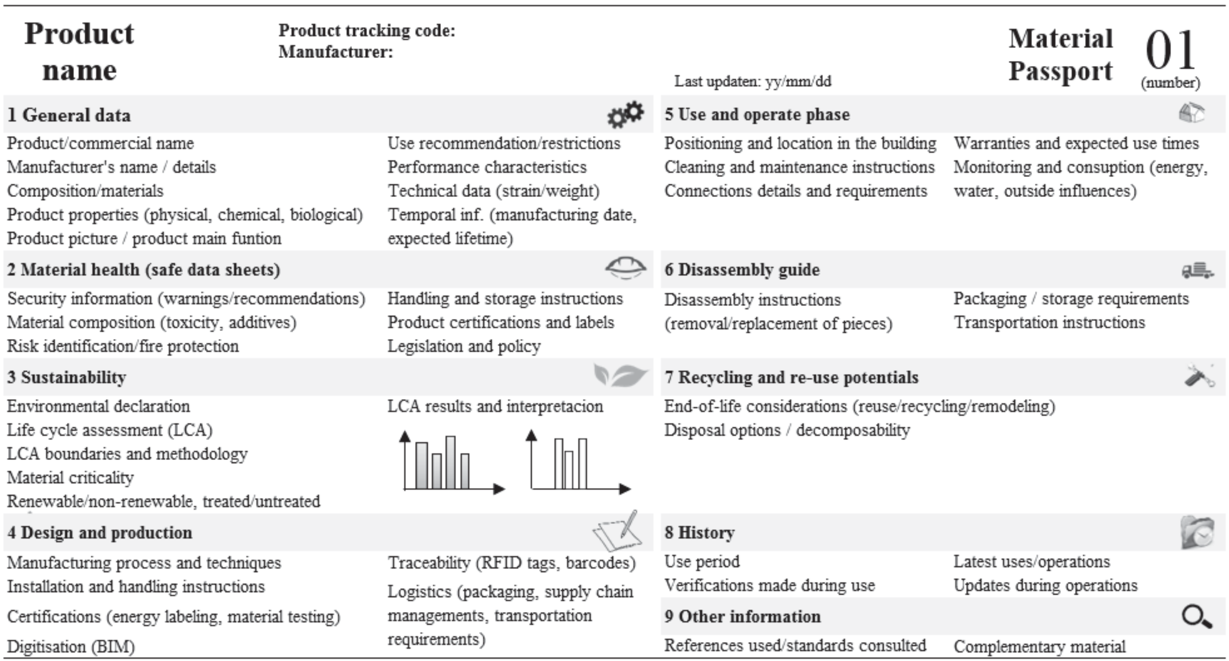

Figure 4. Proposed materials passport model with requirements and information needed for buildings.

Item 1 is for general material and manufacturer data with all necessary performance, use, composition, and function information. Item 2 presents the safety aspects of the material, its risks, and instructions for use and handling. Environmental statements, use of recycled materials, and material Life Cycle Assessment (LCA) are in item 3. LCA is also important on item 4 for design and production, which comprises the entire material manufacturing process, modeling, assembly and uses instructions, material traceability, as well as packaging and transportation requirements. Items 5 and 6 are more user-oriented, as they relate aspects of use, maintenance, warranties, and disassembly instructions. Item 7 characterizes the key CE concept in materials closing cycles, in which the manufacturer should indicate possible forms of reuse, remodeling, remanufacturing, recycling, or proper disposal of the material. Item 8 records material history throughout the useful life, with all checks, tests, and evaluations performed, and item 9 presents supplementary information such as norms and standards used in the material evaluation.

The proposal of this PM model is crucial to clarify the type, form, and those responsible for providing and using this set of information. Information stored in MP is useful when it can be used by the relevant actors at the required time, according to the building's lifecycle stage (Luscuere, 2017). Figure 5 illustrates the different information on the proposed MP in each building's lifecycle stage.

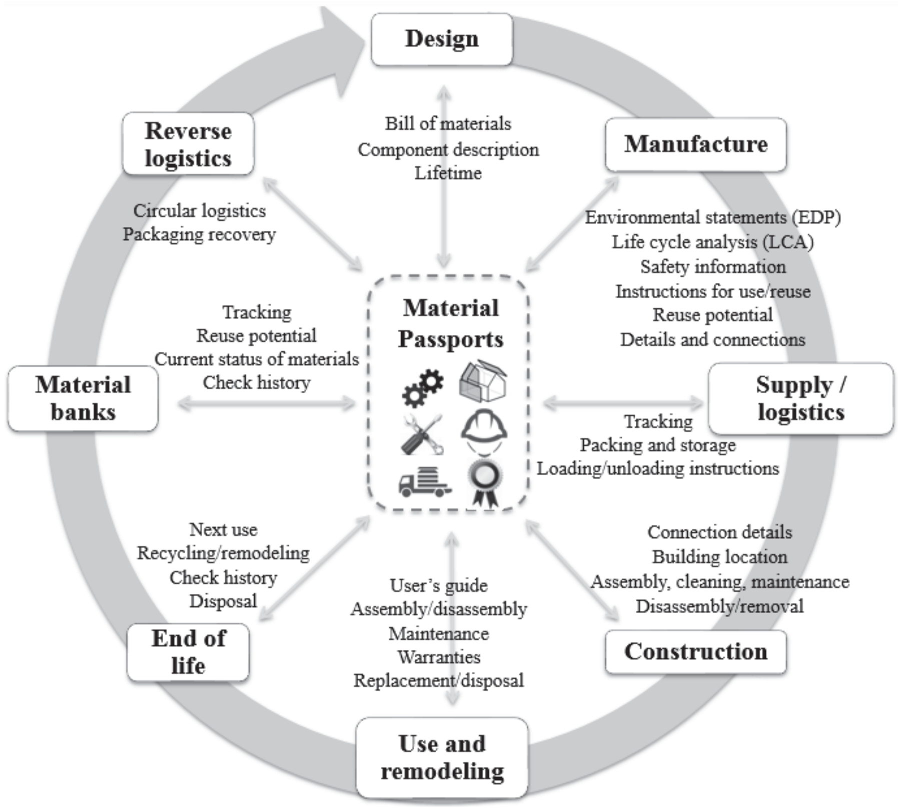

Figure 5. Information shared across a building's lifecycle to improve material recovery and reuse.

MP information will be collected and updated over time. New data will be inserted according to the use of the material and the building's lifecycle stage. The design stage is decisive in the future potential of building components reuse and recycling. MP may provide incentives to design products that meet the CE principle or provide insight into future business models that may be adopted (Heinrich and Lang, 2019). The MP encourages the design for deconstruction, wherein the building can be easily disassembled, and the materials reused, remanufactured, refurbished, or recycled. Strategies such as modularity, adaptability, flexibility, disassembly, and deconstruction will be crucial for MP development.

The MP encompasses documentation on building material composition and supports urban mining practices. The concept of urban mining and MP are closely related to the CE as an effort to reduce resource consumption while keeping goods and products as long as possible in the economic cycle (Honic *et al*., 2019b). The MP can be inserted into existing buildings with a focus on identifying and obtaining resources to reinsert them into production and consumption chains, reducing dependence on raw material extraction and promoting new business opportunities with secondary materials.

6.1 *Main challenges and opportunities of the materials passport*

Table 2 presents the main political, social, and commercial challenges to the adoption of the MP.

Table 2. Main challenges for the implementation of the materials passport.

Challenges			Related aspects	Authors
Political	1	Complex and fragmented supply chain	The lack of integration of the different segments of the construction chain can increase the waste, deadlines, and costs of buildings	BAMB, 2016; Luscuere, 2017
	2	Conflicting environmental and energy policy measures	Prioritization of energy efficiency and high energy performance of buildings can result in construction projects and materials that do not lend themselves to deconstruction and reuse	BAMB, 2016
	3	Lack of data standardization/design information	As data on product properties and specifications are missing, it is difficult to identify the potential for the reuse of products and materials	BAMB, 2016; Luscuere, 2017
	4	Lack of certification and quality assurance for recycled or by-products	Few suppliers offer competitively priced quality assurance by-products and/or recycled materials	BAMB, 2016
Commercial	5	Complexity of materials/ systems/components	Product and material separation is a key challenge to identifying and separating materials, maintaining quality, and ensuring purity	WEF, 2014
	6	Lack of data standardization/qualitative information about the product	Similar to item 3	BAMB, 2016; Luscuere, 2017
	7	Longevity of buildings and infrastructures	Divergences regarding the different life cycles of buildings and their components with maintenance and occupancy profiles over time	Luscuere, 2017
	8	Intellectual property of materials and product-related data	Manufacturers and suppliers are reluctant to provide information that could compromise their business status	BAMB, 2016
	9	Reliable data collection and availability	Stakeholder engagement is required for reliable data to ensure reuse potential and material circularity	3XN Adepa, 2016; BAMB, 2016
	10	Volume and data storage	Managing and storing information about the building elements of a building entails big data	3XN Adepa, 2016; BAMB, 2016;
	11	Lack of knowledge in BIM	BIM bears large potential to serve as a knowledge basis for an MP, as all elements and materials exist in the BIM model however, there is a need for specific knowledge in BIM execution	Honic *et al*., 2019b
	12	Constant update of data and information	The passport information should represent the current state of the materials. This leads to the need to test and examine the status of materials and provide security for their reuse	3XN Adepa, 2016
	13	Incorporation of sensors in materials	Embedded sensors may be able to detect and communicate current passport status while being accessible in real-time	3XN Adepa, 2016
	14	Lack of circular and flexible business models	The way the product is connected to a building is crucial to its potential for reuse without contamination	BAMB, 2016

Social	15	Perception that reversible design leads to high financial costs	While reversible design can reduce long-term construction and maintenance costs, it often entails higher investments. Moreover, it is difficult to estimate financial savings as they occur in the future and depend on the context	BAMB, 2016
	16	Reversible buildings are still widespread	Decision-making protocols for building owners and users are lacking	BAMB, 2016
	17	Other priorities in the construction sector	Including accessibility, health and safety, and energy efficiency	Luscuere, 2017

A crucial challenge is the information gap about materials and products. Often, the composition and properties of materials are unknown or not communicated to the stakeholders (Heinrich and Lang, 2019). There is currently a lack of information on the materials' end-of-life. The use of secondary materials or the reuse of materials is almost nonexistent in the construction sector (Heinrich and Lang, 2019). Stakeholder engagement is required for reliable data collection. Issues such as confidentiality, trust, and competition need to be considered to allow the appropriate sharing of data and, product information into the overall company's ecosystem (Fonseca *et al*., 2018).

Information technology is indispensable for capturing, storing, and analyzing dynamic information over long periods. Emergent technologies are evolving, but often their potential is not always useful for all types of uses. The use of BIM-based MP pointed to challenges to data management due to the inconsistent product naming and elements across multiple databases (Honic et al., 2019b). Digitization in the sector and setting relevant standards for BIM products are essential.

The fragmentation of the construction value chain and the lack of information about CE hinder the introduction of practices and awareness of circular thinking. A change of mentality motivated by environmental awareness is required of the professionals. It is needed to map and develop training plans on the new skills and abilities needed to execute the technical and strategic changes in the design for deconstruction.

Policies around consumer taxation, legal frameworks, recycling targets, lifecycle product accountability, and building code regulation need to be reconsidered. In the case of consumer behavior, policymakers may propose tools to lower resource demand, such as incentives for smaller homes, repairing or renewing products rather than buying new ones, and encouraging a shared economy (Prieto-Sandoval *et al*., 2018). Regulation and policy should support the development of innovative waste collection solutions, economic incentives for cleaner production, broadening the understanding of the economic costs of environmental externalities to support, and increase the circular economy (Prieto-Sandoval *et al*., 2018).

Overcoming the challenges of introducing the MP can facilitate the understanding of the complex and multidimensional nature of building materials, products, and systems. Materials passport can influence innovation and product design, and encourage the design of reversible and resilient buildings, prioritizing materials, and systems that can be dismantled. Table 3 shows the main opportunities for the use of MP in buildings.

Table 3. Business opportunities for the use of MP in the construction sector.

Business opportunities	Aspects of materials passport
Circular index	Know product performance in the circular economy (EPEA, 2015)
Design guidance	By providing the opportunity for a producer to provide essential information about their products, it makes it easy for the user to verify which data is compatible with their purpose and which is missing
A market differential	Opportunity for manufacturers or suppliers to stand out for the transparency or circular potential of their products (Luscuere, 2017)
Information clarity and authentication	A better understanding of products is crucial for innovating and optimizing processes and products (Luscuere, 2017). In addition to protecting companies against industrial counterfeiting, tampering, and misuse (EPEA, 2015)
Increase traceability	Buildings involve a large flow of materials and passports would facilitate tracking in terms of volume, location, and other specifications (3XN Adepa, 2016)
Understand the gain/loss ratio	Instead of waste, materials become part of the building's value chain, which can increase lease and resale value. Besides, if the material is destroyed, for example by incineration, the passport is invalidated or modified to verify the residual value of the ash by measuring the cost of incineration (Hansen *et al*, 2013).
Enable operations	Circular design can enable assembly, disassembly, and material production. This would facilitate removal, repair, maintenance, and replacement services (3XN Adepa, 2016)
Guide users	Inform users about installation, maintenance, cleaning, disassembly, and reuse possibilities to keep products in recoverable condition (EPEA, 2015)
New business models and partnerships	Reversibly designed products and systems may be of interest to property and business models for leasing and material banks (Luscuere, 2017). Business partnerships could be established between waste management companies and product manufacturers (Hansen *et al*, 2013)
Secondary materials market	Take control of material value streams; Increase residual value and reduce material flow uncertainty; Use secondary materials with known and defined content (EPEA, 2015)
Supply security	Passports provide conditions for the reliable recovery of materials, ensuring the supply and improvement of material residual value (Luscuere, 2017)
Decrease environmental footprint	Waste production and demand for new raw materials will be reduced (Heinrich and Lang, 2019)

Materials passport is the connection between the information and the element (3XN Adepa, 2016). Data will be obtained and updated manually, through digital modeling, or by monitoring kits such as electronic chips, barcodes, or Radio Frequency Identifiers (RFID). Data can be advanced to more automated levels, complemented by Augmented Reality (AR). Digital information can be displayed at the construction stages, as well as in existing buildings, useful for urban mining (Heinrich and Lang, 2019). Control of this information can be fragmented by each supply chain member. Besides, the Material Passport Manager may be a future profession by attaching the data and elements of a building to the platform (3XN Adepa, 2016).

Connecting materials to the internet can be useful when incorporating automated data collection devices or monitoring equipment. This may include product consumption or exposure monitoring data to estimate change intervals, service life, or maintenance requirements (Heinrich and Lang, 2019). With the incorporation of these technologies and the generation of big data, the development of Artificial Intelligence plays a vital role in standards-based information evaluation or data collection. Within the machine learning process, it is possible to identify material composition in an automated way in the future (Heinrich and Lang, 2019).

7 Conclusion

In this study, a review of existing literature on MP was conducted. This was needed because the management of building materials for reuse/recycling is rarely usual in the construction sector, and MP information is sparse and not covered in the literature. Thus, the systematic collection of data sets that describe the characteristics of materials and construction components is essential to make buildings material banks.

The main contribution of this article was to deepen the discussion on MP, emphasizing the main types of information that the document should provide at different stages of the building's lifecycle, and guide future directions to adopt this tool in the construction sector. The business opportunities pointed out that the design stage is fundamental for the development of reversible, adaptable, and demountable materials and systems. The integration of stakeholders in the construction value chain is crucial to creating partnerships and industrial symbiosis to close the materials cycle and achieve circular thinking.

Best practices for the theory and implementation of the materials passport in supply chains become required. Greater clarity is suggested in how the MP can improve sustainability, business opportunities, and innovation and communication technology systems. Above all, government support, based on laws and tax incentives, is crucial in the transition to a circular economy. The dissemination of a CE and MP strategy through the whole supply chain, transforming it into a circular one, is the necessity of a systematic regulation and policy system, with better interactions among governmental bodies, policymakers, communities, and manufacturing industries.

8 Implications, limitations and future research

The review showed that materials passport was still in the exploratory phase in the construction sector, without a confirmatory approach and empirical validation. The proposed MP model involves conducting a pilot study. This pilot study could be conducted in a building or company that is part of the construction value chain. The experiences in the pilot study can identify other drivers and challenges related to the model content and format. It can also clarify how the information can be detailed to be useful at each stage of the building lifecycle and each stage of the supply chain. It can be useful to identify where and why supply chain information is retained. This would facilitate the identification of solutions to issues of confidentiality. Also, the pilot can be used to quantify and qualify the benefits of using this tool for companies and the construction sector in general.

Another recommendation is to research what aspects may speed up or hinder the MP implementation. The identification of practices, policies, and methodologies is a starting point to support the implementation of this tool. Related to this, the research could focus on framing public policies appropriate to the instrument.

This study had limitations that must be considered. First, the systematic review conducted explored only academic studies. There would be an additional need to identify the evolution of the latest industry practices and academic research. Secondly, the review was based on a keyword search and only publications in English, which limits the results to combinations of keywords. Research or practical results in other languages have not been reported in this study.

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PAPER A3

Circular Business Models: Current State and Framework to Achieve Sustainable Buildings

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Circular Business Models: Current State and Framework to Achieve Sustainable Buildings

ABSTRACT

The construction sector exerts great pressure on natural resources and their role in the transition to a circular economy (CE) is fundamental. Despite the growing prominence of the circular business models (CBM), based on strategies to maintain or increase materials value, there is uncertainty on how to implement them in the sector. This study analyses how the construction sector approaches business models (BM) to achieve sustainable buildings. Through a systematic literature review, 89 articles were analyzed to (i) explore how the sector is implementing circular strategies; and (ii) verify how these strategies are distributed in the BMs described in the literature. The review showed that CBMs are concentrated in clusters, with a focus on energy efficiency strategies and the search for more information and understanding of circular actions in the sector. From the results, a model for value creation and a framework were created to facilitate the CBM implementation. The model brings the novelty of connecting value creation within CBMs. The framework relates CBMs according to the building life cycle, aiming to introduce circular principles into policies, actions, and value chains. This study contributes to innovation and value creation, associating BM with the circular principle of closing the cycles of materials, and systems in the construction sector.

Keywords: Circular business model; Circular economy; Building; Sustainability.

Introduction

The construction sector has remained a major target for environmental sustainability. In 2018, the sector represented 36% of the end-use of energy and 39% of global carbon dioxide (CO2) emissions (IEA 2019). In addition, the sector is the world's largest consumer of raw materials and generates up to 35% of landfill waste (Ghaffar et al. 2020). The volume of construction and demolition waste (CDW) is the result of the current linear economic model of "take-make-consume-dispose" (EMF 2014). The sector needs to implement strategies to reduce these problems and make a shift towards the adoption of sustainable practices.

Sustainability is a broad term encompassing triple bottom line aspects of – environmental conservation, social equality, and economic security. A gradual approach is required to achieve sustainability in the sector. Since the late 1980s, sustainable development has reshaped the construction industry, and altered the physical structures and working principles of organizations (Zhao and Pan 2015). This scenario has been altering the business models (BM), which are the application of alternative paradigms that shape the culture, structure, and routines of organizations and change the way of doing business. The redesign of BM aims to improve sustainable performance and create value, sustained by innovation (Boons et al. 2013).

The adoption of the circular economy (CE) is a prerequisite to sustainability (Ghaffar et al. 2020). The CE offers an opportunity to reduce the use of primary materials and their associated environmental impacts, through different strategies that replace the end of life, such as reduction, reuse, and recycling of materials in the production/distribution processes and consumption (Kirchherr et al. 2017). In a CE context, circular business models (CBM) interfere with a combination of value propositions, in the interrelationships between elements and in the network-associated values, to find circular solutions based on intensification, dematerialization, closing, narrowing, or slowing resource loops (Geissdoerfer et al. 2018).

It is estimated that the market for a CE in the next 10 years will increase economic growth by up to 4% (ING 2015). The change to a CE is related to public policies and the introduction of CBMs (Bocken et al. 2013; Lewandowski 2016). The construction sector requires a focus on systemic thinking, which allows understanding the whole life cycle of the building and the construction value chain (Carra and Magdani 2017).

Incorporating sustainable or circular principles in BM requires changes in generating value, understanding, and doing business in the companies (Pieroni et al. 2019). The literature presents different BMs strategies grouped into archetypes (Bocken et al. 2014), resource cycles (Bocken et al. 2016), and life cycle stages of the building (Carra and Magdani 2017), or according to the level of circularity of materials (Potting et al., 2017). Despite the heterogeneous literature, the limits and synergies between circular and sustainable BMs are not explored and there is a lack of clarification about existing tendencies and where new insights are needed to incorporate circularity or sustainability (Pieroni et al. 2019; Geissdoerfer et al. 2017).

In addition, the implementation of circular practices in the construction industry is limited. The sector is conservative and has its design process, manufacturing techniques, supply chain, and financial arrangements (Ünal et al. 2019). The sector has particularities about the complexities of the buildings with several interconnected attributes, such as building design, choice of material, operation, and maintenance (Munaro et al. 2020). Furthermore, the fragmented value chain hinders the information shared and the creation of industrial symbiosis. These barriers and the lack of clarity and understanding of the CE principles make it difficult to spread the design and circular construction.

There is an obvious need to understand how the construction sector approaches the BMs to achieve sustainable buildings. A deeper knowledge of the circular practices is essential to identify which practices are being performed and which still need to be implemented or improved. Besides, more information and guidance on how CBMs leverage sustainable building development is needed to achieve cleaner production in the supply chains and to conceptualize the CE more specifically within the context of the sector.

This study aims to analyze how the construction sector approaches business models to achieve sustainable buildings. Through a systematic literature review (SLR), this study sought to (i) explore how the sector is implementing circular strategies; and (ii) verify how the implementation of circular strategies is distributed in the BMs described in the literature. From the results, a method and a framework were created to enable future directions for the innovation and implementation of CBMs in the sector. Figure 1 shows the organization of this study.

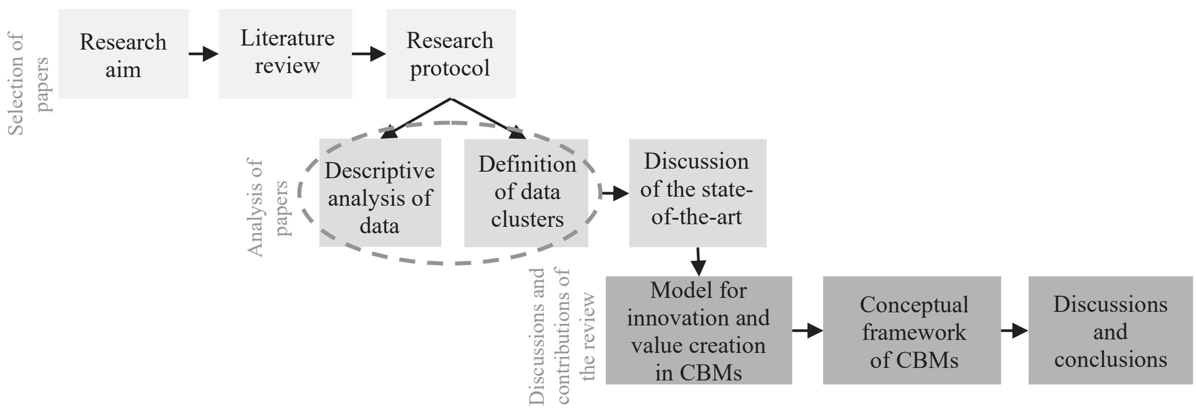

Figure 1. The research process development.

Sustainability in Business Models

A business model defines how a company hands value to customers by attracting them to pay for it and converting those payments into profit (Teece 2010). Reflects the design or architecture of the creation, delivery, and value capture mechanisms, providing data that demonstrates how a business generates profitable and sustainable revenue streams (Teece 2010; Boons et al. 2013; Bocken et al. 2014). A BM has the potential to influence entire value chains as it connects multiple actors, mediates production and consumption, and supports the introduction of new technologies into the marketplace (Teece 2010). Through innovation, the BM is a source of competitive advantage to design or modify a system of activities (Boons et al. 2013).

Innovation refers to the change in the way something is done and is dependent on a context (Carrillo-Hermosilla et al. 2010). Linked to sustainability, the concept of innovation is expanded to meet the holistic and long-term process of sustainable development. Eco-innovations reduce the environmental impact caused by the activities of production, assimilation or exploration of the products, production processes, services or management, and business models. It involves social arrangements broader approaches that trigger changes in existing socio-cultural norms and institutional structures (Carrillo-Hermosilla et al. 2010). The BM innovation is a continuing process of learning and organizational change (Bocken et al. 2016).

The BM literature is heterogeneous and presents different perspectives, including how a company does business (Bocken et al. 2014); how the company converts resources and abilities into economic value (Teece 2010); as an idea of content, structure, and governance to create value (Zhao et al. 2017). The definitions enhance three common themes: value proposition and delivery, value creation features and activities, and value capture, as shown in Figure 2 (Osterwalder et al. 2005).

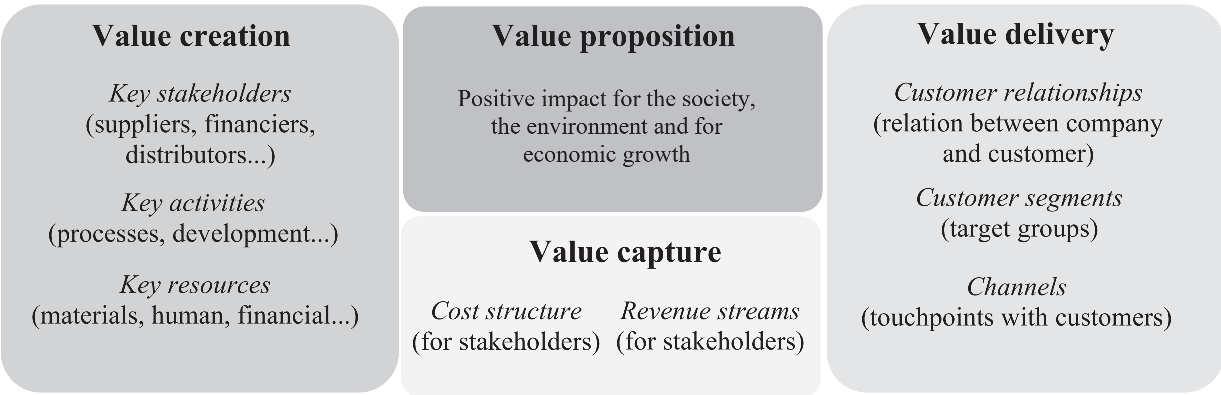

Figure 2. Sustainable business model canvas (based on Osterwalder et al. 2005).

Value creation and delivery describe how to establish the organization to achieve the proposed action. It specifies resources, capabilities, and how to deliver value to a specific customer segment (Bocken et al. 2016). Value capture encompasses revenue collection for users and customers (Bocken et al. 2014; Teece 2010). Sustainable business models define their value proposition from economic, environmental, and social aspects and consider the environment and society as the main stakeholders (Bocken et al. 2014).

Circular Business Models (CBM)

In the current linear economic system, the "extract, transform, use, dispose of" approach causes natural resources to be discarded or incinerated after use. A circular business model considers the CE concept that seeks sustainability goals through a material closed-cycle culture. According to Ellen MacArthur Foundation (EMF 2014), CE is a restorative or regenerative system, whose objective is to maintain products, components, and materials at their highest level of utility and value.

The concept of CBM is well covered in the literature and, at the same time, many attempts have been made to normalize or group the variety of CBMs into standard categories. Table 1 presents the BM strategies defined by six groups of authors. Lacy et al. (2014) considered five CBMs: circular supplies, resource recovery, product life extension, sharing platforms, and product as a service (PSS). Bocken et al. (2014) determined eight models. Bocken et al. (2016) grouped the strategies aimed at closing the resource cycle: slowing (extending the useful life), closing (reinsertion and reuse of materials), and narrowing (reducing the use of resources). Carra and Magdani (2017) explored CBMs relating the benefits to the construction value chain grouped according to the stage of the building's life cycle. Peters et al. (2017) defined four BM strategies for the construction industry. Potting et al. (2017) established a list of circular strategies ordered according to high circularity to low circularity.

Table 1. Business model strategies and definitions described in the literature.

Authors	Business model strategies		Definition
Lacy et al. (2014)	Companies based business models	Circular supplies	Focus on renewable energy, biomaterial, or recyclable material instead of virgin materials
		Resource recovery	Recovers resources/energy from discarded products
		Product life extension	Extends the life cycle of materials and assets by repairing, upgrading, and reselling
		Sharing platforms	Increases the rate of use of products by shared use/access/ownership
		Product as a Service	Offers product function and maintains ownership to internalize productivity benefits
Bocken et al. (2014)	Technological	Maximize material and energy efficiency	Products/services with fewer resources, generating less waste, emissions, and pollution
		Create value from waste	Transforms waste streams into valuable inputs for other productions
		Substitute with renewables and natural processes	Reduces environmental impacts related to non-renewable resources and production systems
	Social	Deliver functionality rather than ownership	Provides services instead of products to satisfy users' needs
		Adopt a stewardship role	Seeks to guarantee long-term health and well-being to stakeholders
		Encourage sufficiency	Strategies to reduce consumption and production
	Organizational	Repurpose for society/environment	Integration between companies and communities to deliver social and environmental benefits
		Develop scale-up solutions	Offers solutions to maximize benefits for society and the environment
Bocken et al. (2016)	Slowing	Access and performance	Provides services instead of products to meet user needs
		Extending product value	Explore the residual value of products or collect products from commercial entities

		Classic long-life model	Focuses on delivering design-backed products for durability and repair
		Encourage sufficiency	Seeks to reduce consumption through principles such as durability and a non-consumer approach
	Closing	Extending resource value	Exploits the residual value of resources to transform them into new forms of value
		Industrial symbiosis	Uses waste from one raw material process to another
Carra and Magdani (2017)	Circular design	Product and process design	Provides planning and design to improve component, system, and asset life
		Circular supplies	Focus on less resource-intensive, recyclable, bio-based materials or enhance renewable energy
	Circular use	Tracking facility	Material and component tracking services for secondary raw material markets
		Sell and buy-back	Sale of a product that will be purchased back after a certain period
		Lifetime extension	Extends the life of products, components, and systems due to disassembly, repair, maintenance
		Product as a service	Deliver performance rather than products
		Sharing platforms	A higher rate of use of products or systems, allowing or offering shared use, access, or ownership
	Circular recovery	Support Lifecycle	Product lifecycle support through consumables, spare parts, and accessories
		Recapture material suppliers	Recaptured materials, components, and parts are sold for use as virgin or recycled materials
		Recycling facility	Turns waste into raw material
		Refurbish and maintain	Recondition used parts and components for sale
		Recovery provider	Collection services to recover useful resources from discarded products or by-products
Peters et al. (2017)	Construction industry based business models	Product / component / material driven	Provides the product or material with additional services (return/reuse)
		Product performance driven	Proposes a performance package for products
		Building performance drive	Proposes a performance package at the building level
		Value Network and Collaboration Driven	Provides services to connect functions, value propositions, and the industry ecosystems
Potting et al. (2017)	Smarter product use and manufacture	R0 Refuse	Make the product redundant or offer the same function as another product
		R1 Rethink	Better use of the product
		R2 Reduce	Reduce the use of resources and materials in the manufacture or use of products
	Extend lifespan of product and its parts	R3 Reuse	Reuse of discarded product
		R4 Repair	Repair and maintenance of the product to be used with the same function
		R5 Refurbish	Restore and update a product
		R6 Remanufacture	Use discarded parts in a new product with the same function
		R7 Repurpose	Use a product or discarded parts in another product with a different function
	Useful application of materials	R8 Recycle	Process materials to achieve the same or lower quality
		R9 Recover	Incinerate material with energy recovery

Table 1 showed numerous BMs; however, in the building sector, the strategies are still incipient and concentrated on reuse and recycling CDW (Munaro et al. 2020). Besides, the diversity of nomenclature and the lack of a common source of information make it difficult to frame a general scope of innovation for BMs (Bocken et al. 2014). However, it is possible to group the different proposed models according to their respective definitions, similarities, and purposes.

Table 2 shows this grouping of BMs into six clusters, following the models established by Lacy et al. (2014). The choice of this author was due to the proposal of a reduced, comprehensive set and simple nomenclature of BM.

Table 2. Classification of business models from the literature into six condensed clusters.

Clusters of BMs	Lacy et al. (2014)	Bocken et al. (2014)	Bocken et al. (2016)	Carra and Magdani (2017)	Peters et al. (2017)	Potting et al. (2017)
Circular supplies	Circular supplies	Maximize material and energy efficiency	Encourage sufficiency	Circular supplies	Building performance drive	R0-R2
					Product/component/ material driven	
		Substitute with renewables and natural processes	Extending product value	Product and process design	Product performance driven	R3-R7
Resource recovery	Resource recovery	Create value from waste	Extending resource value	Recapture material suppliers	Product/component/ material driven	R3-R8
				Recovery provider		
			Industrial symbiosis	Recycling facility		
				Sell and buy-back		
				Tracking facility		
PSS	Product as a Service	Deliver functionality rather than ownership	Access and performance	Product as a service	Product performance driven	R1
Product life extension	Product life extension	Create value from waste	Extending product value	Lifetime extension	Product/component / material driven	R3-R7
				Refurbish and maintain		
				Support Lifecycle		
Sharing	Sharing platforms	-	-	Sharing platforms	-	-
Conceptual	-	Adopt a stewardship role	-	-	Value Network and Collaboration Driven	-
		Develop scale up solutions				
		Repurpose for society / environment				

Research methods

The methodological approach of this study consists of a descriptive and categorized systematic literature review (SLR) based on four stages, as shown in Figure 3. The process followed a succession of stages based on Tranfield et al. (2003), Biolchini et al. (2007), and Rocco and Plakhotnik (2009). SLRs are appropriate for mapping, assessing, and synthesizing literature to develop knowledge in a field (Tranfield et al. 2003). Descriptive analysis of the data examined how the construction sector has explored circular strategies and categorized analysis evaluated how these circular strategies are distributed in the BM concepts described in the literature.

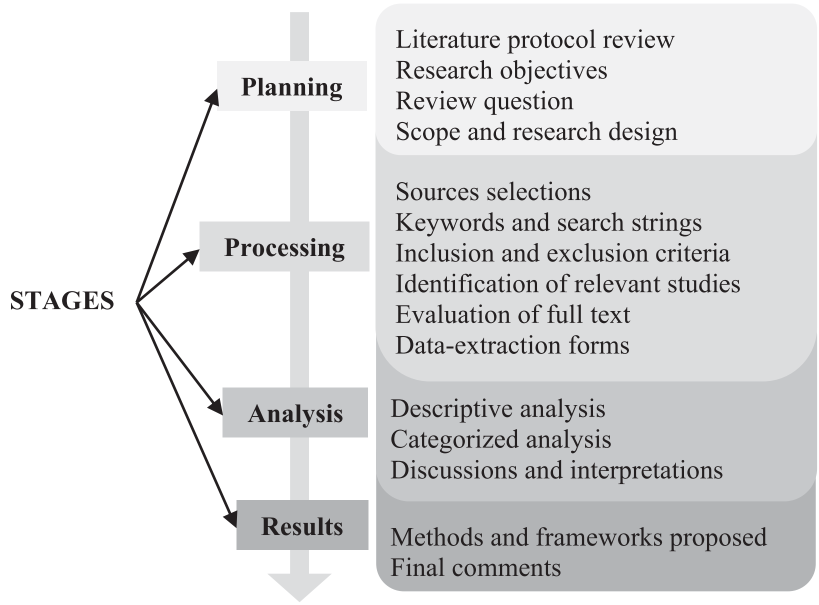

Figure 3. Map of the systematic literature review adopted.

In Stage 1, the planning stage, a research protocol was developed to map and identify the terms that the subject has been inserted in the journals. The research questions were formulated based on the problematization presented. The problematization allows challenging the assumptions that underlie the existing theory, rethinking established ideas, and producing new and inspiring starting points for the development of the theory (Sandberg and Alvesson 2011). The study addresses the following research questions: How does the construction sector approach the business models to achieve sustainable buildings? How is the implementation of circular strategies distributed in the BMs described in the literature? How can the implementation of CBMs be facilitated?

In Stage 2, the processing stage, the sources of information were the academic databases Web of Science of Clarivate Analytics, ScienceDirect, and Scopus of Elsevier. Web of Science was selected because reaches indexed journals with a calculated impact factor in the Journal Citation Report (JCR); ScienceDirect due to the multidisciplinary studies and references in the international scope, and Scopus due it is the largest database of peer-reviewed articles (Carvalho et al., 2013). The filter applied in the Web of Science was “type of documents”, choosing articles, reviews, and proceedings papers. In the other databases, the research criterion was “title, abstract, and author keywords”.

Figure 4 shows the keywords used in the SLR. It was sought to capture the publications containing terms and expressions semantically different, but with the same meaning of the problem. The inclusion criteria were articles, reviews, or proceeding papers, without a temporal cut to cover the entire evolution of the subject and the English language.

The Boolean operators AND and OR were used to combine terms to expand or limit search results. The symbol (*) has the function to include any variation on the terms searched (Carvalho et al., 2013). This stage results in 89 scientific publications.

Search terms / Databases (No articles)				
	Search strings	Web of science	Science Direct	Scopus
a	("circular* business* model*") AND (building* OR construct* OR (built environment*))	26	11	26
b	("circular* econom* business* model*") AND (building* OR construct* OR (built environment*))	8	4	8
c	("business* strateg*") AND (building* OR construct* OR (built environment*)) AND ("circula* econom*")	7	1	9
d	("innovat* business* model") AND (building* OR construct* OR (built environment*))	33	11	100
e	("sustainab* business* model*") AND (building* OR construct* OR (built environment*))	90	28	98
f	("business* model* innovati*") AND (building* OR construct* OR (built environment*))	183	29	189
g	("green* business* model*") AND (building* OR construct* OR (built environment*))	10	4	9
h	("business* model*") AND (building* OR construct* OR (built environment*)) AND ("circular* econom*")	83	36	79
i	(("eco innovat*") OR ("eco-innovat*")) AND (building* OR construct* OR (built environment*))	227	50	147

Processing literature search

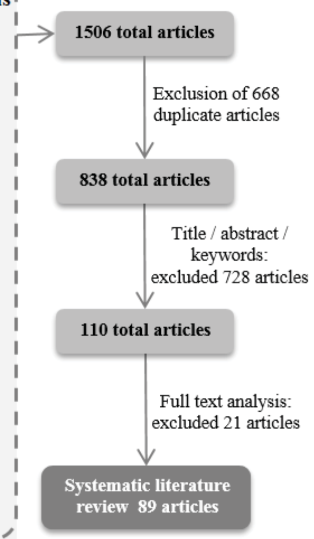

Figure 4. Processing the review in the scientific literature (review date August 2020).

In Stage 3, the analysis stage, a descriptive analysis was developed based on the research methodologies, article year, first author's country, and journal. The categorized analysis followed the organization of the publications in clusters according to the condensed clusters that shelter the other BMs described in Table 2. The articles were classified in clusters (1) because many business models presented in the literature had the same meaning but different nomenclature, and (2) to gather the material in smaller, more significant, and useful units to provide a means of describing the phenomenon, increase understanding and generate knowledge (Elo and Kyngas 2008).

In stage 4, the results stage, after analyzing and interpreting available evidence, a method and a conceptual framework were proposed to lead future developments of circular strategies in the construction sector. The method for value creation was based on the BM literature to guide the decision-making stakeholders. A conceptual framework is made up of theoretical work relevant for situating the study, by defining the main ideas and the network of relationships between them (Rocco and Plakhotnik 2009). The proposed framework sought to associate recurrent BMs in the literature and new CBMs focused on the built environment to guide new research developments and empirical applications.

Analysis of results

The analysis of the results is divided into two sections: (1) a descriptive analysis; and (2) a categorized analysis.

Descriptive analysis

The publications were classified according to the research approach, research aim, the procedure adopted, data source, and data collection, considering management and organization studies (Malhotra 2012). Most of the papers took a qualitative (75%, 67 articles) approach; there was a predominance of descriptive research (72%, 64 articles), followed by exploratory research (28%, 25 papers). Bibliographic research was the most adopted procedure (47%, 42 articles), followed by case studies (28%, 25 articles), modelling (20%, 18 papers), and surveys (4%, 4 articles). The exploratory nature of the research and the predominance of the qualitative methods demonstrated that the CBMs in the sector is still in the initial stages of adoption.

The evolutionary development of the publications is illustrated in Figure 5. The analysis shows the relevance and timeliness of the theme. The articles were published between 2006 and 2020, which proves that the research on this topic has increased in recent years. The number of publications increased over the last 4 years; 71% of the studies were from this period. Interest in the subject has been expanding in the scientific communities since 2014 due to the implementation of public policies and programs in foundations and private initiatives. For example, in 2014, the European Union started its circular economy package, with multiple action plans and legislative proposals focused on the industrial value chain. In the business world, the theme gained worldwide interest in 2014, mainly from the launch of the report "Towards the Circular Economy: Accelerating the Scale-Up across Global Supply Chains" (EMF 2014). The Buildings as Material Banks (BAMB) project in Europe also started in 2015, seeking circular solutions to preserve the value and functionality of building materials (Peters et al. 2017).

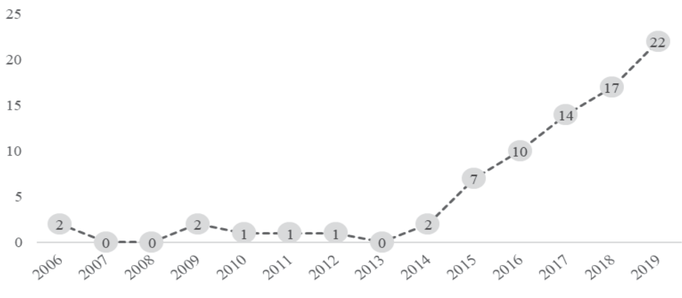

Figure 5. Yearly publications (articles published in 2020 are not represented).

Most of the scientific journals included in the SLR have environmental issues as a focus of interest and are relevant to the CE theme in the construction sector. The articles were distributed in 47 journals (76%, 68 articles) and 17 proceedings papers (24%, 21 articles). The most representative journal and proceedings publications were the Journal of Cleaner Production and the IOP Conference Series: Earth and Environmental Science, respectively. The dispersion of the publications emphasized the large scope of the problem. The variety of research areas involved, from policy instruments (Al-Saleh and Mahroum 2015), occupant behavior (Keskin and Mengüç 2018), and energy-efficiency measures (Chen et al. 2006) to carbon saving materials (Nußholz et al. 2019) emphasized the need for holistic and integrated thinking regarding the flows and value chains of the construction industry.

Europe accounted for 70% of the research (62 articles) covering 18 countries; this was followed by Asia with 24% (7 articles), America with 10% (3 articles), and Oceania with 3% (1 article). Europe and Asia accounted for 91% of the review articles and lead the research community in circular business models. Among the 29 countries shown in the SLR, Italy and the United Kingdom were the leading countries in terms of volume of publications, with 11 articles. The centralization of research in European countries is in line with the development of public policy (Merli et al. 2018). Large countries in terms of geographical area and economy, such as Brazil, India, and Russia, still have no relevance in the field.

Categorized analysis

According to the circular strategies described in the review articles, the 89 publications were categorized into the clusters of BMs described in Table 2. Table 3 presents the categorization of the review studies in these condensed clusters. Many of the review articles did not have a specific definition of the BMs adopted in the study. Table 3 shows the authors and BMs related to each cluster. Because the literature review did not present any study that contemplated sharing business models, the "sharing platforms" cluster is not shown in the table. The “Conceptual, descriptive, and guidance studies” category was created to group the conceptual models' studies category.

Table 3. Categorization of the review articles in clusters according to the similarity of the circular strategies found in the studies.

Cluster	**Ranking (n, %)**	**Related business models**
Circular supplies	1 (36, 40)	Circular supplies; Maximize material and energy efficiency; Substitute with renewables and natural processes; Encourage sufficiency; Extending product value; Product and process design; Circular supplies; Building performance drive; Product/component/material driven; Product performance-driven; R1; R2; R3-R7

Conceptual, descriptive, and guidance studies	2 (34, 38)	Repurpose for society/environment; Develop scale-up solutions; Value Network and Collaboration Driven
Resource recovery	3 (11, 12)	Resource recovery; Create value from waste; Extending resource value; Industrial symbiosis; Recapture material suppliers; Recycling facility; Product/component/material driven; R3-R7; R8
Product as a service (PSS)	4 (6, 7)	Product as a Service; Deliver functionality rather than ownership; Access and performance; Product as a service; Product performance-driven; R1
Product life extension	5 (2, 2)	Product life extension; Create value from waste; Extending product value; Lifetime extension; Support Lifecycle; Product/component/material driven; R3-R7

* Review articles are listed in the Supplementary file.

Discussion of results

The discussion of the categorized analysis is organized according to the five clusters of BMs identified in the SLR.

Circular supplies

Circular supplies were the most representative group in the review (40% of the articles); the BM group focused on strategies to reduce consumption and production and generate less waste, emissions, and pollution in the construction industry. The highlight was the transition to more efficient energy systems, focused on local generation technologies, automated data management, and better storage systems, enabling synergies between multiple sectors and innovative business models.

Many authors have explored BM in the delivery of zero-carbon buildings (ZCB). Zhao et al. (2016) identified key elements of business models, such as value proposition, target customer, and competitive advantage, to facilitate the construction of ZCBs. Zhao and Pan (2017) explored the theoretical interrelationships of BMs with ZCBs, highlighting aspects of value offering, project delivery process, stakeholder network, and revenue generation logic as accelerators in the delivery of ZCBs. Tronchin et al. (2018) investigated energy efficiency measures, local generation technologies, demand management, and storage systems from a multidisciplinary point of view aiming at sustainable energy transitions.

The energy efficiency associated with the useful life of buildings was analyzed by Chen et al. (2006) using a decision-making model based on performance indicators for a building's useful life. Stauch and Vuichard (2019) assessed that both community solar energy and the model of integrated photovoltaic energy in buildings are attractive business models. Cheng et al. (2015) explored energy management through a cloud service to develop an intelligent energy management network to optimize energy savings.

Studies also addressed water, energy, and resource flow with sustainable production, by examining the barriers and opportunities for the implementation of rooftop eco greenhouses in Europe (Cerón-Palma et al. 2012), and in retail parks for the exploration of urban horticulture (Sanyé-Mengual et al. 2018). The use of natural materials to reduce the environmental impact and the use of energy in the sector was evaluated on insulating cork panels as a solution for retrofitting buildings (Sierra-Pérez et al. 2018) and on ecodesign solutions for appearance wood products (Cobut et al. 2016). Bribián et al. (2011) compared the Life Cycle Assessment (LCA) of materials commonly used in construction with eco-materials to guide the selection of materials according to energy and environmental specifications.

Conceptual, descriptive, and guidance studies

The second cluster in terms of the number of articles (34% of articles) comprised conceptual articles on management theory and practices for creating, delivering, and capturing innovative value for the sustainable development of the construction industry.

Ünal et al. (2019) explored factors such as the configuration and adaptation of BMs to internal and external contextual factors, the valorization of local waste, and sustainable behaviors among the actors in the production chain for creating circular value. Abuzeinab et al. (2017a) identified that the optimized use of resources is the most important element among the credibility, financial, and long-term viability benefits of green business models (GBMs). In addition, the main barriers to the implementation of GBMs were categorized as governmental, financial, sectoral, business restrictions, and lack of demand (Abuzeinab et al. 2017b). To drive companies in innovation and value creation for sustainable buildings, Zhao et al. (2018) identified 24 factors related to the market and the economy, policy and legislation, technology and industry, culture, entrepreneurship, and organizational learning. Zhao et al. (2017) developed a model based on financial benefit, cost, corporate benefit, risk, firm reputation, competitive advantage, and environmental and social performance to assess BM performance in promoting more sustainable buildings.

Understanding the types of BMs is fundamental to the innovation of the sector. Jang et al. (2020) quantitatively classified business models of construction contractors in terms of profitability, growth, and market competitiveness and concluded that type of model plays a significant role in a company's performance. Heesbeen and Prieto (2020) described the archetypes of CBMs to guide industrialized production and innovative design roadmaps for circular buildings. Segarra-Ona et al. (2014) indicated that the eco-innovative orientation of construction companies is determined by the relationship between the importance of the sources of market information and the environmental orientation, mediated by the process and the orientation of the product. These studies sought to increase knowledge about BMs and circular actions aimed at the building sector. The need for a better understanding of the BMs, as well as the incorporation of other models and circular actions that have proximity to the built environment, was noted.

Resource recovery

The resource recovery cluster represented 12% of the publications; it covers circular strategies that aim to close the material cycle by recovering resources/energy from discarded products. Ajayebi et al. (2020) developed a framework to map the space-time stock of construction materials to assess the potential for reusing materials. Rose and Stegemann (2018) evaluated the information systems needed for the conceptualization of existing buildings as material banks (E-BAMBs). Mulrow et al. (2017) analyzed the potential for reuse and exchange of materials and knowledge through industrial symbiosis on a facility scale. Romnée et al. (2019) explored industrial symbiosis and the economy of functionality in a greenhouse project made from recovered materials. The use of secondary materials was explored as a way of decarbonizing the sector (Nußholz et al. 2019) and reducing CDW in new construction applications (Ginga et al. 2020; Migliore et al. 2015).

This cluster highlighted efforts to reduce and mitigate CDW at the end of life of materials and buildings. It is suggested that tools such as LCAs, material flow analysis, and materials passports be considered (Munaro et al. 2019; Munaro and Tavares 2021) to monitor the performance of buildings and their systems in all their life cycle stages, especially when considering the extension of the useful life cycle of materials in the use, operation, and maintenance stages. New business models in these building stages need to be explored, such as systems of sharing and PSS.

Product as a service (PSS)

The fourth category of the review (7% of the articles) grouped strategies for delivering a service instead of a product. Azcárate-Aguerre et al. (2018) evaluated PSS in components, such as façades; Johansson et al. (2016) evaluated PSS in the perception of urban mining of CDW. Servitization was analyzed in the process of manufacturing wooden elements (Pelli and Lahtinen 2020); the study verified that to increase efficiency and improve sustainability in prefabrication processes, a better understanding is needed of the innovations and reconfiguration in manufacturing due to the servitization model. In a social context, PSS was analyzed in terms of a supplier's property rights (Ploeger et al. 2019), and the employment offer in the temporary building module manufacturing (Kurdve and de Goey 2017).

Building-as-a-service can only be supported by an interconnected network of information and stakeholders. Due to the magnitude of the information and the variety of stakeholders in the supply chain, a digital method for collecting, manipulating, and exchanging data is indispensable. The reuse of building components and high-value recycling of building materials are still limited due to the lack of data on product design, composition, and use information during its useful life.

Product life extension

The Product life extension cluster was the least represented category in the review (2% of the articles), showing that strategies that explore the residual value of materials, components, and buildings have not yet been unexplored in the construction sector. Giorgi et al. (2019) studied the context of circular strategies that support the regeneration of the stock of existing buildings in Italy. Hagejärd et al. (2020) explored strategies to minimize the use of resources in the renovation of domestic kitchens, highlighting the availability and planning of storage and workspaces. Both studies emphasized the need for a combination of design strategies, identifying improvements in policies, partnerships, and sustainable assessment tools to achieve a higher level of circularity in buildings.

Summary of results

The SLR articles, grouped into five clusters, showed that the introduction of circular actions in the built environment is still incipient and does not involve all the stakeholders, products, services, and systems of the construction industry. A greater effort was observed in energy-efficiency measures, due to government actions and policies. Leising et al. (2018) reiterated the focus on issues like energy use and energy efficiency due to the innovation diffusion rather slowly in the sector.

The second most representative cluster demonstrated efforts to expand the discussion and information on CBMs. A lack of information and knowledge has been recognized about cost and revenue models for producers and suppliers of building materials and products. In addition, restrictions related to some service businesses are seen as a barrier (Peters et al. 2017). From a customer's point of view, some reasons prevent a more sustainable approach; consumers look for variety and novelty, the prestige of proprietorship, and the use of the latest technologies, novelties, or prestige goods. From a systemic perspective, consumer culture, affordability of more durable products, difficulties in defining suitable levels of sufficiency, and concerns about the effects of slower growth may be obstacles (Bocken and Short 2016).

In addition, even with the volume of waste generated by the sector, business models that favor resource recovery, product life extension, and PSS are little explored and understood by the stakeholders in the sector. Despite the countless opportunities to create value through the reinsertion of materials in value chains, CDW is still a major problem for public policy and society in general. Strategies such as urban mining, industrial symbiosis, creation of materials banks, servitization, and materials passports need to be explored to prolong and close the life cycle of materials. However, it is essential to understand how to create value from these actions. Above all, it is important to target actions and CBMs at different stages of the building life cycle, even if the end of life is the focus of current actions in the sector (Munaro et al. 2020).

Of the opportunities to generate circular value presented in the literature, few have been identified in review studies. Thoughtful CE actions linked to product design are needed to extend and maintain operational efficiency in the supply chain. Consequently, products need to be designed with the principles of CE to allow for reuse and recycling. Integrative approaches in BMs, product design, supply chain, and product life cycle management are fundamental to the implementation of the CE principle. A method that drives decision-making based on innovation and value creation from new BMs or existing ones is essential to guide the sector toward sustainability. New strategies that avoid value loss or negative externalities are needed for the incorporation of circular principles in buildings.

Innovation Process in Circular Business Models

The reviewed studies showed the incipient tendency to introduce CBMs, and unexplored models such as sharing value, encouraging sufficiency, and tracking facilities. To expand BM typologies and support the way stakeholders do business, guidelines and a better understanding of the subject are required to introduce circular strategies into value chains. This gap encouraged the development of a value creation model for construction projects and a framework linking CBMs to the entire building life cycle to assist in the transition toward circularity.

As shown in Fig. 2, an SBM is reflected in four pillars. Fig. 6 incorporates these concepts and presents a business model canvas for innovation and value creation in CBMs that incorporates questions to drive stakeholder decision-making, aiming to inspire the generation and discussion of ideas. It also incorporates a value testing stage, aiming to explore the various opportunities for a company to create value from assumptions in certain situations or contexts, making corrections in real-time.

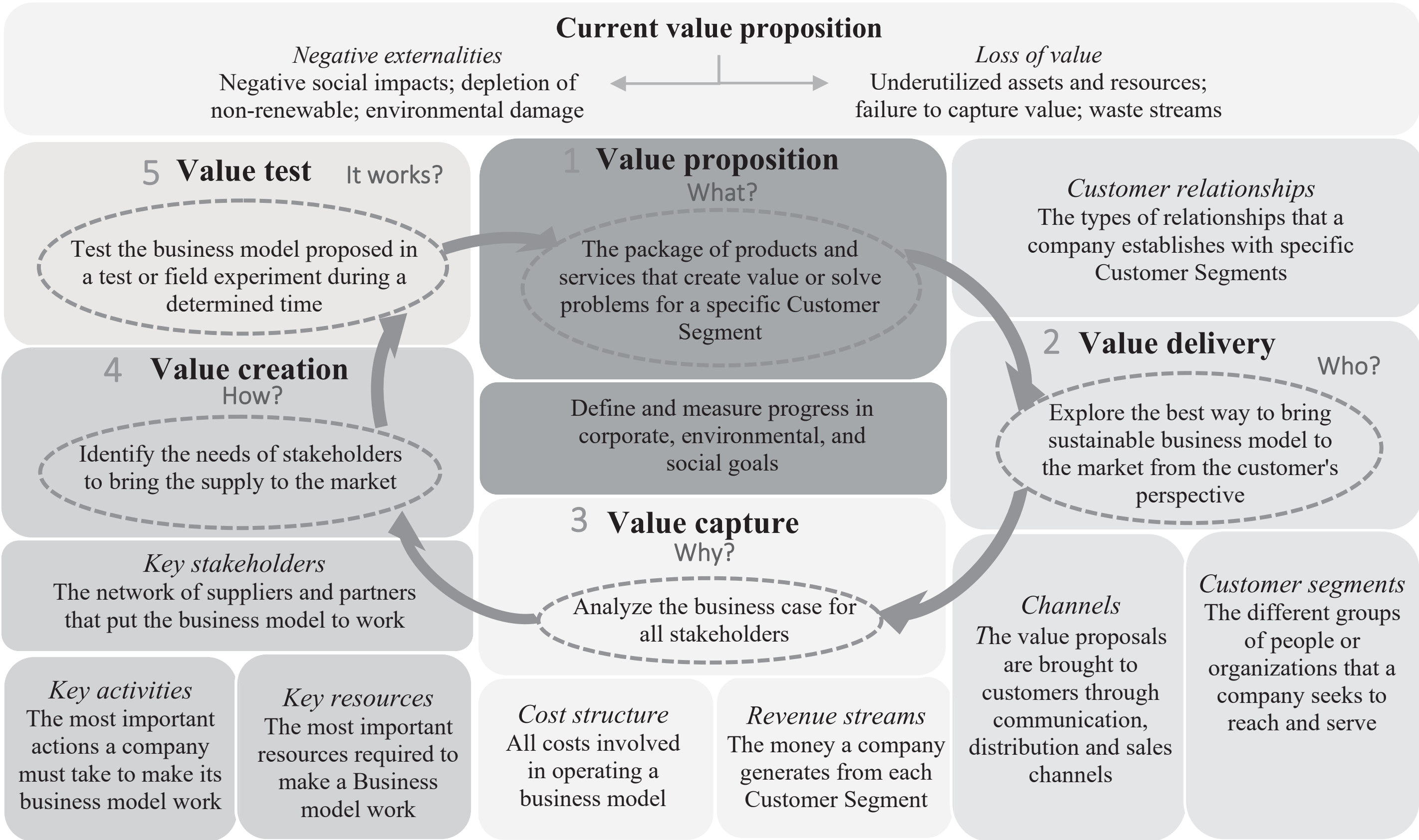

Figure 6. Circular business model canvas for iterative cycle for innovation (Adapted from Osterwalder et al. 2005).

The CBM consists of five interactive and iterative cycles of experimentation, learning, and seeking to create value and innovation across the construction industry, as shown in Figure. The model aims to rethink the value proposition and identify a roadmap for construction companies to capture the economic value and produce environmental and social value, considering the needs of customers, investors, shareholders, employees, suppliers, and partners, the environment, the organization, and society. Loss of value represents situations in which stakeholders waste or do not leverage assets, existing resources, and capabilities. This may be due to poorly designed value creation or capture systems or failure or inability to recognize benefit value (Bocken et al. 2013). Capturing lost value creates new opportunities to expand a business and introduce products and services that offer enhanced benefits.

The model in Fig. 6 is a process of analysis of the systemic condition of the value creation in the sector. A CBM, by targeting the closure of cycles of building materials or services, entails knowing the LCAs of materials and can either stand-alone or be part of a model system that closes a material cycle (Lacy et al. 2014). The operationalization of the model assumes that there may be improvements in each stage and requires (Sebrae 2017)

1. Knowing the stages and processes of the construction value chain and the mapping of the main suppliers, adopted practices, products, and services involved;
2. Identifying risks and social and environmental impacts, considering the life cycle of products and services and key stakeholders;
3. Proposing actions to reduce the identified risks and impacts;
4. Maintaining records and evidence of all actions taken, to facilitate monitoring, verification, and sharing of information; and
5. Experiencing the value proposition through prototypes, tests, campaigns, or isolated actions and monitoring the results obtained.

Circular business models for sustainable buildings

Table 4 incorporates the clusters of the SLR and lists other propositions for CBMs from the literature according to the building life cycle and the main stakeholders. The *conceptual, descriptive, and guidance studies* cluster was not included because it only presents theoretical studies of BMs.

Table 4. The current business model and proposition of CBMs according to the building life cycle stage.

Life cycle stage	Stakeholders	The current cycle of buildings	Proposals for Circular Business Models
Design	Customers Architects Engineers Investors Owners Government regulators	Typically, the residual value of the materials and the building are not considered; The project is not flexible and does not meet the required changes of users; The way of construction and the choice of materials favor the projection and generation of waste	**1 Circular supplies:** Focus on strategies to reduce consumption and production using less resource-intensive, recyclable, bio-based materials or to improve renewable energy **2 Product and process design:** planning and using strategies for building components and systems to improve performance and reuse potential. Guidelines for maintenance repair, reconditioning, or remanufacturing of the asset are established **3 Product life extension:** use of strategies such as disassembly and assembly, repair, maintenance, and/or upgrading to extend the life of products, components, and building systems
Manufacture	Manufacturers Suppliers Procurement experts	The constructions are not designed for disassembly and possible reuse; Manufacturers do not track the performance of materials over their life; Preference for natural resources instead of recycled materials; Lack of clear and organized information on materials, products, and components	**4 Materials Passport:** a list of data and indicators that describe features of materials that give them value for recovery and reuse
Logistics	Providers Suppliers	Materials are not returned to manufacturers; Logistics companies do not track products	**5 Circular logistics:** development of new bio-based materials, using renewable energy, easily segregated or fully recyclable
Construction	Builders Investors Real estate agencies Artisans	Components are cut and assembled on-site, creating waste; Information on the building is not organized into a single format or is not well informed, considering the aspects of maintenance and end of life	**6 Flexible building model:** provision of data and building guidelines to increase the performance and service life of materials and components, as well as the sustainable use of experience of the owners

Use and remodeling	Tenants Owners Investors Builders Facility managers	The owners do not have enough information to reuse or improve the building effectively; Buildings are often underutilized; Leases do not offer sufficient flexibility; The buildings do not have adaptability and reuse potential	**7 Sharing:** focuses on increasing the utilization rate of products or systems, allowing the use or shared access of the asset. At the same time, it favors the flexible design and use of collaborative facilities
			8 Product as a service: aims to deliver performance rather than products. The main revenue stream is generated by the performance provided, such as lighting and mechanization services, but can be extended to all parts of a building
			9 Traceability: aims to enable the tracking of materials, components, and products so that they can be identified, advertised in secondary markets, or properly destined
			10 Sell and buy-back: a product is sold and purchased again after some time, for the same or other purposes, increasing the shelf life
End of life	Demolition contractor Recyclers Recycling organizations	The demolition involves the loss of value of the material because the components cannot be dismantled; Disassembly of the building and separation of components in materials is not trivial or possible processes; The materials are usually recycled, reducing their value	**11 Life cycle support:** Consumables, spare parts, and supplements to ensure greater longevity in the product life cycle
			12 Resource recovery: recovered materials, components, and parts of a system are sold for reuse or recycling
			13 Recycling: aims to transform waste into raw materials. New revenue, business partnerships, recycling technologies, and products can be generated
			14 Rehabilitation and maintenance: reconditioning of parts and components of used materials so that they can be sold and used again
			15 Recovery provider: collection and recovery systems of discarded materials, products, or by-products

Maximizing value in CBMs of the construction industry should consider design requirements, information, and collaboration among stakeholders (Carra and Magdani 2017). In the design stage, assembly/disassembly, building flexibility, and deconstruction requirements are key features (Pieroni et al. 2019), emphasized by the Reversible Building Design Protocol of the BAMB project (Peters et al. 2017). Access to and availability of data and information on costs and conditions of materials, productivity, LCAs, property, guarantee, and traceability is a preponderant factor in decision making and can be obtained through a materials passport (Munaro et al. 2019; Munaro and Tavares 2021). Collaboration among stakeholders in one or more value chains is related to transparency, innovation, sharing, and short- and long-term BM (Carra and Magdani 2017).

The current constructive model is associated with value loss and environmental impacts (Table 4). The review articles showed efforts to create circular actions related to the stages of use, operation, and end of life of buildings. However, the design stage is essential in reducing CDW and closing materials cycles. New business opportunities need to be created in the design phase to make the reuse of materials more attractive. For example, options for potential reuse can be indicated; suggestions from companies or professionals in charge of the restoration, repair, or recycling of building materials can be provided; and the demolition of structures can be funded. These strategies minimize the vision that deconstruction is not attractive in terms of cost and time and increase the viability of secondary materials markets.

To reduce the sector inefficiency, stakeholders need to analyze the product/function and consider the end of life as a possibility for creating value rather than waste. Figure 7 associates the 15 value creation proposals of Table 4 with building life cycle stages.

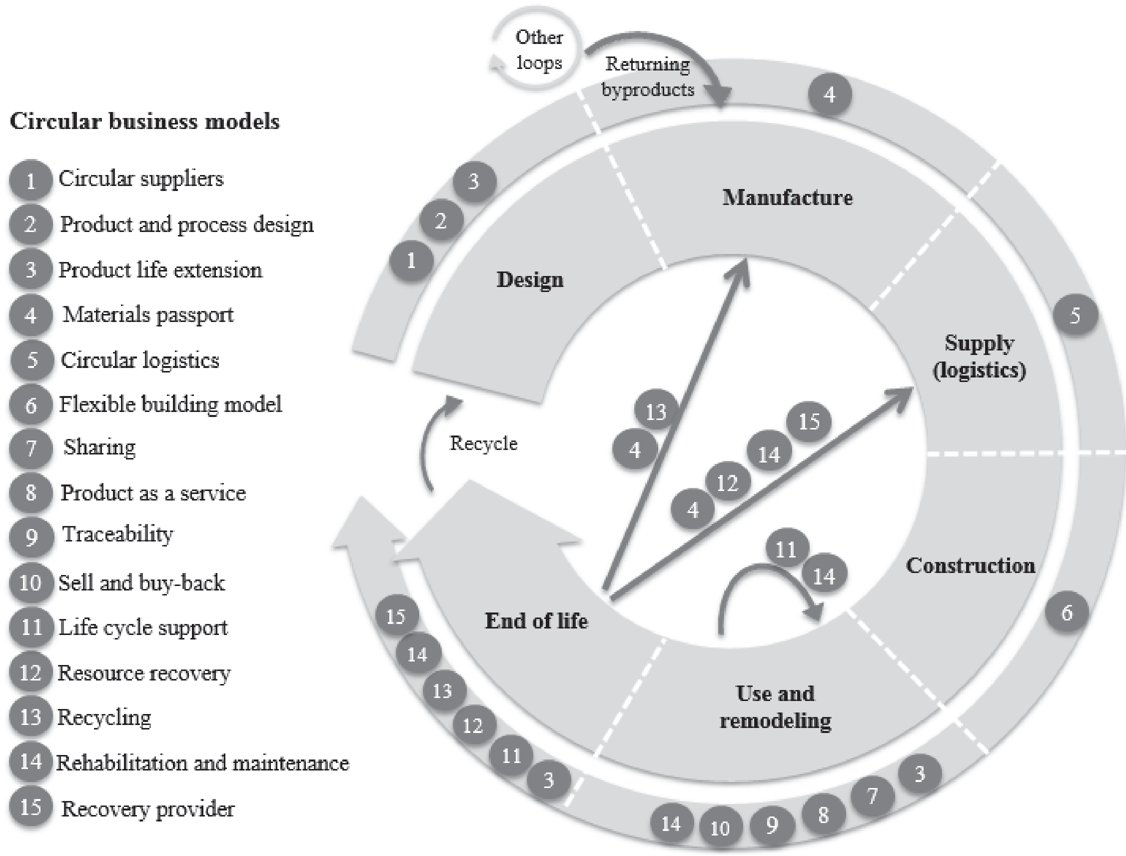

Figure 7. Circular business model framework according to the building life cycle stages.

The proposed CBM represents strategic options, with implications for product development and future value proposition, with features that are used individually or in combination to assist companies to achieve productivity improvements and increase differentiation and value for the customer (Peters et al. 2017; Lacy et al. 2014). Fig. 7 demonstrates the stages in which CBM can be incorporated into the building life cycle to accelerate the adoption of circular practices in the construction scenario. This does not mean that CBMs need to be restricted to a specific stage in the building life cycle. Different CBMs may be associated with different stages in the building life cycle.

In the conceptual framework, designers need to work collaboratively with manufacturers and suppliers to guarantee that the design of a building allows for disassembly and flexibility. Manufacturers and suppliers have a chance to recover materials and products at the end of the life of a building as a secondary source of revenue by remanufacturing, refurbishing, and reselling. Building maintenance provides long-term security, protection against rising commodity prices and material shortages, and opportunities for commitment with customers. Investors and builders need to guarantee that users, manufacturers, and developers implement circular practices throughout the building life cycle. In addition, demolition companies must change their BMs to become material reuse suppliers.

The results of the review indicated that the studies that sought to maximize materials (Sierra-Pérez et al. 2018) and the energy efficiency of buildings (Tronchin et al. 2018) concentrated on the design phase of the projects, in which there is a choice of materials and construction methods. The studies grouped in the resource recovery cluster, such as the mapping of construction material stocks (Ajayebi et al. 2020) and the use of secondary materials (Nußholz et al. 2019) concentrated on the end of life of buildings. The exploration of the use of services, as in the study of the components of the facades (Azcárate-Aguerre et al. 2018) is evident in the life cycle stages of use and remodeling of the building components. The studies in the product life extension cluster, like one study on the regeneration of existing buildings in Italy (Giorgi et al. 2019), focused on both the design stage and the use and remodeling of building elements at the end of life of buildings.

Understanding where change happens to be circular and creating value must be the starting point for organizations or stakeholders. This includes understanding the indicators and technologies available, from scarce resources to consumer behavior, focusing on closing the resource loop between post-use and production. In the CE, the focus is on sharing, and customers are seen as users rather than consumers of products and services, which implies a continuous and iterative vision of the relationship with a client. Innovation in the construction sector requires a transformation in the planning and executing of the value chain of building materials and services.

Discussion

The need for a better understanding of CBMs and the incorporation of circular actions that have proximity to the construction sector is noted. The scientific literature lists numerous BMs that are conceptual and comprehensive and do not relate to cities and the construction value chain (Bocken et al. 2014). It is necessary to associate environmental and social values with each building life cycle stage while maintaining economic benefits, including new forms of production, commercialization, and maintenance of products and materials.

A paradigm shift in the way buildings are designed and built is needed to address the challenges of deploying circular actions in the construction sector. Companies generate concrete actions and influence the behavior and engagement of stakeholders. Depending on their positioning, they may prove to be catalysts or barriers to sustainability (Bocken et al. 2014). There is a need for greater involvement of academia, industry, stakeholders, and relevant oversight bodies in evaluations to improve practical application processes and support decisions on the potential for material reuse.

While enterprises are the foremost means of promoting change for a CE, governments are key in enabling this transition (Lacy et al. 2014). A systemic overhaul of the production and consumption model requires arrangements between supply, demand, policy, and governments to shape market conditions at national and even global levels (Lacy et al. 2014). Policies on consumption taxation, legal frameworks, specific recycling targets, business responsibility for products throughout the life cycle, implementation of tax rewards for the use of regenerated resources, and regulation of building codes need to be reconsidered (Carra and Magdani 2017). In Europe, new construction and retrofit activities have reduced rates of taxation. The Dutch government has been a leader in establishing partnerships with companies to realize a CE (Lacy et al. 2014). Governments need to insert CE into their administration through areas such as public procurement.

CE adoption in the construction industry is in the beginning stage. The sector's delay in changing and a lack of knowledge and clarification about business models and CE principles are critical barriers. Further clarification is needed to elucidate the economic, social, and environmental gains of CBMs for stakeholders in the construction value chain. Also, the CE concept needs to be better understood; this includes the definition of CE system boundaries, challenges in governance and management, and intersectorial material and energy flows. The expected paradigm shift in the sector will only be possible based on public-private partnerships that promote the integration of the actors and closed material cycles.

Conclusions

This study contributes to narrowing the gap in the understanding of value creation through CBMs in the built environment. Business models emphasized the adoption of energy efficiency measures, aiming to reduce carbon emissions, the mining of natural resources, and the environmental impacts of the construction industry. The five clusters defined in the SLR highlighted the need to elucidate the relationship between the CE and the literature of BMs, foreseeing the economic and sustainable development of the sector. For effective CE implementation in the construction value chain, greater clarity is suggested on how circular practices influence stakeholders, supply chains, innovation and communication technology systems, and society.

The main contribution of this paper is the proposal of a circular business model framework that contributes to the CE theory by proposing different BMs according to building life cycle stages for different stakeholders. The framework allows for a holistic overview of the circular actions in the sector to direct actions and create innovative value opportunities. Based on the 15 listed business opportunities, companies in the industry can better target their choice and creation of new BMs and industrial symbioses. The BM canvas and framework proposed in Figs. 6 and 7 are a useful starting point for researchers, practitioners, and stakeholders to insert circular practices in the sector. The product life extension model, based on recycling, recovery provider, materials provider, rehabilitation, and life cycle support models, is a BM that needs to be explored at various stages of the building life cycle and requires systemic thinking about flows and value chains.

This study has limitations that must be considered. First, the methodology adopted selected papers from journals and was focused on academic research in the construction industry. There is an additional need to identify the evolution of the latest industry practices and research. Second, the review was based on a keyword search, which limited the results to combinations of keywords. In addition, although the criteria for article selection were explicit, the selection of articles for review may have been subject to researcher biases.

The propositions of this research did not exhaust the subject; they seek to promote new discussions and the evolution of the field in question. Future research should focus on the search for circular studies and actions in construction companies to verify their effectiveness and effective usability. The proposed theoretical research aims to expand the discussion and development of the BMs seeking more circular constructions. The practical implications were twofold: (1) adopt the business model canvas in the creation value process to guide the implementation of the circular strategies in the sector, and (2) apply the proposed conceptual framework to enable the introduction of CBMs in the construction sector. From an academic contribution perspective, the results of the study helped develop a robust and coherent empirical knowledge base that could also be tested and adopted in different geographical locations and industry contexts.

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PAPER A4

Analysis of Brazilian public policies related to the implementation of circular economy in civil construction

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Analysis of Brazilian public policies related to the implementation of circular economy in civil construction

Abstract

Circular economy (CE) has been receiving increasing attention worldwide to increase the efficiency of the use of resources and minimize the generation of waste, aiming at a better balance and harmony between economy, environment, and society. It is an incipient concept, and its implementation is mainly associated with the support of public policies. Thus, the environmental and social impacts of the construction sector require alternatives to optimize the use of materials, encourage the recycling of construction waste (CW), and the correct disposal of non-reusable waste. This study aimed to analyze the Brazilian public policies that support the adoption of CE in the construction sector. It was possible to identify twelve public policies and their respective instruments, categorized into five guiding axes and according to the 9Rs framework of circular strategies. This study revealed that the adoption of CE is focused on reducing the CW, guided by normative instruments such as the National Policy for Solid Waste (NPSW), through the principles of shared responsibility and reverse logistics. The study contributes to the theoretical literature on public policies in support of CE and helps policymakers to create a circular policy plan to support the decision-making process in the construction industry and encourage the adoption of sustainable strategies.

Keywords: Circular economy. Construction waste. NPSW. Sustainable management.

Introduction

The construction sector represents 36% of the energy end-use and 39% of global carbon dioxide emissions, being a major target for environmental sustainability (INTERNATIONAL…, 2019). In addition, the sector is the world's largest consumer of raw material, generating up to 35% of urban landfill waste (GHAFFAR; BURMAN; BRAIMAH, 2020). In this sense, construction waste (CW) is a social challenge due to its growing volume and its associated environmental impacts, since in Brazil it represents more than 60% of collected urban solid waste (USW) in the cities (ASSOCIAÇÃO…, 2020). The large volume of CW is the result of the current linear economic model of "take-make-consume-dispose" (ELLEN…, 2015). The sector needs to implement strategies to reduce this problem and make a shift towards the adoption of sustainable practices (LIMA *et al.,* 2021).

Sustainability is a broad term encompassing triple bottom line aspects of – environmental conservation, social equality, and economic security. A gradual approach is required to achieve sustainability in the sector. The adoption of a circular economy (CE) is a prerequisite to sustainability (GHAFFAR; BURMAN; BRAIMAH, 2020). CE offers an opportunity to reduce the use of primary materials and their associated environmental impacts, through different strategies that replace the end-of-life, such as reduction, reuse, and recycling of materials in the production/distribution processes and consumption (KIRCHHERR; REIKE; HEKKERT, 2017).

Several approaches, known as R-strategies, have been developed to achieve less resource use and material consumption in product chains. Value retention processes (VRPs) – also called R-imperatives – are key in realizing the cycles in CE (POTTING *et al*., 2017). The three most principles of the CE concept are material reuse, reduce, and recycle (3Rs). Scholars have extended the concept to 6Rs, adding remanufacture, redesign, and recovery (KIRCHHERR; REIKE; HEKKERT, 2017). Potting *et al.* (2017) introduced more refuse, refurbish, and repurpose principles, creating a 9Rs framework (recover, recycle, repurpose, remanufactured, refurbish, repair, reuse, reduce, rethink, and refuse) ordered in a hierarchy from lowest to highest circularity.

These CE principles have gained academic, governmental, and organizational recognition. Globally, Japan and China were the first to introduce circular policies at the national level. In Europe, the CE has become a central aspect of policy and strategy development, and several countries have implemented initiatives, policies, and guidelines, like Germany, the Netherlands, and the United Kingdom (GUARNIERI; CERQUEIRA-STREIT; BATISTA, 2020). Directive 2008/98/EC is considered the European initial document on the implementation of the best waste management practices. In 2014, the European Union started the “Circular Economy Package”, with multiple action plans and legislative proposals focused on the industrials` value chain. In 2020, the strategies were updated to a new Action Plan for the Circular Economy for a cleaner and more competitive Europe (EUROPEAN…, 2020).

Within the Brazilian Policy context, the main regulatory framework that approaches the circular economy principles is the National Policy for Solid Waste (NPSW), introduced in 2010 by Law No. 12305 (BRASIL, 2010). Brazil is considered the pioneer in Latin America and Caribbean countries to implement such legislation related to waste management (GUARNIERI; CERQUEIRA-STREIT; BATISTA, 2020). However, CE is not formally expressed in the national laws and has been approached in a decentralized manner in several public policies and focused on waste management. Despite the large political framework, the transition to implement CE in Brazil is incipient and the concept is still poorly understood.

Therefore, public institutions have an essential role in the development of a governance plan that combines an environmental and regenerative economy. Policymakers have the responsibility and conditions to enable the promotion of cultural changes through political instruments. It is important to develop a complete understanding of public policies that foster and hinder the transition to CE, from a social and economic perspective. This study seeks to analyze the main Brazilian public policies that support the implementation of CE in the construction sector. Through bibliographic and documentary research, the instruments of the public policies were categorized into five policy measures according to the 9Rs framework of circular strategies. The study expands the discussion on the importance of circular public policies in the transition towards more sustainable buildings.

The 9R framework of circular strategies

The transition to CE is a solution to reduce environmental impacts and contribute to economic growth (GHAFFAR; BURMAN; BRAIMAH, 2020). CE acts as a regenerative system in which resources, energy, emissions, and waste leakage are minimized by slowing, closing, and narrowing material and energy loops (BOCKEN *et al*., 2016). A higher level of circularity of materials in product value chains means that smaller amounts of natural resources are needed to produce new materials (POTTING *et al.,* 2017). Then, the 9Rs framework, as shown in Figure 1, is an approach to implementing circular actions in the building life cycle stages, maximizing the value of the materials and the energy recovery throughout production processes and consumption distribution flows in the construction sector.

Overview of generation and collection waste in Brazil

As noted by the 9Rs framework, CE seeks to recirculate resources and materials, and this involves the whole construction value chain. CE approaches waste management in a systemic way, planning and developing products whose waste is minimized or reused. In Brazil, the NPSW regulates both the management of solid urban waste (SUW) and CW, focused on the management of post-consumer waste. There are still few efforts and advances toward preventing the generation of waste and more circular consumption and production since the implementation of NPSW. Besides, waste management has deficiencies regarding the universalization of selective collection, the rates of recovery and recycling, and the final disposal of waste (ASSOCIAÇÃO…, 2020).

Figure 2 presents a history of the generation and collection of SUW and CW in Brazil. The data shown in Figure 2 are from the historical series of the Brazilian Association of Public Cleaning and Special Waste Companies (ABRELPE) from 2010, the initial milestone of the NPSW. The CW data refer to the collection carried out by the public service, which collects waste thrown in public places, as the responsibility for the collection and destination of this waste is generally of the generators.

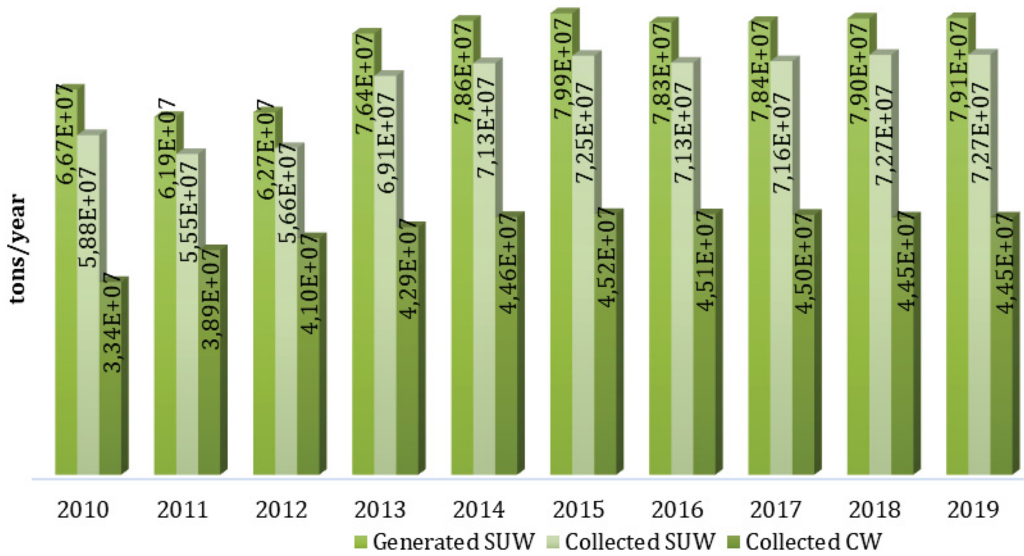
In 2019, more than 44 million tons of CW were collected in the country. Since 2010, the collected CW represents approximately 60% of the total mass of municipal SUW collected annually. According to Brasileiro and Matos (2015), more than 72% of Brazilian municipalities have a CW management service, however, only 7% of the municipalities have some type of waste processing and only 2.23% have CW reuse. To make it possible to recirculate materials, components, and parts of the buildings, waste must be perceived as a raw material for new products. Within this context, environmental legislation needs to be more effective, making waste generators responsible for the disposal of their waste and leading to the adoption of techniques to minimize waste and recycling policies (BRASILEIRO; MATOS, 2015).

Figure 1 - The circular 9Rs framework in order of priority

	Strategies		
Circular economy	Smarter product use and manufacture	**R0 Refuse**	Make product redundant by abandoning its function or by offering the same function with a different product
		R1 Rethink	Make product use more intensive
		R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
	Extend lifespan of product and its parts	**R3 Reuse**	Reuse by another consumer of discarded product which is still in good condition
		R4 Repair	Repair and maintenance of defective product so it can be used with its original function
		R5 Refurbish	Restore an old product and bring it up to date
		R6 Remanufacture	Use parts of a discarded product in a new product with the same function
		R7 Repurpose	Use a discarded product or its parts in a new product with a different function
	Useful application of materials	**R8 Recycle**	Process materials to obtain the same or lower quality
Linear economy		**R9 Recover**	Incineration of material with energy recovery

Source: adapted from Potting *et al.* (2017).

Figure 2 - History of the generation and collection of SUW and CW in Brazil



Source: annually ABRELPE reports (ASSOCIAÇÃO…, 2020).

Public policies for the circular transition

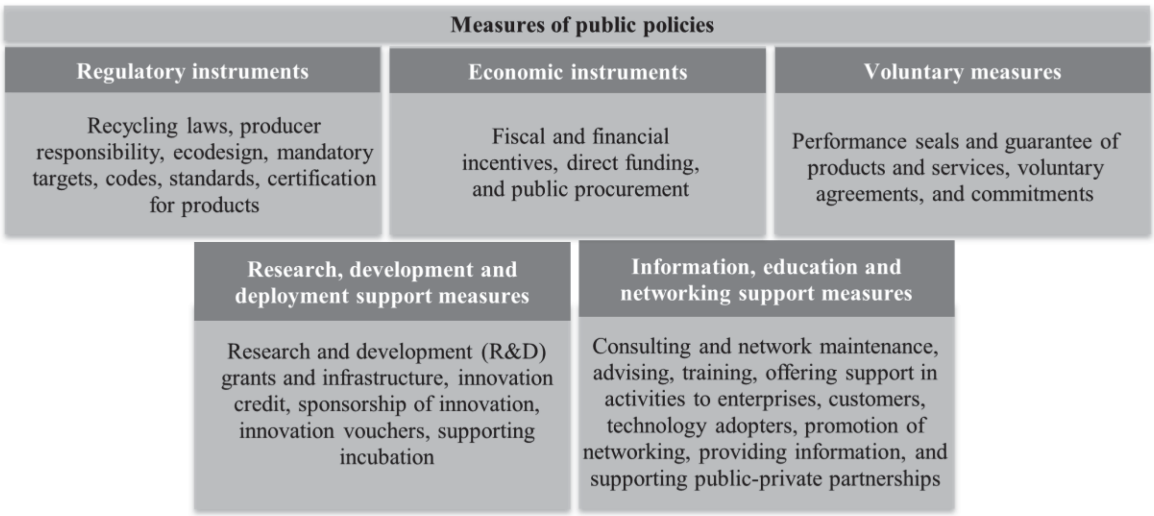
The intensification of social, economic, and environmental problems related to CW led governments to strengthen efforts to solve these problems. At the macro level, the CE implementation is the result of public policies and the performance of other agents, such as foundations and business development agencies (POMPONI; MONCASTER, 2017). To Secchi (2019) public policies are guidelines for political decisions aimed at facing a public problem. The public power has a decisive role in guiding the CW management, using instruments of regulation, inspection, and creation of conditions for the environmentally correct treatment. To Doranova *et al.* (2016) national and local governments can implement five axes of policy measures to promote CE initiatives, as shown in Figure 3.

Public policies are fundamental as inducers of changes that, through instruments and public sector leaders, can encourage circular behaviors and actions. The five axes of policy measures, shown in Figure 3, have different focuses of action, but they all converge on the purpose of establishing a sustainable policy plan. For example, the regulatory instruments deal with the elaboration and promotion of legislative acts that support activities and changes. Economic instruments influence organizations' financial and budgetary issues, representing benefits or inducing the search for alternatives. Voluntary measures reflect people's engagement in the participation and transformation of their societies. Finally, the axes of research, development, and deployment of support and information, education and networking measures are essential to promote social values, knowledge, skills, attitudes, and competencies essential to the quality of life and sustainability.

Research strategy

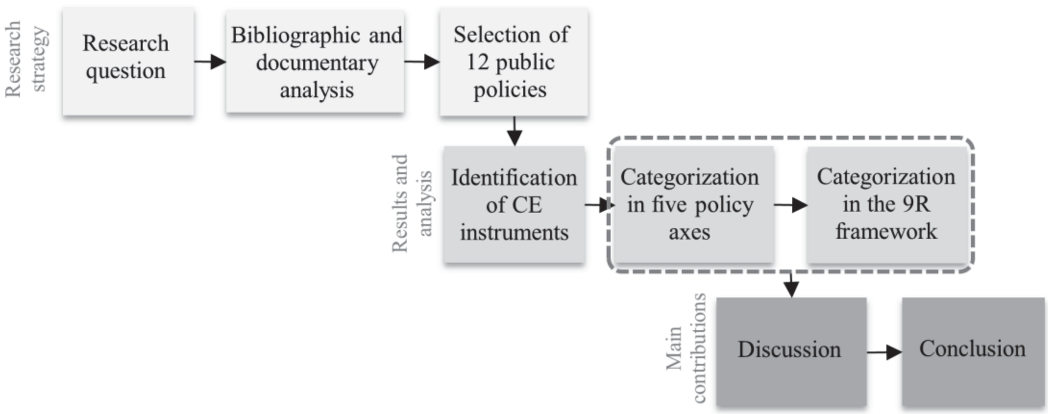
The study sought to answer the following question: What are the Brazilian public policies that relate to the implementation of the CE in the construction sector? The research approach was based on bibliographic and documentary analysis of the main national public policies. The study considers ordinary laws and normative resolutions that make up the Brazilian legislative framework. The identification of the public policies considered the environmental and sustainable consumption legal and institutional framework established by the Action Plan for Sustainable Production and Consumption (PSPC) (MINISTÉRIO…, 2014). Twelve documents were identified and analyzed, and their instruments were two-fold categorized. Figure 4 summarized the research strategy adopted.

Figure 3 - Range of policy measures



Source: adapted from Doranova *et al.* (2016).

Figure 4 - Summary of the research strategy of the study.



Results and analysis

Table 1 presents the main national public policies related to the implementation of the CE in the construction sector. The main instruments concerning each public policy related to the CE were described below.

Law No. 9.795 (BRASIL, 1999) establishes the National Policy for Environmental Education for the qualification and training of educators at all levels and modalities of society. It considers environmental education as a primary factor for the implementation of sustainability in the means of social production and consumption (BRASIL, 1999). The law argues that the government must establish policies that promote education and assume the commitment of society to the conservation, recovery, and improvement of the environment.

Law No. 10.257 (BRASIL, 2001) instituted the City Statute and can be considered a pioneer in the creation of legislation on CW management. Based on this law, the need for the disposal and treatment of construction and demolition waste generated was legally established, as previously, the legislation was limited to prohibiting its disposal on public roads or public places. Thus, waste began to attract society's attention to urban planning and the law-instituted rules that intended to regulate the occupation and use of urban land. The guidelines provide for the guarantee of the right to sustainable cities, understood as the right to urban land, housing, and basic sanitation (BRASIL, 2001).

Table 1 - Brazilian public policies relating to CE in the construction sector

Public policy		Year	Title	Aim
Federal Laws	Law 9.795	1999	National Environmental Education Policy	The development of an integrated understanding of the environment
	Law 10.257	2001	General urban policy guidelines	The development of the social functions of the city and the urban property
	Law 11.445	2007	National basic sanitation guidelines	To establish national guidelines for basic sanitation and the federal basic sanitation policy
	Law 12.187	2009	National Policy on Climate Change (NPCM)	Sustainable development to face climate change and meet the needs of populations
	Law 12.305	2010	National Solid Waste Policy (NSWP)	Integrated and environmentally sound management of solid waste
	Law 14.026	2020	Updates the legal framework for basic sanitation	Updates the legal framework of the basic sanitation system
Resolutions	Resolution No. 307	2002	CONAMA Resolution No. 307, July 5, 2002	To establish guidelines, criteria, and procedures for the management of construction waste
	Resolution No. 348	2004	CONAMA Resolution No. 348, 16 August 2004	To include asbestos in the hazardous waste class
	Resolution No. 431	2011	CONAMA Resolution No. 431, May 24, 2011	To establish a new classification for plaster as belonging to class B
	Resolution No. 448	2012	CONAMA Resolution No. 448, January 18, 2012	To update some requirements of Resolution No. 307
	Resolution	2015	CONAMA Resolution No. 469,	To update some requirements of Resolution

	No. 469		July 29, 2015	No. 307
Plan	Action Plan	2011	Action plan for sustainable production and consumption (MINISTÉRIO…, 2014)	To encourage dynamics and actions that contribute to the sustainable development of Brazilian society

In addition, the City Statute addresses guidelines for the ordering and control of land use to prevent the misuse of urban properties, the underutilization or non-use of properties, pollution, and environmental degradation. It cites legal and political instruments provided for in civil law, such as expropriation, adverse possession of the urban property, installations, buildings, listing, and land tenure regularization. Furthermore, national, regional, and state plans for territorial ordering and social-economic development are established; tax and financial institutes; in addition to the Environmental Impact Study (EIS) and Neighborhood Impact Study (NIS) in the implementation of housing projects (BRASIL, 2001). One of the most important instruments of the law is the Master Plan as a basic instrument of urban development and expansion policy.

Law 11.445 (BRASIL, 2007) establishes national guidelines for basic sanitation, considering a set of services for the public supply of drinking water; collection, treatment, and final disposal of sanitary sewage; drainage and management of urban rainwater, as well as urban cleaning and solid waste management (BRASIL, 2007). Urban cleaning and solid waste management are comprised of waste collection, transshipment, and transportation activities; sorting for reuse or recycling purposes; treatment, including composting, and waste final disposal. It also refers to the waste originating from sweeping, weeding, and pruning trees on roads and public places and other urban public cleaning services. The law also prioritizes the universalization of services, the reduction, and control of water losses, encouraging the rationalization of its consumption by users and promoting energy efficiency, the reuse of sanitary effluents, and the use of rainwater (BRASIL, 2007).

The institution of the National Policy on Climate Change (NPCC), created by Law 12.187 (BRASIL, 2009), represented an important milestone in the regulation of climate protection at the national level. The NPCC encourages the adoption of activities and technologies with low emissions of greenhouse gases (GHG), and sustainable production and consumption patterns (BRASIL, 2009). The law establishes sectoral plans to meet gradual targets for reducing quantifiable and verifiable anthropogenic emissions considering sectors such as public transport and the construction industry. Although, it is still in the implementation phase and the protagonism of the State must merge all sectors of society for its effective implementation.

In 2010, Brazil passed Law 12.305 (BRASIL, 2010), which instituted the National Policy for Solid Waste (NPSW). NPSW establishes principles, objectives, instruments, and guidelines for the management of solid waste, the responsibilities of generators, public authorities, and consumers, as well as the applicable economic instruments. The law covers and correlates important principles such as prevention and precaution, polluter-pays, eco-efficiency, shared responsibility for the product's life cycle, recognition of waste as an economic and social value asset, and the right to information (BRASIL, 2010).

The NPSW encourages the development of environmental and business management systems aimed at improving production processes and the reuse of solid waste, including recovery and energy use. The Policy establishes as its main objective the non-generation, reduction, reuse, recycling, and treatment of solid waste, as well as the environmentally appropriate destination of the waste (BRASIL, 2010). This goal is reinforced by the institution of the shared responsibility for the product's life cycle, covering manufacturers, importers, distributors, traders, consumers, and owners of public services for urban cleaning and solid waste management.

In article 33, the NPSW establishes the system of reverse logistics, articulated with the selective collection, for the implementation of shared responsibility (BRASIL, 2010). This system is one of the main milestones of the law and aims to enable the collection and return of solid waste to the business sector, for reuse, in its cycle, in other productive cycles, or another environmentally rigorous destination. The law determines who is obliged to structure and implement reverse logistics systems to increase recycling and reduce the deposit of waste in landfills. Concerning the CW, the NPSW clarifies that the construction companies are subject to the elaboration of a solid waste management plan, by the regulations established by the bodies of the National Environment System. This management plan must comply with the Municipal Solid Waste Management Integrated Plan.

Law 14.026 (BRASIL, 2020), called the new regulatory framework for basic sanitation, encourages competition, and the privatization of state-owned public sanitation companies, among other innovations to reduce environmental and public health problems caused by insufficient sanitation in Brazil (BRASIL, 2020). The law establishes goals for universal sanitation and new deadlines for the closure of dumps by municipalities. It is worth mentioning that laws 11.445 and 14.026 have common points for the treatment of solid waste, as well as law 12.305. In addition, it makes provision for the rationalization of water consumption, by demanding that new condominium buildings must adopt environmental sustainability standards, such as the individualized measurement of water consumption by real estate units (BRASIL, 2020).

Resolution 307 of the National Environment Council (CONAMA) established guidelines, criteria, management procedures, and the classification of civil construction waste into four classes (Class A, B, C, and D) to facilitate environmentally correct final disposal (CONSELHO…, 2002). The Resolution also instituted the Municipal Construction Waste Management Plan, which includes actions related to the transport, receipt, sorting, storage, or CW final disposal. The Plan establishes that the generators of CW must be responsible for the residues from the construction, renovation, repair, and demolition activities of structures and roads, as well as those resulting from the removal of vegetation and excavation of soils. The other resolutions (348, 431, 448, and 469) implement and update some directive information for the effective reduction of the environmental impacts generated by the CW (CONSELHO…, 2004; 2011; 2012; 2015).

The Action Plan for Sustainable Production and Consumption (PSPC) directs the actions of the government, the productive sector, and society towards more sustainable patterns of production and consumption (MINISTÉRIO…, 2014). It is a goal-based plan with progressive implementation and a participatory approach, reflecting advances in other public policies. In its first cycle (2011 to 2014) it sought to strengthen existing initiatives and voluntary adhesions and demonstrate measures aimed at promoting changes in production and consumption patterns. The initiatives established in the Sustainable Constructions area sought to introduce practices that improve socio-environmental performance, from the project to the construction, considering the selection of materials and alternatives that have less impact on the environment and human health (MINISTÉRIO…, 2014). The main guidelines concerning the circular principles were the promotion of programs that seek energy efficiency, the rational use of water and its reuse, the use of environmentally friendly materials and techniques, and waste management.

Categorization of Brazilian public policies

The complexity of Brazilian public policies and the numerous instruments and objectives related to each law makes the political scenario influence the relationships between stakeholders of the construction value chains and between the stages of the building's life cycle. To better understand and combine the law instruments, promote actions, and mediate conflicts, the identification of the axes of political intervention is important. Table 2 presents the categorization of the main instruments present in each public policy according to the five thematic axes established by Doranova *et al.* (2016). It is worth noting that no voluntary measures were observed in the analyzed public policies.

Law 9.795 (BRASIL, 1999) presented lines of action linked to school and education to develop an integrated understanding of the environment in its multiple and complex relationships. In-Law 10.257 (BRASIL, 2001), regulatory and economic instruments were highlighted regarding the use and planning of urban territory. The instruments aim at the regularization of constructions, reforms or expansions carried out, the optimized use and occupation of the soil and buildings, considering the environmental impact resulting from them to obtain the licenses or authorizations for construction, expansion, or operation under the responsibility of the Municipal Government.

Laws 11.445 (BRASIL, 2007) and 14.026 (BRASIL, 2020), on basic sanitation, presented regulatory, economic, research, and information support instruments. Both laws establish fundamental principles for obtaining more sustainable buildings by stimulating the development of water supply, sewage, urban cleaning, and solid waste management services appropriately for public health, the conservation of natural resources, and the protection of the environment. Law 14.026 (BRASIL, 2020) also encourages the reduction and control of water losses and the promotion of energy efficiency.

The regulatory instrument of Law 12.187 (BRASIL, 2009) is the reduction of GHG emissions in the construction sector aimed at increasing the residual life of building materials through circular practices. National targets for reducing GHG emissions in buildings are the main factors for promoting the development of Design for Disassembly (DfD), the reuse of construction materials, and, consequently, the demand for secondary materials in the market.

Law 12.305 (BRASIL, 2010) is the most representative in terms of instruments that contribute to CE in the sector. The information systems and inventories proposed in the law, in the information category, are important instruments for collecting and analyzing data and generating information to guide the decision-making of political and private bodies about solid waste. Sectoral agreements and environmental education are instruments to connect interested parties and promote CW management. The law also provides the development of scientific and technological research for the creation of new products or technologies that aim to slow down, close, and narrow the cycles of resources and materials. Besides, reverse logistics requires greater integration among industry stakeholders and can create new circular business models. The law shows the need for integration between the stakeholders in the construction value chain to enable the implementation of the NPSW and achieve efficiency in the CW reduction.

Resolution 307 (CONSELHO…, 2002) and other amendments present regulatory instruments regarding the classification and final disposal of the different types of CW. Those instruments enable the development of Management Plans and the direction of solutions for solid waste, to consider the political, economic, environmental, cultural, and social dimensions, under the premise of sustainable development.

The PSPC presented instruments to improve the socio-environmental performance of buildings. The Federal Government norms for sustainable housing programs started to incorporate variables such as the use of local resources; saving water and energy in construction; promoting the rational use of building materials; promoting the collection and recycling of solid waste; adopting solutions to improve the internal comfort of homes and promoting environmental education for residents.

Finally, when studying the instruments separately, it is essential to consider that specific actions are not sufficient from the CE point of view, which determines the incorporation of a systemic view. Strategies that consider only economic, environmental, or social issues will not achieve circularity. The implementation of a public policy depends on the engagement of the stakeholders in interconnected and dependent value chains, in articulation with governments, organizations, communities, and individuals.

Table 2 - Categorization of public policies related to CE

Categories	Law 9.795 (BRASIL, 2001)	Law 10.257 (BRASIL, 2001)	Law 11.445 (BRASIL, 2007)	Law 12.187 (BRASIL, 2009)
Regulatory instruments		Spatial planning and economic and social development plans. Legal and political institutes. Environmental Impact Study (EIS) and Neighborhood Impact Study (NIS).	Water supply, sanitation, urban cleaning, and solid waste management. Availability of drainage and stormwater management services. Reduction and control of water losses.	National Plan on Climate Change. Action Plans for the Prevention and Control of Deforestation in biomes. Establishment of quantifiable and verifiable standards and targets for the reduction of GHG emissions. Sustainability indicators.
Economic instruments		Tax and financial institutes.	Economic efficiency and sustainability.	Fiscal and tax measures aimed at the reduction of GHG emissions. Credit and financing lines.
Research development and deployment	Training; Development of studies, research, and experimentation. Production of educational material.		Encouraging research, development, and use of appropriate technologies.	Development of research; Records, inventories, estimates, assessments of GHG emissions. Disclosure, education, and awareness-raising measures.
Information, capacity building, and networking support			Articulation with urban and regional development, housing, anti-poverty and eradication policies, environmental protection, health promotion, water resources social interests.	Stimulate the development of processes and technologies that contribute to GHG emissions reduction. Establish preference criteria in public tenders, including public-private partnerships.
Categories	Law 12.305 (BRASIL, 2010)	Law 14.026 (BRASIL, 2020)	Resolutions (CONSELHO..., 2002, 2004, 2011, 2012, 2015)	PCPS (MINISTÉRIO..., 2014)

Regulatory instruments	Solid waste plans. Selective collect; reverse logistic; shared responsibility. Environmental and health Boards. Municipal agencies for the control of solid waste services. National Environmental Policy Instruments. Terms of commitment and conduct adjustment.	New deadlines for the environmentally appropriate final disposal of tailings (closure of open dumps). Adoption of individualized measurement of water consumption by real estate unit. Connection of the urban buildings into the public water supply and sewage networks available. Progressive reduction and control of water losses.	Resolution No. 307 CCW classification, Plans, and proper disposal. Resolution No. 348 Institutes hazardous waste materials containing asbestos. Resolution No. 431 Plaster becomes Class B. Resolution No. 448 New guidelines for Waste. Management Plans. Resolution No. 469 Empty ink packaging - Class B	Sustainable public procurement. Increased recycling of solid waste. Sustainable retail. Sustainable Buildings.
Economic instruments	Tax, financial and credit incentives. National Environment Fund. Incentive to consortia or cooperation.	Stimulate free competition, efficiency, and economic sustainability in the provision of services.		
Research development and deployment	Cooperation between the public and private sectors to develop research.	Promote environmental education; technical training of the sector; scientific and technological research.		Education for sustainable consumption.
Information, capacity building and networking support	Inventories and annual solid waste reporting system. Creation of cooperatives of waste pickers. Environmental education. National Information System on Solid Waste Management. Sectoral agreements. Encouraging consortia or cooperation.	Encourage the integration of databases. Encourage cooperation between entities to provide, contract, and regulate services.		Environmental Agenda in Public Administration.

Circular strategies in a broader policy context

Table 3 shows the impact of Brazilian public policies on different circular strategies. The 9R framework (shown in Figure 1) was adopted as a parameter to analyze the circularity of public policies in the construction sector.

Public policies have actions in different circular strategies, with an emphasis on strategies aimed at prolonging the useful life of materials, which aim to adapt the screening of CW for recycling or recovery of parts of the material, for example, through the incineration of wood as energy fuel. The NPSW features instruments for both recycling and promoting the reuse, repair, or redirection of materials to extend the useful life of resources. Law 10.257 (BRASIL, 2001) uses instruments such as compulsory use and adverse possession that contribute to the reuse/repair of existing buildings and the prolongation of the building's useful life.

Laws 11.445 (BRASIL, 2007) and 14.026 (BRASIL, 2020) encourage the conscious consumption of water and the reuse of effluents and rainwater, reducing pressure on natural resources and stimulating the development of more sustainable technologies and systems for sanitary facilities. The strategy of reducing the extraction of natural resources is encouraged by the reduction of GHG emissions (Law 12.187 (BRASIL, 2009)) and by the PSPC which encourages the increase of efficiency and management of resources and construction materials. Initiatives such as Resolution 348 (CONSELHO…, 2004) also promote a more conscious use of building materials and the well-being of users.

Table 3 - Correlation of Brazilian public policies with the 9R framework

Strategies		Public policies	Circular instruments
↑ Circular economy	R0 Refuse	-	-
	R1 Rethink	Resolution 348 (CONSELHO..., 2004)	Tiles and other objects and materials containing asbestos are dangerous materials
	R2 Reduce	Law 11.445 and 14.026 (BRASIL, 2007, 2020)	Reduction and control of water losses, encouraging rationalization, and promoting energy efficiency; Adoption of individualized measurement of water consumption
		PPCS (MINISTÉRIO..., 2014)	Takes advantage of the natural resources of the local environment; manage and save water and energy in construction; promote the rational use of construction materials
		Law 12.187 (BRASIL, 2009)	Reduction of greenhouse gas emissions
	R3 Reuse	Law 10.257 (BRASIL, 2001)	Use of unused, underutilized, or unused urban land; Adverse possession of the urban property; Regularizing buildings following current legislation
		Law 11.445 and 14.026 (BRASIL, 2007, 2020)	Reuse of effluents and the use of rainwater
		Law 12.305 (BRASIL, 2010)	Selective collection, reverse logistics and shared responsibility
	R4 Repair	Law 12.305 (BRASIL, 2010)	Solid waste plans; Selective collect, reverse logistics, and shared responsibility
	R5 Refurbish		
	R6 Remanufacture		
	R7 Repurpose		
	R8 Recycle	Laws 11.445 and 12.305 (BRASIL, 2007; 2010)	Solid waste management
		Resolutions 307 and 448 (CONSELHO..., 2002, 2012)	Classification and proper destination of construction waste. Waste management plans
		Resolution 431 (CONSELHO..., 2011)	Plaster as class B recyclable waste
		Resolution 469 (CONSELHO..., 2015)	Reverse logistics for empty paint packaging
Linear economy	R9 Recover	Law 14.026 (BRASIL, 2020)	Extinction of open-pit dumps

Public policies have a concentration on less circular strategies. Law 14.026 still establishes the need to extinguish open-air dumps. CONAMA resolutions focus on raising awareness of the need to separate and classify CW. Although the current political framework has numerous circular instruments, it is necessary to create a centralized strategic plan with measures to foster research, technologies, and circular business models that promote the development of the CE in a manner compatible with the need for national economic development.

Discussion

The transition to a CE in the construction sector is still incipient and lacks systemic thinking. It is possible to find links between Brazilian legislation and policy guidelines that relate to and contribute to the introduction of circular principles in the sector, however, there are no specific public policies and efforts are lacking for the application and consolidation of the existing ones. For Guarnieri, Cerqueira-Streit, and Batista (2020) this fact demonstrates the lack of awareness and understanding of the fundamental role that a sectoral agreement can play in enabling industrial transitions to the CE.

The choice of NPSW as a national example of propositions capable of directing the circular transition process is justified by principles such as non-generation, reduction, reuse, and recycling of solid waste. This law highlights the importance of a systemic view of construction value chains, reducing resource consumption, and recognizing the economic and social value of waste. The law does not act in isolation but is characterized by articulating with policies regulated by other legislation, such as the National Basic Sanitation Policy, the NPCC, and the PSPC. The institution of reverse logistics promotes new circular business opportunities, the use of by-products, and the establishment of secondary material markets. However, its operation faces challenges due to the absence of carbon-neutral targets; absence of specific objectives; lack of coordination between manufacturers, distributors, and traders for an efficient process of storage, collection, and recycling; and lack of technology, infrastructure, and qualified knowledge (GUARNIERI; CERQUEIRA-STREIT; BATISTA, 2020; JABBOUR *et al*., 2014). The authors argued that the barriers to the implementation of reverse logistics also apply to the obstacles that hinder CE implementation.

There is a need for a better understanding of the CE principles, and fundamentally, the public policies need to be reformulated focusing on the preservation of resource value instead of the efficiency in waste management. This must discuss within the reach of everyone involved in the construction value chains, from architects, builders, to users and recyclers, who are sometimes unaware of the importance of their performance or the harmfulness of certain conducts. Defining objectives for the sector and demanding its effectiveness seems to be of paramount importance and, perhaps, the only way to introduce circular principles and achieve sector sustainability.

The study showed that the profile of Brazilian public policies is concentrated on regulatory instruments at the organizational level, characterizing the pioneering essence of governance in adopting the circular model. Other countries such as China and Japan already have a more structured policy framework. In 2009, China pioneered the establishment of specific legislation aimed at the CE, with a focus on the symbiotic relationships of industrial parks (IWASAKA, 2018). Japan, since 1991, has been showing a progressive evolution in policies aimed at the cyclical use of materials (GHISELLINI; CIALANI; ULGIATI, 2016).

The European Union's efforts have been taking place since 2008, and each member country has been applying efforts according to their local realities. For example, Germany is a pioneer in actions related to solid waste management, with an action implemented in 1976 aimed at regulating the flow of packaging and products (GHISELLINI; CIALANI; ULGIATI, 2016). The Netherlands implemented a national strategy for the implementation of CE in the country by 2050, focusing on the stages of the materials production process, seeking to disseminate attractive circular alternatives (IWASAKA, 2018). Since 2014, the United Kingdom has been applying economic measures, such as taxation, and different rates applied to products that incorporate some CE principles (IWASAKA, 2018). The more advanced development of other countries, such as the European ones, directs new opportunities for Brazilian public managers to formulate policies aimed at CE. Local, regional, and national authorities must guarantee policies, regulations, and financial support; facilitate dialogue between companies, civil society, and research organizations; and lead or participate in the development of projects (DORANOVA *et al*., 2016).

Conclusions

This study presented the main Brazilian public policies related to the implementation of CE in the construction sector. When considering the scope of the public policies, Brazilian legislation is already reasonably adhering to the concept of the CE. The NPSW addresses in an orderly manner the main issues related to the production and destination of solid waste in the country. However, despite being a consistent legal framework, the great challenge is the correct execution of this policy, in an integrated manner between the Union, States, Municipalities, and the private sector.

This study aims to expand the discussion on the importance of circular public policies and to support policymakers develop a circular plan based on a set of policy tools and measures to regulate resource efficiency, waste reduction, and management and create a more sustainable sector. For academics, managers, practitioners, and researchers, it can direct and expand knowledge about the potential applications of CE, as well as about the implementation of reverse logistics and circular principles relevant to the management of solid waste in the sector.

This study has as its main limitation the non-comprehensiveness of the whole Brazilian legislative framework for analyzing the proposed problem. The selection of the twelve public policies were based on previous readings, the PSPC report, and the analysis of Federal laws aimed at sustainability, not including municipal and state laws. Additional studies could cover other governmental perspectives that contribute to CE implementation and in the non-governmental organizations. In addition, future research could analyze the development of circular policies in other countries, to direct national actions towards a governance plan that considers and applies CE principles.

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PAPER A5

The ecodesign methodologies to achieve buildings' deconstruction: A review and framework

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The ecodesign methodologies to achieve buildings' deconstruction: A review and framework

ABSTRACT

The ecodesign methodologies in the design stage enable buildings to be adapted to the needs of users and deconstructed at the end-of-life. Although ecodesign methods incorporate circular economy (CE) principles, they are little explored in projects and constructions. This study analyses how the construction sector approaches ecodesign methods to achieve buildings' deconstruction. Through an integrative literature review, 288 articles were threefold analyzed: i) bibliometric, ii) conceptually about ecodesign methods, and iii) categorically. The results showed a lack of understanding of the ecodesign concepts, and an integrated methodology was proposed. The most inclusive and sustainable ecodesign method for buildings deconstruction was Design for Adaptability and Disassembly (DfAD). The review shows the concentration of the studies in three categories and a framework was created relating DfAD strategies. The sector needs more information on ecodesign methods, deconstruction strategies, reusing of materials, and in the life cycle tools as decision support to make sustainable buildings.

Keywords: Design for adaptability and disassembly; Circular economy; Ecodesign; Building's end-of-life.

1 Introduction

The construction sector is responsible for one of the highest amounts of resource use, waste, and emissions of all industries (Pomponi and Moncaster, 2017; GloalABC, 2019). Despite being the world's largest consumer of raw materials, only 20-30% of these resources are recycled or reused at the end of a building's useful life (WEF, 2014). In 2018, the sector represented 36% of the end-use of energy and 39% of global carbon dioxide (CO_2) emissions (GlobalABC, 2019).

To reduce the environmental impacts produced by the sector, strategies have been adopted, mainly concerning energy efficiency and the management of construction and demolition waste (CDW). However, the demand for more energy-efficient buildings often leads to operational strategies that increase the built-in energy (Azari and Abbasabadi, 2018). The environmental savings of reusing/renovating a building can vary from 4 to 46% compared to a new building (Azari and Abbasabadi, 2018). Instead, reuse and recycling reduce waste from landfills, and even the processes involved in recycling make up for in general terms of incorporated energy and carbon emissions.

Deconstruction is an end-of-life (EOL) scenario that favors the recovery of construction components for relocation, reuse, recycling, or remanufacturing of construction (Kibert, 2003). Design for Deconstruction is an ecodesign method that enables the assembly and disassembly of buildings to recover building components. Ecodesign methodologies consider the stage design issues over the life cycle of the building linked to environmental and human health (Pigosso et al., 2010). Despite efforts to mitigate CDW through deconstruction, information on deconstruction projects and the deconstruction process is limited. To Dorsthorst and Kowalczyk (2002) less than 1% of buildings are completely demountable, and since then the scenario has not changed (Kanters, 2018).

The concept of ‘Design for Deconstruction’, which is also known as 'Design for Disassembly' both known by the acronym DfD, appeared in the construction sector in the 1990s (Kibert, 2003) by ecodesign methodologies from the manufacturing industry (Macozoma, 2002). DfD can be associated with Design for Adaptability (DfA). An adaptable building can be modified by users to meet their constant needs. The adaptability and deconstruction project integrates flexibility to the configuration of space and the recovery of EOL components. The method seeks to maintain building components, parts, and materials at their highest level of utility and value, supporting the introduction of circular economy (CE) principles in the sector. CE is a restorative economic model that seeks to dissociate economic development from the consumption of finite resources (EMF, 2015).

Several studies have established strategies to guide the incorporation of CE principles for buildings deconstruction. Durmisevic (2001; 2019) demonstrated a Reversible Building Design method based on spatial changes (aspects of the extensibility of the space, replaceability, and change of the functions) and technical changes (accessibility, the extensibility of systems, disassembly, and independence). Thormark (2001) developed eighteen design strategies based on the choice of materials, design of construction, and choice of joints and connections. Nordby et al. (2007) developed a system based on 31 strategies for the recovery of materials. Sassi (2008) established criteria for the closed-loop building materials cycle. Crowther (2016) listed 27 design principles for disassembly.

Although, DfD is not mainstream in the construction sector. There is a gap in the literature on circular business opportunities to introduce practices aiming at closing the material cycle (Munaro et al., 2020). In addition, the sector is conservative and has its design process, manufacturing techniques, supply chain, and financial arrangements that fail to match the complex nature of the building resulting in inadequate development of CE-focused design guidance and tools. For these reasons, the sustainability of buildings depends on several interconnected attributes, such as building design, choice of material, operation, and maintenance (Sanchez and Haas, 2018). Besides, ecodesign methods have been studied in the sector with different terminologies and definitions. The language used by practitioners and their different interpretations of a design for buildings EOL may lead to misunderstandings about the design objectives (Pinder et al., 2017; Rockow et al., 2019). The conceptualizing of the main ecodesign terms related to deconstruction and a categorized picture of the state-of-the-art of ecodesign methods to achieve deconstruction of buildings are fundamental to understanding and implementing CE principles in the sector.

This review aimed to study how the construction sector approaches the ecodesign methods to achieve buildings deconstruction. A study has not yet been published that explores the current state of ecodesign concepts aiming at the recovery and reuse of building components. Through an integrative review, this study sought to (i) provide a bibliometric analysis of studies on ecodesign methods for buildings' deconstruction; (ii) conceptualize the main ecodesign terms related to the deconstruction; and (iii) propose a framework of the categorized studies to achieve buildings' deconstruction. Figure 1 shows the organization of the study.

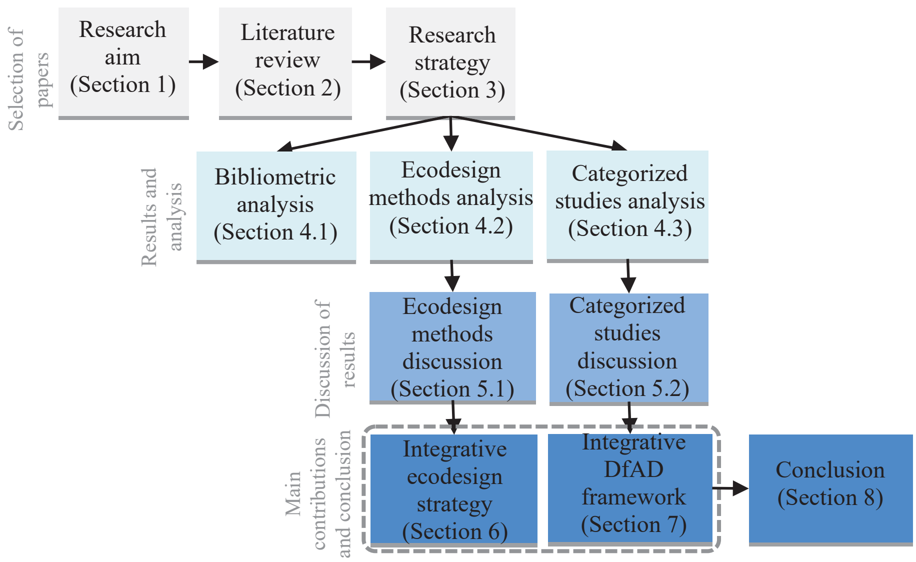


Figure 1. The research process development.

2 Ecodesign definition

Sustainability and Industrial Ecology were highlighted in the environmental scenario in the 1980s and 1990s to reduce waste production and pollution in material-intensive sectors.

The term eco-efficiency and methodologies such as Ecodesign or Design for the Environment (DfE) appear as alternatives to redesigning existing products (Hauschild et al., 2005). Ecodesign can be defined as the consideration of the environmental performance of the product/project over the entire life cycle. Pigosso et al. (2010) consider as a method to develop products aligned with the concept of sustainable development and lifetime thinking. The methodology proposes products to be flexible, reliable, durable, modular, dematerialized, and reusable, moreover, to prove economic reasonableness and social compatibility (Hauschild et al., 2005).

2.1 Ecodesign methodologies in the construction sector

Different ecodesign methods have been developed to assess the environmental impacts of products. The term 'Design for' or 'DfX' has become common, where X represents the design objective regarding the EOL scenarios of a product. Much of the literature under the sustainable design umbrella has focused on consumer goods. In the product design and manufacturing industry, such frameworks are Design for Recycling; Remanufacturing; and Disassembly (Hauschild et al., 2005).

In the construction sector the methodologies of 'Design for' started being incorporated to improve high-level recycling of the building materials and components (Dorsthorst and Kowalczyk, 2002). However, the design, construction, and maintenance characteristics of buildings are different from consumer goods. Buildings have greater longevity, large capital investments, and a multiplicity of stakeholders throughout the life cycle. Particularities increase the complexity of adopting ecodesign methods. To implement ecodesign methodologies in the sector it is needed to consider that buildings are formed by a system of components, parts, and materials with different useful lives. Given the complexity of the buildings, it is pertinent that the understanding of the ecodesign terms is clarified. Particularly regarding terminology, the meanings practitioners associate with the different DfXs methods, how these meanings are communicated, and how to implement them in the building industry.

2.2 The deconstruction approach in the context of a circular economy

The need to build flexible and demountable projects began when human beings needed to be nomadic. The mobility and temporary structures became issues of survival. Later, the concept of ephemeral architecture was an important milestone for the development of cultures and structures for temporary events (Crowther, 2016). Since the 1970s, rules for deconstruction have been established in conventions, guidelines, or declarations, to increase usability and extend the functional life of buildings. In 1976 the research of DfD had included works on complete house moving and support systems (Cai and Waldmann, 2019). In 1992, Berge presented principles for the direct reuse of building materials (Nordby et al., 2007). Brand (1994) advised the design of the building on separate layers. In 1999, a group was created by the International Council for Research and Innovation in Building Construction (CIB) to produce an analysis, meetings, and reports to make deconstruction and reuse of building materials feasible options.

Methodologies to assist and evaluate deconstruction have been developed. Akinade et al. (2015) projected an evaluation system associating material selection based on Building Information Modeling (BIM). Akanbi et al. (2018) developed a model to estimate the life cycle performance of structural components recovery. Sanchez and Haas (2018) established a model for selective disassembly sequence for adaptive reuse of buildings. Recent studies have focused on cost and environmental impact analyses carried out at the end of the buildings' life cycle (Tatiya et al., 2018; Buyle et al., 2019), and on challenges and opportunities in the practice of deconstruction activities (Rios et al., 2015; Akinade et al., 2019).

At the macro level of the construction sector, policies that aim to close the material cycle have also gained prominence. Many political programs and plans have been developed to implement circular principles in the sector. Ellen Macarthur Foundation (EMF, 2015) developed a program in which organizations collaborate to enable the creation of new CE opportunities. The European Commission has developed the Circular Economy Action Plan and the Buildings as Material Banks (BAMB). BAMB adopted the concept of Reversible Building Design based on the repair, reuse, and recovery of materials (BAMB, 2021). Despite efforts, Design for Adaptability or Deconstruction/Disassembly is very limited in the sector. The sector is still very conservative in adopting and doing things differently (Kanters, 2018). A major challenge identified in the literature is that building projects do not have enough information about how they could be deconstructed (Adams et al., 2017; Akinade et al., 2019). Understanding the relationship between the different 'DfX' methods and the CE is essential for reducing environmental impacts, implementing circular strategies, and positioning the DfD within the building sustainability ecosystem.

3 Research strategy

The research methods adopted consist of an integrative literature review based on six stages, as summarized in Figure 2. The process followed a succession of six steps based on Torraco (2005), Whittemore and Knafl (2005), and Tranfield et al. (2003). An integrative review is the broadest methodological approach to reviews and incorporates different purposes for a complete understanding of the analyzed phenomenon (Whittemore and Knafl, 2005).

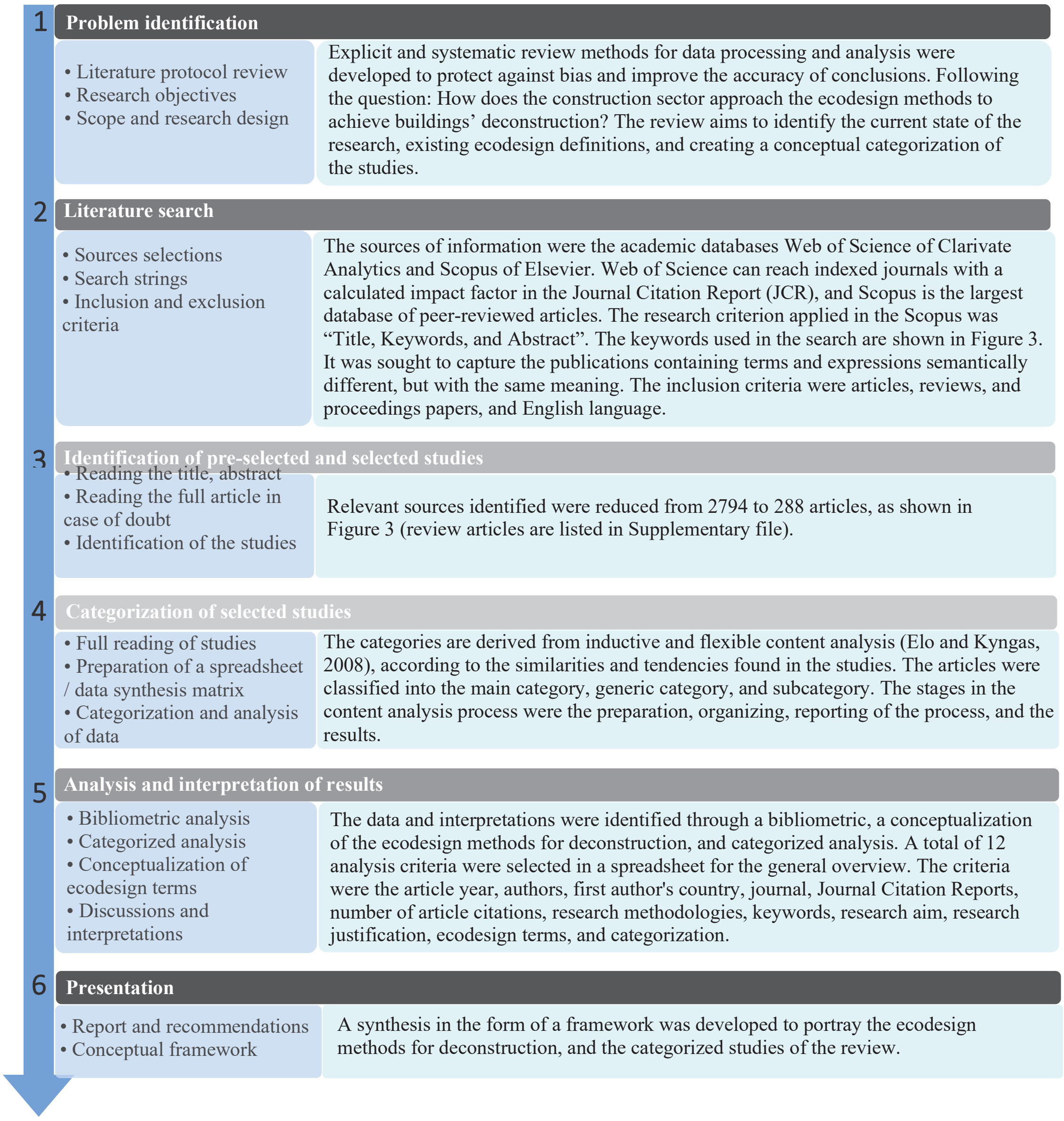


Figure 2. Stages, decisions, and processes of the integrative review.

The selected articles were analyzed under three lenses: bibliometric, analysis of the ecodesign methods, and content analysis. The content analysis attains a condensed and broad description of the topic, and the outcome is categorized by describing the phenomenon (Elo and Kyngas, 2008). Figure 3 shows the processing of the review in the scientific literature. The search terms were based on a previous analysis of the literature. Duplicate studies, from other areas of knowledge, and that did not match the research question were removed.

	Search terms / Databases (No articles)		
	Search strings	Web of science	Scopus
a	("circul* buil*" OR "circul* construct*")	118	189
b	("design* for adaptab*" OR ("design* adaptab*" AND buil*) OR ("design* adaptab*" AND construct*))	45	86
c	("design* for deconst*" OR "design* deconst*")	34	48
d	("design* for disassemb*" OR ("design* disassemb*" AND buil*) OR ("design* disassemb*" AND construct*))	244	348
e	(("design* for modula*" AND buil*) OR ("design* for modula*" AND construct*) OR ("design* modula*" AND buil*) OR ("design* modula*" AND construct*))	128	223
f	(("design* for transforma*" AND buil*) OR ("design* for transforma*" AND construct*) OR ("design* transforma*" AND buil*) OR ("design* transforma*" AND construct*))	34	47
g	(("design* out waste*") OR ("design* waste*" AND buil*) OR ("design* waste*" AND construct*)	38	50
h	(("design* for change*" AND buil*) OR ("design* for change*" AND construct*))	18	35
i	(("build* deconst*") OR (build* AND deconst* AND circular*))	47	57
j	(("flexib* build*" AND "sustainab*") OR ("flexib* AND build*" AND "circular* econom*") OR ("flexib* build*" AND deconst*))	15	29
k	(("revers* build*") OR (revers* AND build* AND circular* econom*))	29	46
l	(("demount* build*") OR (demount* AND build*))	55	120
m	("transform* build*" OR (transform* AND build* AND "circular* econom*"))	136	170
n	("build* reus*" OR (build* AND reus* AND "circular* econom*"))	121	284

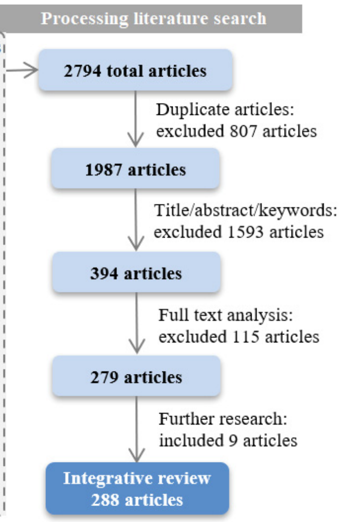


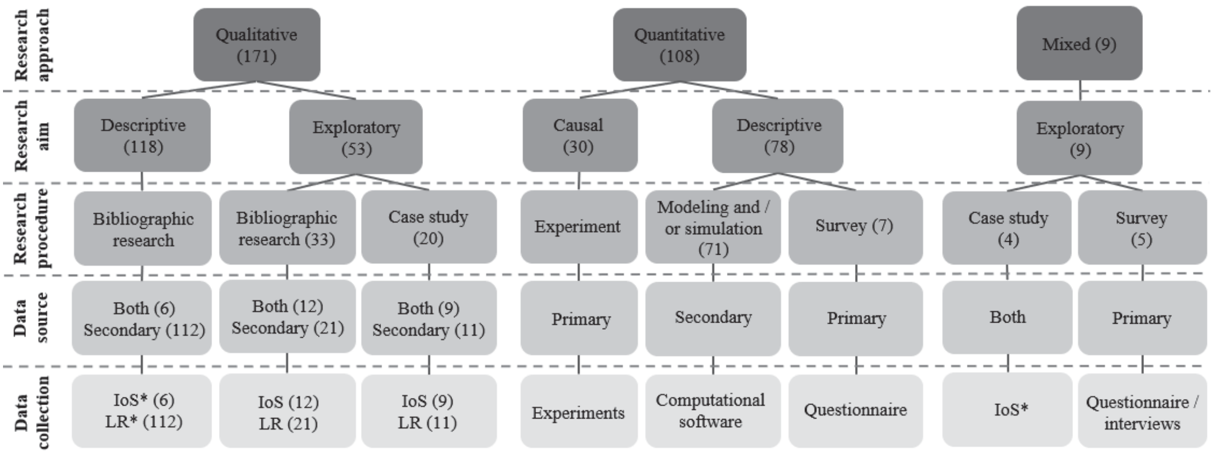
Figure 3. Processing the review in the scientific literature (review date: February 2020).

4 Results and analysis

The analysis of the results was divided into three sections: i) a bibliometric analysis, ii) an ecodesign methods analysis, and iii) a categorized analysis.

4.1 Bibliometric analysis

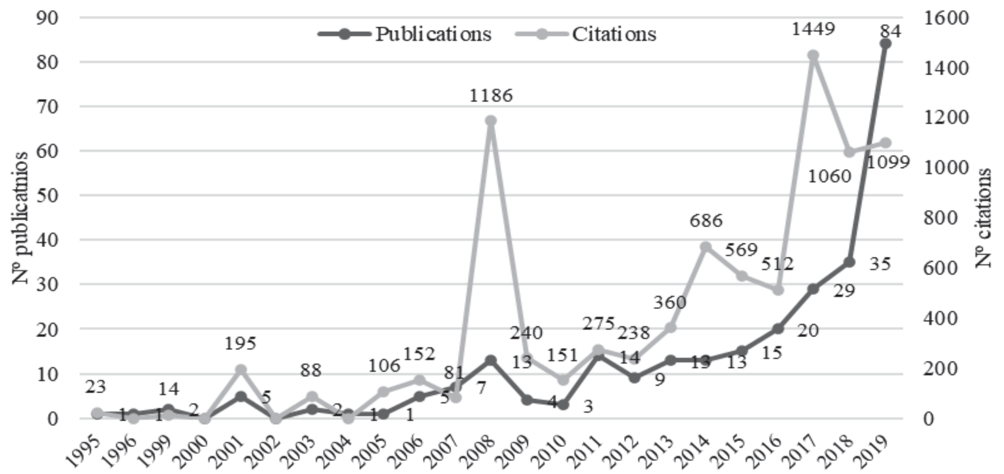
Figure 4 shows the research methodological approach of the studies. The publications were classified according to the research approach, research aim, the procedure adopted, data source, and data collection (Malhotra, 2012). The articles presented a majority qualitative approach (59% of articles), followed by quantitative (38%), and a mixed approach (3%). The predominance of the research aim was descriptive (68%), followed by exploratory (22%), and causal type (10%). Bibliographic research was the most adopted technique (52%), followed by modeling and/or simulation (25%), experiments (10%), case studies (8%), and surveys (4%). Literature review (50%) was the most representative type of data collection. The predominance of descriptive qualitative studies shows the sector's tendency to describe and correlate aspects of deconstruction practices in buildings, in line with exploratory studies, which aim to provide greater familiarity with the problem and make it more explicit for the community of interest.



*IoS= Interview and other sources
*LR= Literature review

Figure 4. Research methodological procedure (number of articles = 288).

Figure 5 shows the evolution of the number of publications and citations. The DfD concept emerged in the 90s (Kibert, 2003) and the first publication reiterates the need to leverage the existing stock of vacant commercial buildings into new housing as an effort toward more sustainable urban development (Barlow and Gann, 1995). After 2010, the increase in publications remained constant over the years, a point that corroborates the developments in CE linked to the institution of the first circular law in China (Munaro et al., 2020). The highest number of publications in 2019 considers the publication of the proceeding's papers of the final event of BAMB-CIRCPATH: A Pathway for a Circular Future. The last four years account for 61% of the research, indicating the interest in the adoption of ecodesign practices in the sector. Citations showed an increasing trend over the years, with a peak in 2008 due to the article by Osmani et al. (2008), which is the most cited in the review and investigates the role of architects in minimizing the generation of construction waste in the design phase.



*The articles published in 2020 are not represented. **Total citations were obtained on November 30, 2021.

Figure 5. Total publications and citations by year.

The studies are distributed in 86 journals (59%, 170 articles) and 62 proceedings papers (41%, 118 articles), emphasizing the extension and decentralization of the subject. Most of the scientific journals have environmental issues and CE as a focus of interest. The two most representative journals were the Journal of Cleaner Production and Resources, Conservation & Recycling. As for the proceedings paper, the highlight was the IOP Conference Series: Earth and Environmental Science with 42 publications (15%), because of the publications of the studies of the final BAMB-CIRCPATH conference.

Figure 6 shows the geographical distribution of the publications according to the first author's country. Europe accounted for 64% of the research covering 24 countries, followed by North America and Asia with 14% each. These regions accounted for 90% of the review studies. Among the 41 countries, the United Kingdom (UK) is the leading in volume (48 articles) of the publications, followed by the United States of America (25 articles), Germany (23 articles), and Italy (21 articles). The predominance of England studies is related to the adoption of public policies and regulatory support (Ajayi et al., 2017). Large countries in terms of geographical area and economy, such as Brazil, India, and Russia, still have no relevance in the subject.

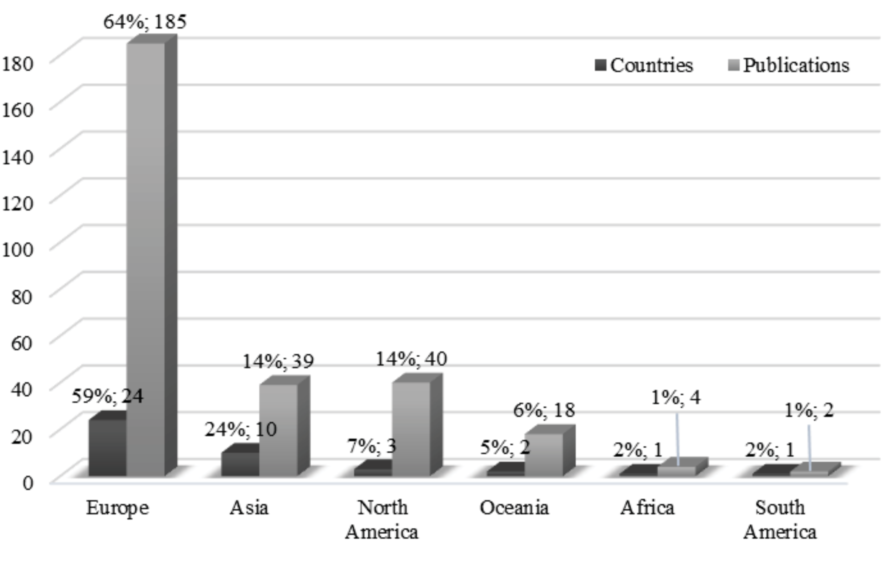


Figure 6. Geographic distribution of publications (number of articles = 288).

The most frequent keywords in publications are listed in Table 1. The keywords were grouped according to the similarities of the meanings of the expressions. Design for Disassembly/Deconstruction leads the number of occurrences, followed by the group of expressions on sustainability, and CDW, demonstrating that the research is strongly related to these two themes. Terms such as Life Cycle Assessment (LCA), BIM, and adaptive reuse indicate the growing attention and the importance of these themes to introduce CE actions in the sector.

Table 1. Frequent keywords identified in the review.

Keywords	Occurrence
design for disassembly/deconstruction / DfD or disassembly, demountable	68
sustainability or sustainable building/construction/design	63
demolition / construction & demolition waste / C&DW / construction waste / waste reduction/management/minimization/avoidance	55
circular economy / CE	50
reuse or material/building/product reuse	51
deconstruction or building/planning/programming deconstruction	42
life cycle assessment / LCA / life cycle costs / LCC / lifecycle building/thinking	39
recycling / recycle / reuse & recycling	32
adaptive reuse / adaptive building reuse or adaptability / design for adaptability	32
bolted joints or connections or shear connectors	22
building information modeling / BIM	20
concrete structure/component/connection or precast concrete	15
timber or wood building/structure	13
end-of-life / end-of-life stage/scenario	13
composite beam/structure/system	10
steel or steel structure/component	9

4.2 Ecodesign methods analysis

The review studies presented different expressions of ecodesign to relate to the subject of deconstruction building at the design stage, as shown in Table 2.

Table 2. Main ecodesign terms, and definitions in the construction literature.

Ecodesign term	Definition	References
Adaptive reuse	It is the process of reusing an obsolete and derelict building by changing its function, meeting current standards, and maximizing the reuse and retention of existing materials and structures	Sanchez et al., 2019; Vardopulos, 2019
Deployable design	Deployable structures are designed to be transportable, adaptable, flexible, easy to mount, and quick to manufacture with modular elements	Brancart et al., 2017
Design for Adaptability (DfA)	A design characteristic that embodies spatial, structural, and service strategies which allow malleability of the structures as a response to accommodate change throughout time	Schmidt et al., 2010
Design for Flexibility	A building that can accommodate changes or allow rearrangement of its internal fit-out and arrangement to suit the changing needs of occupants for a long period	Gosling et al. 2008; Sadafi et al., 2014
Design for Durability	A method to ensure that a building can withstand various conditions that it will be exposed to overtime	Macozoma, 2002
Design for Change	It fosters future transformations and allows buildings to be refurbished and adapted effectively to meet changing users' demands	Brancart et al., 2017
Design for Deconstruction	Aims to maximize flexibility and ensure deconstruction for reusing and recycling of building components at the end of a building's useful life	Kibert, 2003; Shami, 2006
Design for Disassembly (DfD)	A method to design a building/product to enable the disassembly of building/components and reuse/recycling of its parts. The components need to be assembled in a sequence planning suitable for maintenance and reconfiguration of their variable parts	Crowther, 1999; Thormak, 2001
Design for Adaptability and Disassembly (DfAD)	Approach oriented towards lifetime extension. The building components can be disassembled to be repaired/reused, recycling, and replaced whenever necessary, and the layout of the building can be adjusted/adapted by the users whenever new requirements arise	Webster, 2007; Anastasiades et al., 2020
Design for Dismantling	The process of dismantling building components in the reverse order as to how they are constructed based on the end-customers needs, thus engaging them in the early decision making	Dantata et al., 2005; Elmaraghy et al., 2018
Design for	The method is associated with Industrial, Flexible, and Dismountable systems	Sadafi et al., 2014

Demountability	(IFD), where the disassembly of components allows the separate replacement of components with different useful lives	
Modular building	Modular construction entails applying modules that are manufactured in a precast plant before shipment to construction sites. The method avoids unnecessary demolition and allows modules multiple cycles of use	Li et al., 2018
IFD	It is a construction method for creating flexible housing based on mass production, demountable connections, and easy adaptation of buildings	Geraedts, 2011
Design for Recycling	A method to achieve the ideal reuse of building materials and construction elements. It can be divided into Design for Adaptability, Design for Deconstruction, Design for Dismantling	Dorsthorst and Kowalczyk, 2002
Design for Reuse	The reclaimed building components and materials can be used again, repaired, remanufactured, or recycled and includes facilities for anticipating deconstruction	WRAP, 2016
Design out waste	A concept where waste is an opportunity to be transformed into a new resource. It considers the entire building useful life and privileges strategies and construction methods that extend the useful life of materials	Bilal et al., 2015; Mangialardo and Micelli, 2017
Circular building	It is a building that is designed, planned, built, operated, maintained, and deconstructed consistently with CE principles. Considers the associated dynamics of processes, materials, and stakeholders that accommodate circular flows of resources and materials	Geldermans et al., 2019
Reversible building	A method that systematically plans the decommissioning phase of the building elements, which facilitates transformation in building function and structure	Klinge et al., 2019; Wang et al., 2019

Adaptive reuse, Deployable design, Design for Adaptability, for Flexibility, for Durability, and for Change were terms used in studies that addressed the changing needs of users and external factors throughout the life cycle of buildings. Adaptive reuse is intrinsically linked to urban mining, retrofit activities, and the reuse of historic buildings linked to the needs of the local population (Sanchez et al., 2019). Deployability allows the opening or closing of a structure to transform it from a compact configuration to an expanded one, which allows the development of the design for change where a building system can be adapted with a minimum of intervention, giving the user the control to perform changes (Brancart et al., 2017). Design for Adaptability (DfA) was a recurring term because of increases in the capacity for change of the buildings over time (Schmidt et al., 2010). It is an opportunity to explore new design potentialities and to develop new materials and construction methods to address changing climate strategies (Boeri et al., 2016). Building technologies and designs that enable adaptability have also been identified with flexibility, as Design for Flexibility. But it is important to note that the terms 'durability' and 'adaptability' are closely related, and both aspects need to be considered and balanced (Pinder et al., 2017; ISO, 2020).

There is little agreement in the literature between the concepts of ‘adaptability’ and ‘flexibility’. To Gosling et al. (2008) flexibility is a proactive attribute to change or react with little penalty in time, effort, cost, or performance. To Geldermans et al. (2019) flexibility is the capacity to attend to the changing needs of users while reorganizing the infill components of the structure. Gijsbers and Lichtenberg (2014) reiterated that flexibility is the way to design a building for multipurpose and adaptability to the capacity of a building to have continuous physical changes. To Sadafi et al. (2014) flexibility refers to the adaptability of buildings' features to the needs of its users, and adaptability is the ability to change the construction to accommodate both the physical and the user's changes. For the authors, designing for flexibility can guarantee adaptive use and the dismantling of the materials and components for reuse or recycling. Thus, it is necessary to design for durability and for recycling to achieve a flexible design. Macozoma (2002) reiterated that a balance between durability and adaptability is called flexibility. Many authors consider that adaptability is not the same as flexibility, which has more to do with rapid changes to meet the functional needs or variety of space states, but it can be part of the general adaptive capacity of a building (Heidrich et al., 2017; Rockow et al., 2019).

Design for Deconstruction was found with definitions like the design for disassembly and dismantling. To Kibert (2003), the concept aims to close the cycle of building materials by including principles that allow their deconstruction. Kanters (2018) considers that it facilitates adaptation, renovation, and reuse of building materials and components. The method opens a new vision of design with the EOL in mind (Charef et al., 2019), and has environmental benefits, preserving the embodied energy, reducing carbon emissions, a social benefit for creating jobs, and economic benefits. To Leso et al. (2018) DfD has the potential to improve CDW management and reduce the environmental impact of a building.

Design for Disassembly was the most frequent term found in the review. The concept is an important strategy to conserve raw materials (Durmisevic and Yeang, 2009), increase building material reusability (Ong et al., 2013), and in the adaptive reuse process of the buildings (Sanchez and Haas, 2018). Pongiglione et al. (2017) consider the building as a kit of components that needs planning upfront in all its assembly and disassembly steps. Moreover, different terminologies have been noted with regards to 'selective deconstruction', 'demountable building', and 'circular building'.

An emerging strategy that incorporates the principles of design wherein building components should be easy to disassemble and adapt with changing constraints is the Design for Adaptability and Disassembly (DfAD). The application of these strategies should increase the probability that the building's useful life will be extended, allowing its components, parts, and materials to be reused or recycled (Webster, 2007). The Canadian Standards Association used the DfAD to reduce the environmental footprint of the building industry (Clapham et al., 2008).

The expressions Design for Dismantling, Design for Demountability, modular building, and Industrial, Flexible, and Demountable building system (IFD) were used in studies related to the trend in the development of the industrialization of buildings. Design for Dismantling or selective deconstruction (Dantata et al., 2005) was a term associated with deconstruction processes in alignment with the lean principles (Elmaraghy et al., 2018). Likewise, the term Design for Demountability was considered an extension of the IFD system that allows simple adaptation of buildings through the replacement of components extending the life of the building (Sadafi et al., 2014). The focus of this set of terms is standardization and modularization in designs that are directly related to early decision making and appropriate compatibility focused on planning and coordinating construction projects (Jaillon and Poon, 2010).

To incorporate waste minimization into the design stage, the literature has shown efforts related to Design for Recycling (DfR), Design for Reuse, and Design out waste. Dorsthorst and Kowalczyk (2002) considered DfR according to three different levels of reuse: construction, element, or material reuse. Bilal et al. (2015) considered design out waste as a non-trivial concept that offers opportunities for preventing CDW. They developed a plan with multiple strategies of design, like the design for reuse and recovery, resource optimization, off-site construction, resource-efficient procurement, and design for future. Baldwin et al. (2009) considered the perspective of prefabrication as a significant opportunity to design out waste. For the Waste and Resources Action Program (WRAP, 2009), Design out waste is an ecodesign method that aims to influence design decisions to reduce construction waste through five strategies: a design for reuse and recovery; design for off-site construction; design for materials optimization; design for waste efficient procurement; and design for deconstruction and flexibility.

The expressions circular building and reversible building adhere to the concepts of CE and Cradle-to-Cradle, emphasizing the closing and coupling of material loops to establish effective and efficient resource flows. DfD was considered a fundamental aspect of the circular construction project where the materials are expected to be shared, maintained, reused, refurbished, and recycled (Kanters, 2018).

It is noted that the different ecodesign terms found in the literature (Table) have similar definitions and common objectives. However, the differentiation in the nomenclature causes a negative perception among stakeholders (Pinder et al., 2017; Rockow et al., 2019), which increases the lack of understanding of ecodesign methods in the construction sector. These issues make it difficult to implement waste management strategies in the design phase of construction and, consequently, all guidelines related to the building deconstruction.

4.3 Categorized studies analysis

The 288 studies were divided into three main categories according to their similarities: (i) Design and planning process; (ii) Buildings' end-of-life; (iii) Circular assessments and strategic values. Subcategories with similar events and incidents are grouped in the main categories. Table 3 indicates the categorization of the publications.

Table 3. Categorization of publications analyzed in the integrative review.

Main category (No; %)	Generic category (No; %)	Subcategory (No)
Design and planning process (107; 37%)	a) Architectural values (3; 1.0%)	Communication, competence, and knowledge (2)
		User perspectives (1)
	b) Assembly/disassembly phase (5; 1.7%)	Planning methods (5)
	c) Construction principles (53; 18.4%)	Deployable structures (5)
		DfD overview (18)
		Functional independence and layering building (4)
		Modular systems (6)
		Open building and IFD system (20)
	d) Materials and connections (46; 16.0%)	Aluminum structures (1)
		Composite structures (7)
		Masonry buildings (2)
		Steel elements (2)
		Steel-concrete structures (29)
		Timber and fiber composites (5)
Buildings' end-of-life (111; 39%)	a) Building stock potential (9; 3.1%)	Material banks (5)
		Urban mining (4)
	b) Construction and building renovation (31; 10.8%)	Adaptive reuse (24)
		Extension/regeneration (7)
	c) Material/resource recovery assessment (32; 11.1%)	Recycling components (2)
		Reuse and recycling analysis (10)
		Reuse components (20)
	d) Selective deconstruction (23; 8.0%)	BIM compliant tools (13)
		Deconstruction automation (2)
		Optimization approach (8)
	e) Waste management (16; 5.6%)	BIM to reduce construction waste (2)
		Codes of practice / legislation (14)
Circular assessments and strategic values (70; 24%)	a) Environmental and cost analysis (29; 10.1%)	GHG emissions / energy consumption (4)
		Lifecycle tools (25)
	b) Pilots and case examples (24; 8.3%)	Circular buildings (21)
		Circular cities (3)
	c) Transition to circular buildings (17; 5.9%)	Barriers and drivers (3)
		Management policies and circular frameworks (14)

4.3.1 Design and planning process

The category with 37% of the studies focused on the design phase of the building's life cycle and was subdivided into four generic categories. The most eco-efficient sustainable strategies for deconstruction are those conceptualized since the beginning of the project, considering the choice of materials, the construction technique, and the needed Information and Communication Technologies (ICTs).

a) Architectural values

The minimization of waste in the design phase leads to rethinking the values and skills of professionals involved in building projects. In the 'communication, competence, and knowledge' subcategory, Ajayi et al. (2016) recognized that proficiency in project tasks, design expertise, and knowledge related to construction are important skills to minimize CDW. While socialization and collaboration with professionals are contextual skills needed to design waste.

The holistic view when designing a building incorporating social aspects must consider specific benefits for end-users. In the 'user perspectives' subcategory, Geldermans et al. (2019) explored the synergistic potential of the criteria of flexibility, circularity, and user capacity for the circulation of material in the building and the user benefits. The authors argue that the replicability of circular concepts depends on user integration for a sustainable transformation.

b) Assembly/disassembly phase

Hübner et al. (2017) discussed strategic and planning methods for deconstruction projects, considering requirements such as time, resource program, and project costs. Feng et al. (2015) stressed the need to increase productivity and automation in the construction industry and developed a robotic system capable of automatically generating assembly plans from computational projects on construction sites. Charef et al. (2019) used BIM to manage the asset's EOL and highlighted economic, political, sociological, and technological barriers regarding the deconstruction phase.

c) Construction principles

In the subcategory 'deployable structures', transformable structures were explored due to the ability to adapt in form or function according to the required changes of users and local circumstances. The subject is supported by the understanding that structures are not designed in a final state (Brancart et al., 2017). Transformable structures are allowed by mechanisms implementable or reconfigurable components (de Temmerman et al., 2012).

An overview of Design for Disassembly was provided in the subcategory 'DfD overview'. The concept called 'design for deconstruction and disassembly' by Kibert (2003) is the key to the transformation capacity of buildings, evaluated in three dimensions: spatial, structural, and material dismantling (Durmisevic and Yeang, 2009). To Akinade et al. (2017) the factors for effective material recovery are related to legislation and policy, design process and competencies, design for material recovery and reuse, and for building flexibility. Kanters (2018) noted a lack of an internationally agreed set of guidelines for deconstruction projects, as well as time and cost constraints. More flexible legislation that tolerates the reusing of construction materials and the description of the environmental and financial benefits can stimulate the demand in the design process. The incorporation of the disassembly stage on the LCA can highlight the environmental advantages, and direct actions to extend the useful life of the buildings (Crowther, 1999).

‘Functional independence and layering building’ subcategory argues that adaptive building means designing a building to allow its hierarchical layers to change, each on its timescale (Brand, 1994; Gosling et al., 2008; Heidrich et al., 2017). By combining the concept of extending the building's useful life cycle and the concept of layers, it can be argued that the cycle of obsolescence of materials returns to the cycle of continuous relevance in buildings (Rockow et al., 2019).

The ‘modular systems’ subcategory encompasses studies wherein the building's flexibility is increased by decomposing it into modules. Industrialization creates new requirements for the design, where not only the performance of the construction is important, but also the needs of the production plan outside the construction site. The reduction and standardization of the interfaces between the modules can reduce the interdependencies between the installation activities (Isaac et al., 2014). Li et al. (2018) highlighted the need to integrate a modular architectural performance to meet occupants' comfort, flexibility, and energy savings requirements. Økland et al. (2017) stressed the punctuality and quality of project delivery and the need to develop more efficient suppliers to meet demand.

The ‘Open building and IFD system’ subcategory explored these two construction systems to achieve quality, flexibility, and sustainability in construction. The Open building design approach covers that the user should have a role in the housing process and includes other related ideas such as distinct levels of intervention in the built environment and that the design process is in constant change (Heidrich et al., 2017). IFD system is a method based on the principles of Open building and is a key to achieving building flexibility (Nijs et al., 2011). Prefabrication is the first degree of the construction sector industrialization (Jaillon and Poon, 2010), thus prefabricated buildings are the reorganization and optimization of resources and the effect of market selection, and improved productivity. Geraedts (2011) established a plan with recommendations for market players to start projects with the IFD system. Nijs et al. (2011) designed a typology of flexible interfaces to standardize connections and create compatibility between construction products. Strategies regarding the reduction of waste should consider the use of by-products, reusing spare parts and components, the design for adaptability and dismantling, and the use of tracking technologies (Minunno et al., 2018). The major challenge is a change in the mindset regarding how buildings are designed, built, and used (Jaillon and Poon, 2014).

Despite the environmental impacts concerning the life cycle of concrete structures, in terms of embedded energy and greenhouse gas (GHG) emissions, the precast elements have positive aspects regarding their disassembly such as the use of dry connections, sizes, and weights for handling and transportation. However, DfD and IFD building systems are not common practices in the building industry (Jaillon and Poon, 2010). Besides, aspects that support the transformation capacity, such as functional decomposition, systematization, element specification, life cycle coordination, and other aspects are still missing and need to be reconsidered (Salama, 2017).

d) Materials and connections

In the 'aluminum structures' subcategory, Mrkonjic (2007) reiterated that the environmental costs and impacts in the production of aluminum compensate due to recyclability, durability, and lightness of the material. The incorporated energy in the materials was also emphasized in the subcategory 'masonry buildings'. Youssef et al. (2019) showed a removable solution in masonry with dry joints, which allows the reusing and recycling of materials.

'Composite structures' subcategory shows that the use of renewable materials stimulates the supply of new raw materials, manufacturing, reuse logistics, and data sharing. Geldermans et al. (2019) explored biodegradable compounds in the construction of walls, but possible damage during disassembly and reassembly can compromise reusing and remanufacturing cycles. Fragiacomo and Lukaszewska (2011) explored the economic advantages of prefabricated timber concrete composite slabs. Dahy (2019) used bio-based materials to produce CO_2 neutral, recyclable, and/or compostable elements.

In the 'steel elements' group, Pongiglione et al. (2017) combined the requirements of resistance and deconstruction with a steel connection model without welding and a higher degree of reuse. The authors emphasized that the flexibility and the total recycling capacity of steel speed up the assembly/disassembly processes and expand the capacity for repair and reuse of metallic structures.

The 'steel-concrete structures' subcategory presented the largest number of publications. Studies on the structural performance of concrete structures with reversible connections were evaluated in a multi-story apartment block (Ong et al., 2013), in a flooring system consisting of pre-cast concrete planks (Eckelman et al., 2018), in the composite shear connector to build composite floors (Sencu et al., 2019), on demountable headed stud shear connectors (Wang et al., 2017). Moradi et al. (2016) investigated that steel fibers in precast concrete slabs can increase the load capacity and ductility of the structures. Wang et al. (2017) proposed a design formula for the shear strength of demountable headed connectors. Xiao et al. (2017) evaluated those connections fabricated of natural aggregate concrete or recycled aggregate concrete demonstrated an easily mechanical removal process.

‘Timber and fiber composites’ subcategory presented wood-based modular construction systems that offered the advantages of prefabrication and opportunities for reducing GHG emissions. Lehmann (2013) explored the cross-laminated timber system for the construction of residential buildings. Campbell (2019) presented suggestions for the assembly of solid wood systems, identifying future markets, and improving the durability of constructions. Klinge et al. (2019) explored wood waste from buildings to promote the life cycle extension of the materials.

4.3.2 Buildings’ end-of-life

The ‘Buildings’ end-of-life’ category represented 39% of the review and was subdivided into five generic categories. Different business opportunities in the end-of-life stage of buildings were explored, avoiding obsolescence, and ensuring the continued use of materials.

a) Building stock potential

The ‘material banks’ subcategory understands buildings as temporary stocks of materials that need to track and communicate stocks and flows of materials for reuse or recycling. The Urban Mining and Recycling unit project is a temporary storage of materials and a laboratory that monitors and evaluates the circular potential of materials through an online platform (Heisel and Rau-Oberhuber, 2020). Cai and Waldmann (2019) proposed a database/bank of materials and components based on BIM to promote the recycling and reusing of materials. Gepts et al. (2019) explored the importance of combining databases to favor the potential for reuse and recycling materials.

In the ‘urban mining’ subcategory, methodological approaches were developed to quantify construction material, stocks, and component and material flow that can be reused. Kootstra et al. (2019) evaluated a roadmap for the reconstruction of Amsterdam considering the flows of materials, resources, and transport movements. Arora et al. (2020) developed a methodology to estimate the potential of urban mining of public housing developments. Based on urban mining of more than 350 building components, recovery time averaged 1 to 12 minutes and an estimated cost of S$0.8 to S$9 per building component, evidencing regulatory requirements for demolition permits can provide sufficient time for urban mining without affecting project schedules (Arora et al., 2021).

b) Construction and building renovation

The renovation and adaptive reuse of underutilized or unused buildings can revitalize localities and communities and obtain sustainable benefits. In the 'adaptive reuse' subcategory, Sanchez et al. (2019) observed a decrease in the environmental impacts and the construction building cost of an adaptive reuse project. Eray et al. (2019) proposed a system to optimize the building reuse process by helping to manage documents, communications, and relationships between stakeholders. Hsu and Juan (2016) developed a model with an accuracy of 89% in predicting the best type of project reuse. Chen et al. (2018) revealed that changes in economic, social, and natural factors influenced the order of priority of alternative buildings to reuse. Vardopoulos (2019) identified that land conservation, cultural heritage protection, community action, and involvement empowerment are critical factors in the development of reuse projects.

In the 'extension/regeneration' subcategory, guidelines for zero energy buildings are explored. Boeri et al. (2016) adopted a methodology to assess the environmental impacts of reform projects. Paduart et al. (2008) formulate technical principles for the use of adaptable and reusable components. Giorgi et al. (2019) identified improvements in policies, strategic partnerships, and tools for assessing the environmental and economic life cycle to support the regeneration of the building stock.

c) Material/resource recovery assessment

Most publications prioritize reusing secondary materials instead of recycling. In the subcategory 'recycling components' Nußholz et al. (2019), compared companies that produced building materials with secondary inputs to estimate the carbon savings potential.

In the subcategory 'reuse components', Brütting et al. (2019) presented a reduction of up to 63% in the environmental impact of reused structural truss components. Höglmeier et al. (2013) found that 25% of the wood incorporated in buildings is suitable for reuse in new projects and that 21% can be used for other secondary applications. Zaman et al. (2018) analyzed those great quantities of recovery materials had great potential in saving energy, reducing carbon emissions, and creating new businesses and jobs. Van den Berg et al. (2020) concluded that an element will be recovered when an economic demand is identified; there are routines to dismantle it, and performance control until integration into a new building.

In the 'reuse and recycling analysis' subcategory Gorgolewski (2006) analyzed the issues for increasing steel recycling and reuse. Sansom and Avery (2014) estimated that 91% of steel construction products are recycled in the UK. Akanbi et al. (2018) develop a BIM-based Whole-life Performance Estimator to assess the recovery performance of building components.

d) Selective deconstruction

The subcategory 'BIM compliant' analyses the compatibility of methods for deconstruction using BIM. Sanchez et al. (2019) described a semi-automated deconstruction programming with quantitative analysis. Akinade et al. (2015) developed the BIM-based Deconstructability Assessment Score. Akanbi et al. (2019) settled an integrated disassembly system possible to create performance analyzes throughout the building's life cycle. Akbarnezhad et al. (2014) analyzed factors such as energy incorporation of materials, distances covered, energy use, and cost associated with recycling processes to obtain sustainable deconstruction strategies.

Systematic deconstruction is a promising field for the application of automated and robotic technologies to improve the productivity of resources, labor, and urban mining. In the subcategory 'deconstruction automation' Volk et al. (2018) developed a mobile sensor system combined with software for the acquisition of construction information, reconstruction, object detection, generation of construction inventory, and optimized project planning.

The subcategory 'optimization approach' presents plans for selective disassembly projects. The analysis of physical, environmental, and economic aspects of the deconstruction methods is important to assess different plans for dismantling a structure (Aidonis, 2019; Sanchez et al., 2020). Queheille et al. (2019), suggested an algorithm to integrate options of equipment's use, services, and waste treatment to assess the interrelationships between deconstruction plans. The economic issue is still a major challenge in selective deconstructions. Deconstruction costs can be 17 to 25% higher than demolition, due to the cost of labor, disposal costs, and resale value of deconstructed materials (Dantata et al., 2005).

e) Waste management

In the ‘BIM to reduce construction waste’ subcategory, Bilal et al. (2016) presented an architecture based on Big Data, supported by BIM, for analysis of CDW in the design stage of a building. In the ‘codes of practice/legislation’ subcategory, Osmani et al. (2008) revealed that CDW management is not a priority in the design process and that restrictions such as customers' lack of interest; perception to waste minimization; and training, act as a disincentive to the implementation of waste reduction strategies. Llatas and Osmani (2016) developed a waste reduction model, considering the causes of waste, the design strategies adopted and the potential quantified reduction levels. The mitigation of waste can be improved by a collaborative delivery process, with the early involvement of contractors and the proper coordination of the project between the areas involved (Ajayi and Oyedele, 2018). Attitudes changing and dynamic interaction between stakeholders can reduce CDW by at least 50% (Ding et al., 2016). Ajayi et al. (2017) highlighted the need for standardization and dimensional coordination, renewal of construction methods, component flexibility, and the use of BIM for waste efficient projects.

4.3.3 Circular assessments and strategic values

The third category represented 24% of the publications and sought to promote the circular vision in the construction sector, highlighting principles of CE and strategic tools for efficient choices of materials, components, and services that support a closed life cycle.

a) Environmental and cost analysis

In the 'GHG emissions/energy consumption' subcategory the reduction in GHG emissions and energy spending was analyzed using a building classification system by Aye and Hes (2012), and in the recovery of wooden structures by Diyamandoglu and Fortuna (2015). Tingley and Davidson (2011) described the importance of a life cycle approach to materials from the perspective of minimizing the carbon incorporated.

The ‘Lifecycle tools’ subcategory connected deconstruction methodologies with an economic and environmental assessment of the materials' life cycle. A demountable floor system (Brambilla et al., 2019), and reusable walls (Buyle et al., 2019) have more environmental and economic benefits than conventional systems, even with greater initial environmental impact. However, the high energy incorporated in the steel wall system is only compensated by high rates of reuse (Rios et al., 2019). Cost forecasting models for deconstructing buildings and reusing materials have been developed to support decision-makers, using techniques based on artificial intelligence (Tatiya et al., 2018), life cycle cost and environmental issues (Vares et al., 2020), and a multidisciplinary approach involving economic and real estate assessments (Fregonara et al., 2017). Wang et al. (2019) developed a model to assess the main value factor of flexible design that translates to higher market value.

b) Pilots and case examples

In the ‘Circular buildings’ subcategory, examples of circular actions incorporated in buildings were explored. Maerckx et al. (2019) presented a public project that encourages projects to reuse materials and better manage human and material resources. Bertino et al. (2019) presented the HOUSEFUL project to demonstrate circular strategies with a focus on the optimal management of resources. Deployable designs, based on light and flexible structures have been explored in temporary projects, such as the Serpentine Gallery Pavillion in London (Bishop and Eng, 2011). In contrast to current technologies and materials, traditional Korean architecture has been explored as an example of adopting flexible and demountable structures (Sung-Hwa and Beisi, 2012). In the ‘circular cities’ subcategory, Gravagnuolo et al. (2019) reviewed CE actions in cities and highlighted political-strategic areas as the cultural heritage, energy, and mobility to implement circular cities.

c) Transition to circular buildings

The ‘barriers and drivers’ subcategory presented the challenges and opportunities in deconstruction activities. Adams et al. (2017) stressed the lack of information about circular principles, the absence of incentives to design demountable buildings and the need for an economic plan supported by metrics and tools. Akinade et al. (2019) mentioned the lack of legislation and policies, information in the design phase, the market for secondary materials, difficulty in developing business models for deconstruction, and effective tools. Besides, Rios et al. (2015) reiterated the negative perception of the consumer regarding reusing materials, the time, and the cost of deconstruction.

The subcategory 'management policies and frameworks' emphasized the development of projects that meet circular requirements. Pomponi and Moncaster (2017) highlighted the importance of interdisciplinary research and both individual and collective initiatives to promote economic models and implement circularity. Leising et al. (2018) developed a collaborative tool to support and operate circular buildings. Clapham et al. (2008) described the development of a Canadian National Standard for building disassembly and adaptability. Rahla et al. (2019) emphasized the complexity of buildings, data collection, and management, and the use of obsolete and arbitrary indicators in the development of metrics to quantify circularity.

5 Discussion

The discussion of the review results was presented in two sections: i) the ecodesign methods discussion, and ii) the categorized studies discussion.

5.1 Ecodesign methods discussion

The variation of DfX expressions in the sector occurred due to the use of synonymous words, the lack of standardization, and different interpretations of the terms. A plausible reason for the variation is the adoption of DfX methodologies from the consumer goods industry. In Task Group 39 of CIB, Macozoma (2002) argued that technologies from industrial manufacture were adopted for application in construction. Design for Deconstruction is an emerging concept that borrows from the fields of design for disassembly, remanufacturing, and recycling in the consumer products industries (Guy and Shell, 2002).

When considering the different ecodesign terms found, even if most publications have adopted the terms Design for Disassembly/Deconstruction, the meaning of ecodesign methodologies has not yet reached consensus in the scientific community. The language used by professionals and their interpretations of concepts and terms can be a barrier to the development of demountable and adaptable buildings. It is important to clarify and develop methods that can favor a clearer articulation of the clients' needs regarding building ecodesign methodologies.

To elucidate the meaning of ecodesign methodologies, the terminology of the terms was evaluated. Terms like deconstruction, disassembly, demountable, and dismantling have been found in publications with similar meanings. Deconstruction was referred to as selective dismantling (Dantata, 2005), an alternative to demolition (Kibert, 2003), and the reverse of construction (Shami, 2006). Disassembly is defined as the deconstruction of the building, the reversal of the construction process (Crowther, 1999). Demountable systems are capable of major reconfiguration to be dismantled without damage (Sadafi et al., 2014).

According to the Merriam-Webster dictionary, deconstruct and disassemble means to take apart or examine something; demount means remove from a mounted position, disassemble; and dismantle disconnect the pieces. It is perceived that the meanings of these expressions are synonyms, thus, when expanding them to DfX methodologies, the terms are shown in Table, Design for Deconstruction, Design for Disassembly, Design for Dismantling, and Design for Demountable have the same meaning in the construction context.

The terms Design for Recycling, Design for Reuse, and Design out waste, also defined in Table, both consider the reduction of CDW in the design phase. This means that the building components, parts, and materials must be planned for deconstruction, reuse, or recycling, considering the useful life of each material. Dorsthorst and Kowalczyk (2002) establish the DfR as a combination of methodologies to minimize CDW on different layers of the building. Mangialardo and Micelli (2017) considered that the principles of designing buildings in different layers should consider designing out waste, design for adaptability, and disassembly. Therefore, these methods have the same practical significance as the other methodologies related to the term deconstruction, as seen above.

Researchers suggest that the DfR combined with the Design for Durability is a condition to achieve flexibility in the buildings (Sadafi et al., 2014). Flexibility can also be achieved when designing for adaptability (Schmidt et al., 2010; Gijsbers and Lichtenberg, 2014). DfA or flexibility is an important strategy that allows changes in the buildings to accommodate the needs of users. Despite being common terms in the literature, there is still no agreement on the meanings of the words in the building context. These words are associated with the durability and recyclability of building materials. Some authors used the words as synonyms, others distinguish them in conflicting ways, linking flexibility as a characteristic of adaptability and vice versa. Schmidt et al. (2010) reviewed the definitions of adaptability and subdivided the concept into six strategies (available, extendable, flexible, refitable, moveable, and recyclable) that relate to the type and frequency of changes that occur in buildings. Pinder et al. (2017) concluded that adaptability meant different things to different people, as a reflection of conventions, practices, and priorities in the sectors. Despite the lack of consensus, the word adaptability was most used than flexibility in the review, and the definition by Schmidt et al. (2010) was adopted (Table).

Likewise, the terms adaptive reuse, deployable design, and Design for Change relate to a range of building adaptation activities that improve existing conditions and extend the useful life of buildings. By introducing transformative capability at different design levels through DfA, the sustainability of structures and components over time will be maximized and the waste of resources will be minimized.

It is possible to consider that the different ecodesign terms found in the review can be grouped into two main parts of the circular design: Design for Disassembly (DfD), which encompasses design for deconstruction, dismantling, demountable, recycling, reuse, and design out waste; and Design for Adaptability (DfA), which covers design for flexibility, durability, change, deployability, and adaptive reuse. It is worth mentioning that although the term Design for Disassembly has origins in the consumer goods industry, it is the most widely used term among authors in the sector, and for this reason, it was adopted in this review as a standard term, instead of Design for Deconstruction.

It is observed that the terms reversible (or circular) building design can be interchangeable with DfAD. Although, the authors believe that the term 'circular building' is a broad concept, and in addition to considering ecodesign methodologies, such as DfAD, it should consider other aspects capable of turning buildings into a bank of materials. Thus, in addition to a reversible design, the use of BIM in project management and coordination, the use of a materials passport to ensure the traceability and retention of the value of materials and components (Munaro and Tavares, 2021), and the use of circular business models should be considered guided by the principles of social, environmental, and economic sustainability. Thus, DfAD is one of the requirements capable of incorporating the full potential of the CE principles in the sector.

5.2 Categorized studies discussion

The categorization of the studies shown in Table 8 identified the concentration of the studies in three main stages of the life cycle of buildings. The 'Design and planning process' category concentrated on studies focused on the building design and construction phase. 'Buildings' end-of-life' underlined the buildings' deconstruction in the EOL stage. 'Assessments and strategic values' category presented both EOL studies and a more general context aimed at building a more circular vision in the sector.

In the 'Design and planning process' category, the predominance of studies was in steel-concrete structures and precast concrete elements. The use of prefabricated components and materials, modular design, and mechanical joints are the most explored construction principles in the context of DfD. Although modular and prefabricated buildings show DfD principles, they are not fully related to the methodology, as they are planned for easy transport, handling, and assembly, but not necessarily to be demountable and reused at the end-of-life. Few efforts have been noticed with the use of wood and other types of materials. Strategies must be implemented by using cleaner, more environmentally friendlier, and higher resource-efficient materials.

The design is the most important phase in waste reduction (Osmani et al., 2008). Architects and designers need the necessary knowledge and skills to obtain a systemic view of the design for a deconstructable and adaptable building. It is important to mobilize the professionals involved at the base of the projects to take the lead as drivers of change. The limited designed DfAD buildings reaffirm the sector's delay in the necessary changes towards circularity. Current legislation needs to impose efficient guidelines at the design stage to minimize CDW.

The coordination of the design process through BIM was emphasized in the review. BIM is seen as one of the main tools for the prevention of waste, the compatibility of projects, the provision of information, and the collaborative process. Plans and schedules, such as the assembly and disassembly plan, and the documentation of the construction materials and components for reuse is potentially facilitated by BIM. However, none of the existing BIM products yet offers waste forecasting and minimization functionality. Efforts to better explore construction modeling and barriers such as the lack of BIM knowledge by the professionals, the lack of compatibility with other software, or even the lack of storage capacity and compatibility of the models, need to be explored.

New business opportunities can be created in the design phase to make the reuse of materials more attractive. For example, indicating options for potential reuse; providing suggestions from companies or professionals in charge of the restoration, repair, or recycling of building materials; fund the demolition of structures, among others. These strategies can minimize the vision that deconstruction is not attractive in terms of cost and time and increase the viability of the secondary materials markets. Public policies should encourage the construction sector to develop technologies and materials recovery capabilities, promoting networks of partners to access secondary materials.

It is interesting to enlarge the participation of the end-user in the design process because they have a great responsibility for the sustainability of the built environment. Open building practices and greater integration would facilitate the understanding of circular design, a more conscious use/consumption of buildings, and the replicability of DfAD concepts. Also, it could improve the general perception of reused materials. According to Rios et al. (2015), they are seen as an inferior quality to virgin materials, both aesthetically and for safety reasons.

The 'buildings' end-of-life' category emphasized the focus on reusing construction materials and components, the adaptive reuse of buildings, and deconstruction methodologies. However, there is a lack of critical analysis of the possible effects that reuse, and recycling can have on the complete life cycle of the buildings. The reuse of building materials must overcome challenges related to insurance, warranty, quality, and performance of materials. To enable high rates of material reuse and recycling, it is important the knowledge of the composition of building materials. Designers and manufacturers should review products to make them more reusable or suitable for recycling. New roles can be created to support the design team and further integrate value chains in product creation.

Most studies focused on the reuse of steel components, as they are easier to deconstruct and reuse, than concrete and masonry structures. Besides, the reuse of other types of components is more complex due to the lack of data about material performance. The use of identification and research technologies considering aspects of contamination or effects of aging of concrete, which can lead to deterioration and reduced useful life of structural elements, must be considered. Likewise, a classification system is necessary to facilitate the standardization of recovered products according to their performance and the best type of reuse.

Storage space for recovered materials will also have a major impact on the cost and schedule of the project. Building contracts and tenders must be adapted to incorporate the EOL phase, making clear the responsibilities of each stakeholder. Reverse logistics policies can be an instrument for applying shared responsibility for the life cycle of products. It is important the regulate the management and distribution of EOL materials by creating markets and information exchange services for recovered products. For example, adaptive reuse of buildings is a subject that is gaining interest in the sector. However, economic barriers and technical difficulties, such as the lack of reliability of the reused materials and the underestimation of the resources incorporated in the building make it difficult to adopt this technique.

Selective deconstruction is still a limited practice in the sector. A great effort is observed in using BIM for the disassembly process. However, the digitization of the sector is in the initial stages, and further research needs to deepen the method of recovering the disassembly data from the BIM model efficiently and automatically. Likewise, investigations of deconstruction protocols are needed, incorporating the rates and costs of labor, deconstruction time, and environmental impact of different strategies for the total or partial dismantling of structures.

The third category corroborates the importance of the life cycle tools to predict and assess the environmental impacts of different EOL scenarios. However, there are challenges related to the lack of data and information for the construction, maintenance, retrofit, and reuse/recycling phase of the materials. The different methodologies to predict the environmental impact of material could be more standardized. It is necessary to expand the assessment for reused and recycled materials and, to broaden the consensus on the quantification of the environmental impacts and benefits of the reinsertion of secondary materials. Environmental impact calculations can cover different EOL scenarios, such as incorporating components into a new structure, restoring components before reuse, recycling, or discarding parts of the system. The compatibility of LCA tools with BIM still needs to be further explored to allow an independent integration of other software and plug-ins.

6 Conceptualization of an integrative ecodesign strategy

This study proposed the integration of the main ecodesign concepts shown in the review. The integration aims to facilitate the understanding of the methodologies and expand the agreement of terminologies and meanings of ecodesign approaches in the sector. Figure 7 presents the DfAD as the umbrella ecodesign methodology.

The Design for Adaptability and Disassembly (DfAD) methodology is not widespread in the sector, only two studies mentioned this method (Webster, 2007; Anastasiades et al., 2020). The method combines the advantages of DfD and DfA, wherein building components can be disassembled to be replaced and repaired whenever necessary, and the layout of a building can be adjusted when required. It can be considered that among the range of ecodesign methodologies, DfAD synthesizes them in a single concept. Webster (2007) assumes that DfAD will assure superior market value in buildings. To Anastasiades et al. (2020) DfAD acts as an important symbiosis between the micro and mesoscale, aligning the development of construction materials with a focus on adaptable and demountable buildings.

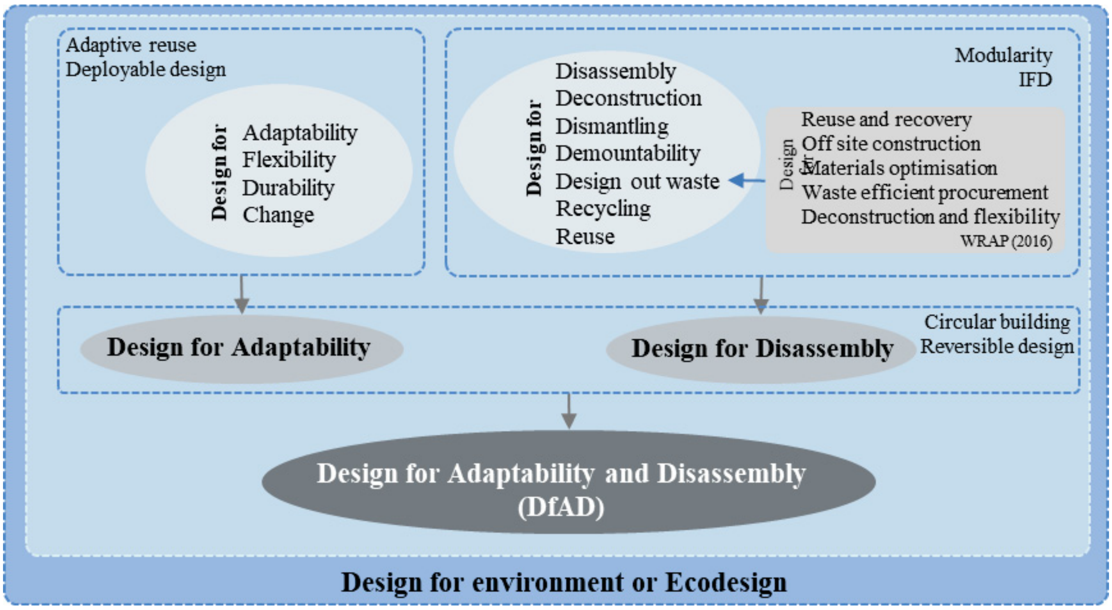


Figure 7. Integration of the ecodesign strategies in the Design for adaptability and deconstruction (DfAD).

From this integration, it is possible to standardize the communication of the principles of CE in the sector through the term DfAD, or by the two separate methods, DfD and DfA. Eased communication makes it possible to increase the awareness and knowledge of stakeholders about the circular principles of deconstruction and adaptability of buildings. Therefore, overcoming the barrier of lack of communication on the DfAD method is crucial for the reduction of CDW and the consumption of virgin materials in the construction sector. It is noteworthy that international standardization requirements such as The Standards Council of Canada (Clapham et al., 2008) and International Organization for Standardization (ISO) 20887 (ISO, 2020) have been adopting the DfAD term as a positive contribution to construction sustainable development.

7 Conceptualization of an integrative DfAD framework in the construction sector

Figure 8 presents a conceptual framework with the categorized studies of the review, related to the stage of the building life cycle. The framework considers that the categorized studies corroborate the unified DfAD methodology, proposed in Figure. This framework is proposed to expand knowledge and the adoption of the DfAD concept in the sector. The approach emphasizes the 12 generic categories of studies, organized into the three major categories of the review, outlined in three building lifecycle stages.

The starting point of the framework is to consider that DfAD understands that all phases of the building life cycle must be planned in the design phase. For best results, the project must be accompanied by a CDW management plan. Therefore, clarifying the CE and deconstruction practices to the stakeholders involved in the design phase is crucial to provide a solid basis for the improvement of building deconstruction strategies and to stimulate the production of secondary materials. The subcategories of the design and construction phase present, in addition to the focus of research on the subject, strategies, and directions to enable the research and development of circular tools suitable to implement the practice of deconstruction in new construction projects.

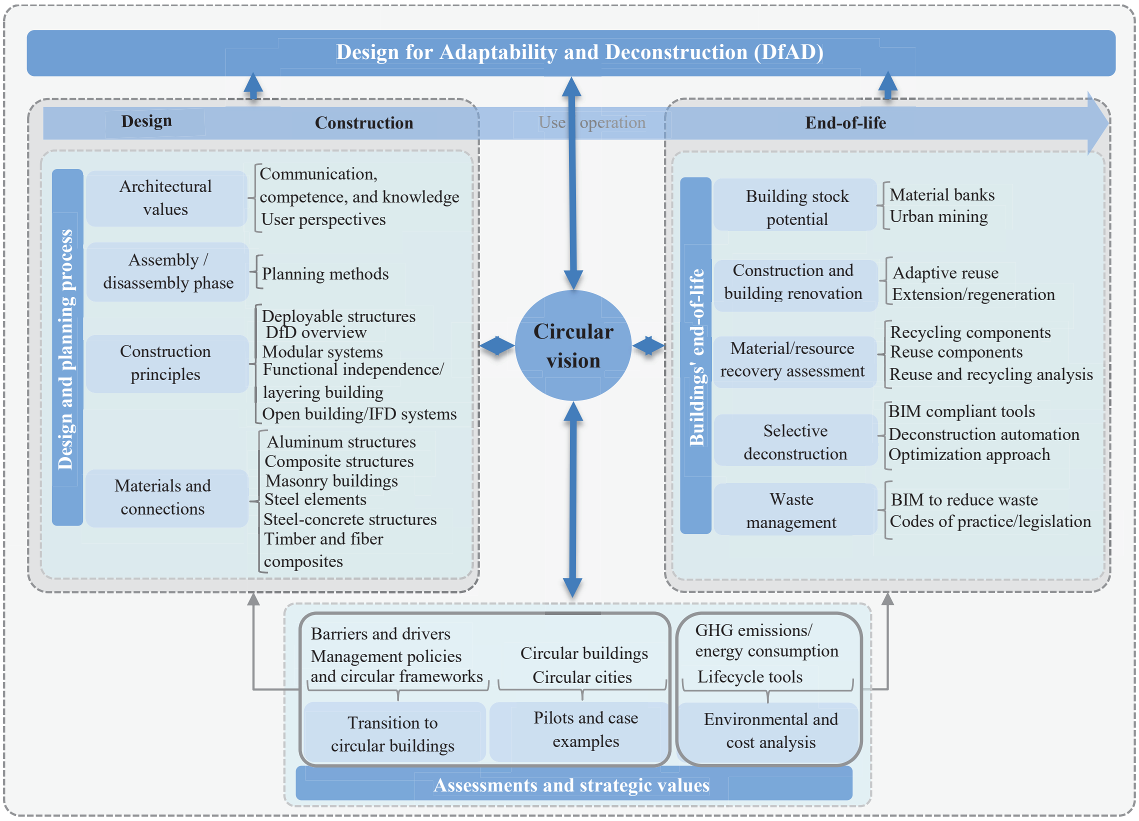


Figure 8. Conceptual framework of categorized studies for the implementation of DfAD in the construction sector throughout the building life cycle.

In the EOL stage, selective renovation or deconstruction gives way to the conventional demolition of buildings. The renovation of buildings is a trend observed in the practices of adaptive use, aiming at seeking energy efficiency and conserving the historical and social values of buildings. Selective deconstruction accompanied by appropriate collection and segregation techniques maximizes efficiency in the recovery of materials and building components and the establishment of secondary material markets. The subcategories indicate areas of activity and research that will promote circular practices to make buildings a bank of materials.

The third category presents tools and examples of applying circular strategies to reinforce the creation of a circular vision in the construction value chains. The aim is to reinforce that the implementation of DfAD can be a strategic policy for the reduction of GHG emissions in the sector, by favoring the reuse and recycling of materials. Besides, the study of practices, programs, and public policies implemented in cities or regions provides guidelines and benchmarking on the deconstruction practices that are working and that need to be improved.

It is also interesting to discuss the different actions needed to increase the useful life of building materials during the 20 – 50 years of the building's life. Two fundamental points need to be considered: the obsolescence of building materials and components and the energy efficiency of buildings. Monitoring the obsolescence of materials is crucial to obtaining an adequate intervention plan and avoiding loss of efficiency, unnecessary renovations, or demolitions. The use of tools such as the materials passport will be necessary to monitor the status of the buildings and the history of the constant maintenance actions of the materials over the time of the building (Munaro and Tavares, 2021).

Maintainability is a crucial factor in preventing physical obsolescence and ensuring an adaptable building. Lack of maintenance is one of the main reasons for the decision to demolish a building (Rockow et al., 2019). In this way, adaptability has a market value mainly in facing the accelerated changes that society faces, such as urbanization, political instability, climate change, and technological transformation (Ross et al., 2016).

Circular economy, material reuse, and open building movement play a key influence in the development of building adaptability (Heidrich et al., 2017). Several modifications can be made to return the building to relevance. According to Ross et al. (2013), the four enablers of adaptability are accurate construction information, the reserve capacity in construction systems, separation of construction systems, and internal spaces free of structures and other elements. Conejos et al. (2013) identified a list of design criteria concerning the adaptation of buildings and a model was created that predicts useful life as a function of physical life and obsolescence and allows the calculation of adaptive reuse potential at any point in the cycle of a building's life.

Both building adaptation and urban mining are linked to climate change strategies. Heidrich et al. (2017) lists different initiatives linked to the adaptability of buildings and reiterate that the adaptation of buildings aims to manage the consequences and reduce the damage that can be caused by climate change. In this sense, mitigation and adaptation efforts are synergistic in achieving energy efficiency in the use/operation phase of buildings. In addition, material reuse-driven urban building mining can contribute to net-zero carbon targets and climate mitigation efforts in the construction sector (Arora et al., 2021).

However, both the development of DfAD buildings in the design phase, as well as adaptation actions in the use/operation phase, as well as selective dismantling, and urban mining efforts at the building's EOL, require greater multi-stakeholder involvement and market push for reuse in the sector. Furthermore, the circular vision creation to allow DfAD needs greater rigor in legislation to support the ecodesign methods. Public policies could guarantee the method's compliance and comprehensiveness throughout the sector. There are no relevant approaches to include DfAD in building codes. The first approach was taken by the Canadian Standards Association (Clapham et al., 2008). Recently, a new International Standard (ISO 20887:2020) was developed considering DfAD principles, requirements, and guidance. The ISO considered adaptability based on three principles: versatility, convertibility, and expandability; and disassembly based on seven principles as simplicity, independence, and standardization. Other methodologies that assess, classify and certify the sustainability of buildings concerning a set of eco-efficiency parameters, such as the Building Research Establishment Environmental Assessment Method (BREEAM) and the Leadership in Energy and Environmental Design (LEED) do not yet establish a score referring to DfAD.

8 Conclusions

The study presented the state-of-the-art of ecodesign methodologies to reach buildings' deconstruction in the construction sector. The main contributions were i) integrating the ecodesign methods to simplify the understanding and implementation of the strategies for allowing building materials reuse and recycling, and ii) a theoretical DfAD framework of the categorized studies in the sector.

Ecodesign methods aimed at buildings deconstruction are not widespread in the sector. The proposed ecodesign methodologies integration was an important strategy for enlarging the understanding and knowledge of the mechanisms of buildings' EOL. The Design for Adaptability and Disassembly (DfAD) was the main mechanism recommended to minimize the generation of waste in construction. Besides, it can create countless opportunities for business in the different building life cycle phases. The practical implications were to propose directions for future research to expand the discussion and development of the ecodesign methods, seeking cleaner productions and more circular constructions.

The categorized studies stressed the importance of modular and prefabricated structures, selective deconstruction, and the use of recovery materials. With the growth of secondary materials markets, urban mining activities, analysis of resource and material flows, and the adaptive use of buildings will be further explored. The digitization of the sector is indispensable to managing and sharing the large volume of data and information on construction materials and components throughout the life cycle of the building.

The proposed theoretical framework outlines the main aspects involved in CE from the perspective of implementing DfAD. This structure considers the main circular strategies found in the literature that make it possible to deconstruct and recover components, parts, and materials at the end of the building's life. This framework can be used as guidance for academics to expand knowledge about the potential applications of the DfAD concept. It can also be used by professionals in the implementation of CE in the construction sector.

The sector's delay to changes, the lack of knowledge and clarification about the different ecodesign methodologies, and the CE principles, are critical barriers. It needs to elucidate the economic, social, and environmental gains of the DfAD to the stakeholders of the construction value chain. It is noticed that the expected paradigm shift in the construction sector will be possible based on top-down and bottom-up mechanisms. Efficient legislation and public policies that promote the reuse and recycling of construction materials and components are required. The joint action of the stakeholders with the government can further promote the CE development, strengthening the supervision and implementation of green buildings, actively implementing circular actions, combined with the necessary incentive measures.

This study has limitations that must be considered. First, the literature review was focused on academic research. There would be an additional need to identify the evolution of the latest industry practices. Secondly, the review based on keywords search limits the results. Besides, although the criteria for article selection were explicit, the selection of articles for review might be subject to researcher biases. Furthermore, the literature sample includes only articles published in English. In future research, it is proposed to raise business opportunities that DfAD can develop for different stakeholders in the construction value chain. Besides, to propose a system of guidelines for the deconstruction of buildings based on different stages of implementation of the ecodesign methods for deconstruction.

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PAPER A6

A review on barriers, drivers, and stakeholders towards the circular economy: the construction sector perspective

MUNARO, Mayara Regina; TAVARES, Sergio Fernando. A review on barriers, drivers, and stakeholders towards the circular economy: the construction sector perspective. (SUBMITTED)

A review on barriers, drivers, and stakeholders towards the circular economy: the construction sector perspective

ABSTRACT

The construction sector is one of the most responsible worldly for resource consumption, waste generation, and greenhouse gas emissions. The transition to a circular production and consumption system is crucial to reducing the impacts of the sector. However, the lack of clarity and understanding of the principles of circular economy (CE) and the complexity of the construction value chain makes it difficult to implement circular principles in the sector. Through an integrative literature review, this study analyzes the barriers, drivers, and stakeholders that influence the implementation of the CE in the sector. The barriers and drivers were classified into five categories (economic, informational, institutional, political, and technological) and the main stakeholders were identified. From the results, the political and technological barriers categories were the most representative, highlighting the need for a governance policy based on regulatory and tax actions, and an integrated waste and information management system. The study's categorical analysis revealed that the lack of CE awareness and communication is the central interrelated agent to promote circular principles in the sector. The sector needs a joint action between government and construction stakeholders to the establishment of public-private partnerships and effective and segmented communication aimed at the circular transition in the sector.

Keywords: Circular economy; buildings; barriers; drivers; stakeholders.

1 Introduction

The world population is projected to reach 8.5 billion in 2030, and to increase further to 9.7 billion in 2050 (UN, 2015). The population growth, coupled with a rising urban middle class, led to an increase in the consumption of resources and the demands and pressures on urban infrastructure and government resources. This scenario is intensified with the issues of climate change and the establishment of the Sustainable Development Goals (SDG), by the United Nations (UN), where countries members have been looking for strategies and policies to achieve sustainable management and efficient use of resources, and reduce the generation of waste through prevention, reduction, recycling, and reuse (UN, 2020).

These issues influence the construction sector, which is responsible for the highest amount of resource use, waste, and emissions of all industries. The sector is the world's largest consumer of raw materials and generates up to 35% of landfill waste (Ajayi et al., 2015). It is responsible for 36% of the end-use of energy and 39% of global carbon dioxide (CO_2) emissions (IEA, 2019). Although more than 90% of a building's content can be reused, only 20-30% of these resources are recycled or reused at the end of a building's useful life (WEF, 2014).

The construction sector has remained a major target for environmental sustainability. A change to circular production and consumption patterns is needed to ensure a resilient sector. Circular economy (CE) offers an opportunity to reduce the use of primary materials and their associated environmental impacts, through different strategies that replace the end-of-life (EOL), such as reduction, reuse, and recycling of materials in the production/distribution processes and consumption (Kirchherr et al., 2017). The adoption of CE is a sustainable and profitable alternative to decouple the growth of primary raw materials and provide socio-economic benefits, including increased gross domestic product and employment opportunities. CE development path in Europe could result in a 32% reduction in primary material consumption by 2030 (EMF, 2015). It is estimated that the market for a CE in the next 10 years will increase economic growth by up to 4% (ING 2015).

There are many different definitions of CE (Kirchher et al., 2017) and there is still no clear and accepted definition in the construction industry (Adams et al., 2017). Thus, CE initiatives seem to be going in different focuses and directions, such as deconstruction design, construction, and demolition waste (CDW) hierarchy, secondary materials markets, building information modeling, urban mining, etc. This fragmented development makes it difficult to adopt CE in the sector (Eberhardt et al., 2020). Besides, the dichotomy between top-down (driven by governance) and bottom-up (social movements and social innovation) approaches in the implementation of CE practices questions the role of different stakeholders responsible for the circular transition of the sector.

The implementation of circularity in buildings also has particularities to the complexities of buildings with several interconnected attributes, such as building design, choice of material, building operation, and maintenance (Eberhardt et al., 2020). Furthermore, the sector is conservative and has its design process, manufacturing techniques, supply chain, and financial arrangements (Hart et al., 2019). Compared to the consumer goods industry, buildings have greater longevity, large capital investments, and a multiplicity of stakeholders throughout the life cycle.

The lack of clarity and understanding of the CE principles and the complexity of the construction value chain makes it difficult to disseminate knowledge and guidelines that support the design and circular construction. There is an obvious need to understand the barriers, drivers, and stakeholders that influence current developments in the construction industry to conceptualize CE more specifically within the context of the sector. The literature already presents some studies on this theme; however, three important issues are observed: (i) most studies are not focused on the construction sector and, therefore, the conclusions cannot always be applied in the sector; (ii) studies are more numerous in the analysis of CE barriers and drivers are often overshadowed; and (iii) the identification of the stakeholder's role in implement CE is still not clear and widespread in the sector.

Based on these limitations, this study aims to answer the question: what are the major barriers and drivers to a circular economy in the construction sector? What is the role of the construction stakeholders in this transition? To answer the research questions an integrative review was realized, sought to (i) analyze the relationships between CE barriers, drivers, and stakeholders in the sector; and (ii) to assess the relevance that the different categories of barriers and drivers have in the transition towards the circularity of the construction sector. Figure 1 shows the organization of the study.

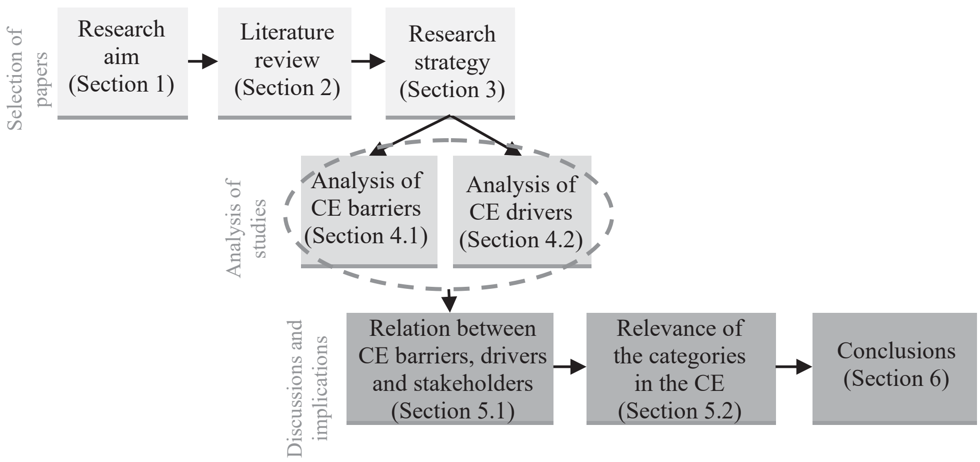

Figure 1. Organization of the study.

2 Theoretical perspectives

Efforts to identify the barriers and drivers related to the circular economy have been made by the research community since the spread of this concept. Research on CE barriers has been conducted at different scales, for example on business models, supply chains, small-medium enterprises (SMEs), regions, and countries. According to Vermunt et al. (2019), the implementation of different circular business models (CBM) must overcome two types of barriers: i) internal, related to financial, organizational, and knowledge pressures within a company; and ii) external, related to supply chain, market, and institutional. The authors found that key challenges were related to the firm's external environment. On the other hand, Guldmann and Huulgaard (2020) showed that barriers to CBM innovation are found at all socio-technical levels by companies: at the organizational level, followed by the value chain, the employee, and, finally, the market and institutional level.

According to Mangla et al. (2018), the application of circular principles in the circular supply chain (CSC) must overcome 16 barriers, mainly the lack of environmental laws and regulations and the lack of fiscal policies to promote CBM. Govindan and Hasanagic (2018) raised 39 barriers and highlighted the barriers external to the organization, such as the consumer perception towards components that are reused; technological limitations by tracking recycled materials; and lack of public awareness. Drivers, on the other hand, were related to the potential for job creation and compliance with laws and policies on waste management and climate change. Masi et al. (2018) highlighted the lack of awareness and a sense of urgency, limited attention to the EOL phase in product design, and high management and planning costs at the company level. Besides, they noted that companies prefer to adopt circular practices that have an economic rather than an environmental focus.

To increase knowledge and the implementation of the CE in SMEs, Rizos et al. (2016) emphasized the lack of a supply and demand network for support, capital, and government funding and that the main facilitators are company environmental culture, networking, and support from the demand network. Gupta and Barua (2018) identified 36 barriers to green innovation in SMEs, highlighting the barriers related to technological and resource, financial and economic, and market and customer. The rank solutions to overcome these barriers are designing effective policies and frameworks by government and policymakers to reduce environmental degradation, developing internal research practices, and focusing on investment recovery to reduce wastage of material. Ormazabal et al. (2018) observed that companies are more concerned with their profits and revealed two types of barriers: i) hard barriers that can be overcome by fiscal incentives and technological modernization, as they are linked to the lack of financial resources, technology, inadequate information systems; ii) and human-based barriers that include issues such as company leadership or the lack of customer interest, highlighting the focus on CE awareness.

Several studies have been conducted to identify barriers to implementing CE at the macro level. de Jesus and Mendonça (2018) classified the barriers to green and sustainable innovation as hard (technical and economic factors) and soft (institutional and social factors). They stressed that hard barriers are crucial, mainly related to technical factors, such as inappropriate technology, the lag between design and diffusion, and lack of technical support and training. Among the enablers, the soft factors category was related to institutional/regulatory, associated with increasing environmental legislation and standards, and waste management directives. On the other hand, Kirchherr et al. (2018) classified cultural barriers as the main barriers to CE in the context of the European Union (EU), especially related to lack of interest and consumer awareness and hesitant company culture. The authors did not report any technological barriers as critical and stated that the CE is still a niche for debate among sustainable development professionals.

In the construction sector, Mahpour (2018) concluded that sorting, transport, and recovery processes on construction and demolition waste management (CDWM) and using finitely recyclable construction materials are the most important barriers. Ajayi et al. (2015) also identified critical factors in the CDWM, such as end-of-line treatment of waste, externality, incompatibility between waste management and design tools, lack of holistic solutions in waste management, and high perceived cost or unexpected waste management, and industry culture. To overcome these barriers, the study suggests design stage implementation; whole life consideration; Building Information Modelling (BIM) compliant solutions; economic strategies; improved legislation and applied research and education.

Campbell-Johnston et al. (2019) examined the barriers to the circular transition of some cities and highlighted the lack of knowledge of appropriate technologies and opportunities for implementation, the low quality of waste streams, the difficulty in addressing these issues on an urban scale, and the linear mentality of actors relevant. To promote sustainable construction, Häkkinen and Belloni (2011) highlighted the development of customer awareness, the increase, and adoption of sustainable methods and tools, and the need for competence and training of the designer team. Adams et al. (2017) concluded that customers, designers, and subcontractors are the least informed about CE. The lack of incentive to design for EOL issues, followed by the lack of market mechanisms to assist further recovery and an unclear financial case are the main barriers in the sector. Bilal et al. (2020) found that the current state of CE implementation in the sector is unsatisfactory. The study highlighted that the lack of environmental regulations and laws and the lack of public awareness and support from public institutions are hampering the implementation of CE.

The focus on CE barriers, with little emphasis on providing strategies to overcome barriers to sustainable innovation, emphasized that comprehensive CE integration and a methodology framework are yet to be developed in the sector (Hossain et al., 2020). The focus of the studies on supply chains and SMEs can underestimate or does not cover issues related to large-scale organizations (Gupta et al., 2020). The identification of the stakeholders involved to overcome the challenges or direct the drivers is not overlooked in the studies.

Besides, the construction sector is still poorly studied for the implementation of circular practices, and the sector's focus is on CDWM (Munaro et al., 2020).

2.1 The categories of CE barriers and drivers

The literature presents different classifications of barriers and drivers for CE implementation. de Jesus and Mendonça (2018) are classified as hard (technical and economic) and soft factors (institutional and social). Guldmann and Huulgaard (2020) grouped the barriers at four levels: market and institutional, value chain, organizational, and employee levels. Kirchherr et al. (2018) adopted four main categories of barriers: cultural, regulatory, market, and technological, and defined that the barrier categories can be considered nested. Hart et al. (2019), adopted cultural, regulatory, financial, and sectoral barriers. Masi et al. (2018) increased another category: financial, institutional, infrastructural, societal, and technological. Ritzén and Sandström (2017) reinforce the classification in five categories, considering the barriers in financial, structural, operational, attitudinal, and technological. Govidan and Hasanagic (2018) proposed different classifications for barriers and drivers, with five clusters for drivers: policy and economy, health, environmental protection, society, and product development; and seven clusters for the barriers: governmental, technological, knowledge and skill, management, CE framework, culture and society, and market.

Despite the lack of a standard categorization, many authors have used similar categorizations in the classification of CE barriers and drivers. In this study, it was first chosen to adopt the same classification for barriers and drivers. Second, it was decided to group some categories listed distinctly in the literature, to cluster related themes and minimize the number of categories. Table 1 presents the classification and definition for the five categories adopted of CE barriers and drivers.

Table 1. Coding and definition of the categories of CE barriers and drivers.

Categories	Themes related	Barriers	Drivers
Economic	Economic / financial / market	Lack of financial aid and subsidies to circular business models	Creation of incentives and circular business models
Informational	Informational / Socio-cultural	Lack of awareness, knowledge, and circular initiatives in society in general	Measures to support research, education, and information
Institutional	Institutional / organizational	Lack of knowledge, integration, and cooperation between stakeholders	Improved stakeholder awareness, integration, and information
Political	Political / regulatory legislative	Lack of government policies, regulatory instruments, and fiscal actions	Establishment of a governance plan
Technological	Technological / operational / management	Lack of technologies and infrastructure	Development of tools and technologies that promote circular buildings

2.2 The stakeholders in the construction sector

The identification of stakeholders related to the barriers and drivers for the CE implementation, whether in the construction sector or other market segments, is essential to achieve more sustainable production and consumption. According to Pomponi and Moncaster (2017), interdisciplinary research is lacking in the built environment for the understanding and application of the CE. Since the stakeholders are individuals or groups that can affect the functioning, the objectives, the development, and even the survival of an organization. Thus, they are beneficial when they assist in the achievement of objectives and antagonistic when they are opposed to the organization's mission (Chinyio and Olomolaiye, 2010).

The list of stakeholders in a construction project is often large and each of them has different influences on the project or the organization's mission. Some exercise their influence more often than others. In this study, the stakeholders of the construction value chain were classified as internal and external, according to Chinyio and Olomolaiye, 2010. Table 2 presents the classification and the main members related to each generic stakeholder level.

Table 2. Types of stakeholders in the construction sector.

Level	Generic stakeholder	Abbreviation	Members
Internal (I)	Clients	cli.	owners, users, consumers
	Project professionals	proj. pro.	project managers, designers, architects, engineers, facilities managers, investors, subcontractors, real state agencies, builders, employees
	Suppliers	suppl.	manufacturers, process, and service providers
External (E)	Public	publ.	media, community representatives, neighbors, the press, the academy, pressure groups, civic institutions, visitors, the natural environment
	Government	gov.	legal authorities, regional development agencies, civic institutions, government establishments

Internal stakeholders are the members of the project coalition or those who provide funding, and external stakeholders are those affected by the project significantly (Chinyio and Olomolaiye, 2010). The internal members are directly related to the project, as are the professionals working on the project, suppliers, and customers. External members correspond to society and the government, for example, who are affected by the project but are not actively involved in the execution/achievement of the project/organization objectives. It can be seen in Table 2 that it was decided to group different stakeholders into five generic groups to facilitate the standardization and analysis of the results.

In terms of decision-making, it is worth considering that stakeholders can be supportive, neutral, or opposite to the organization (Chinyio and Olomolaiye, 2010). When associated with the CE barriers and drivers in the sector, each type of stakeholder has greater or lesser influence and power of action in the circular transition of the organization and the sector. Besides, it is worth noting that some stakeholders can have several dimensions of performance and belong to both levels (external/internal – E/I). Given the various dimensions in which stakeholders can be interpreted, they can be members of two or more types of classification (Chinyio and Olomolaiye, 2010). In this study, there was a general sorting of the types of stakeholders in each barrier and driver found in the review. It is worth mentioning that is not intended to understand the relationships between an organization and its stakeholders. The purpose of the study is to demonstrate the diversity of stakeholders involved in carrying out a project and that they have a corporate role in the management of an organization.

3 Research strategy

The research strategy consisted of an integrative literature review with explicit and systematic review methods for data processing and analysis to protect against bias and improve the accuracy of conclusions. The review was not intended as an exhaustive study, but rather as a representation of the current state of barriers and drivers for a CE in the construction sector. The review followed a succession of six steps based on Torraco (2005), Whittemore and Knafl (2005), and Transfield et al. (2003), as shown in Figure 2.

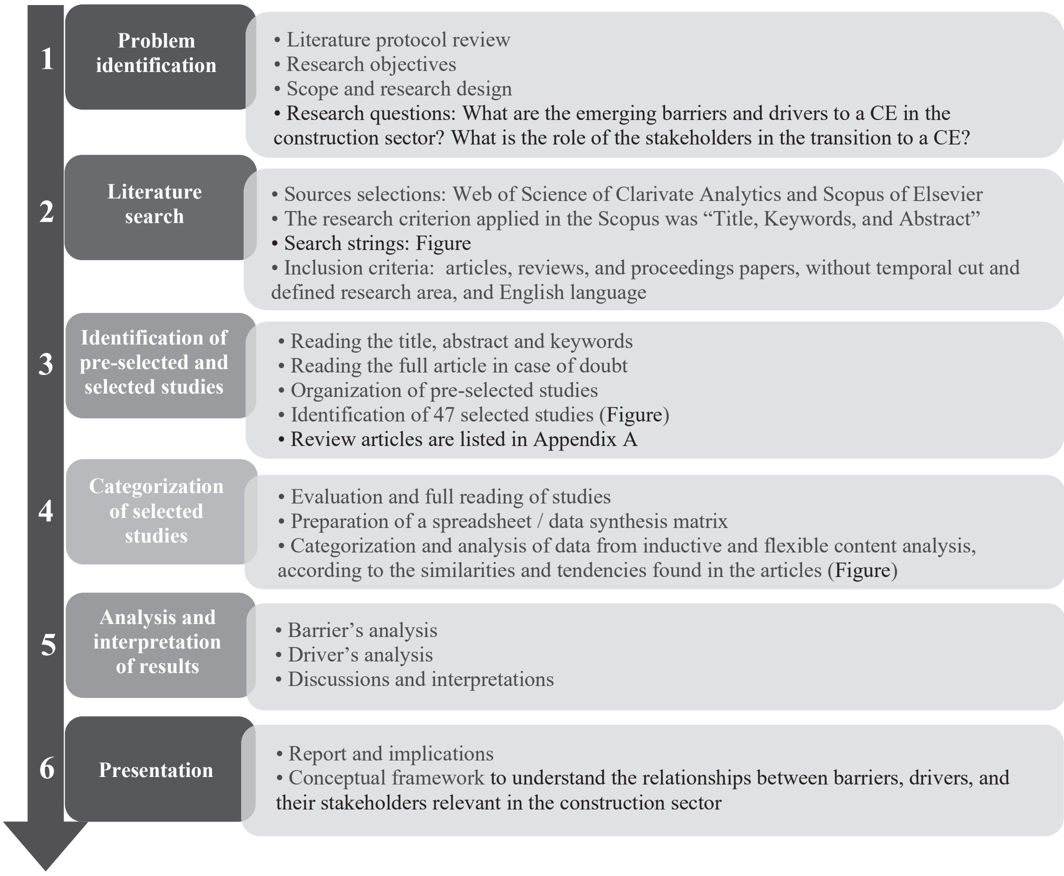

Figure 2. Summary of the integrative literature review stages.

The first step was problem identification. The study aims to give a comprehensive overview of the academic studies about the barriers and drivers to implementing the CE principles in the construction sector. Examining the contextual relationships between barriers, drivers, and their stakeholders relevant in the sector is important to increase the understanding of these dynamics and to overcome the identified barriers toward effective implementation of circularity in the construction sector. The second step determined the protocol developed in the literature review, based on search strings established on a previous analysis of the literature, as shown in Figure 2. By focusing on the review (third step) relevant sources identified were reduced from 569 to 47 articles (Figure 3).

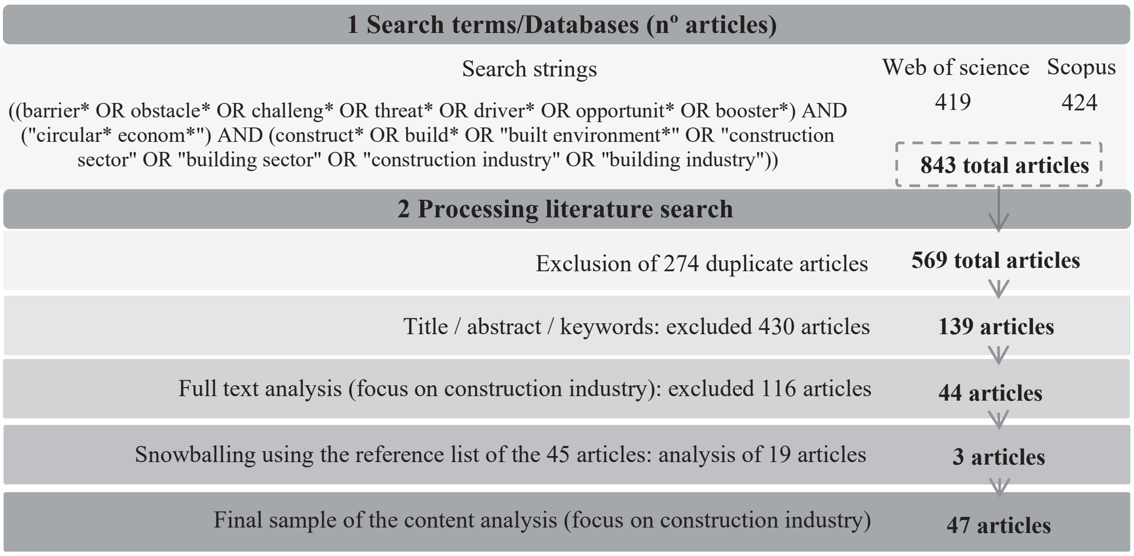

Figure 3. Processing the review in the scientific literature (review date: December 2020).

The fourth step was the content analysis of the data to attain a condensed and broad description of the subject and the outcome is categorized to describe the problem (Elo and Kyngas, 2008). Figure 4presents the categorization of the barriers and drivers adopted in the review. The classification followed three levels (icon, group, and category) and was proposed to fit and standardize the data within criteria for further analysis of the results. The categories used were previously determined in Table 1. After categorization, the main stakeholders according to their role in implementing CE were determined, following the typology of Table. Sequentially, the data was analyzed and discussed (fifth step), and synthesis in the form of a framework was developed to comprehensively portray the process of the review (sixth step).

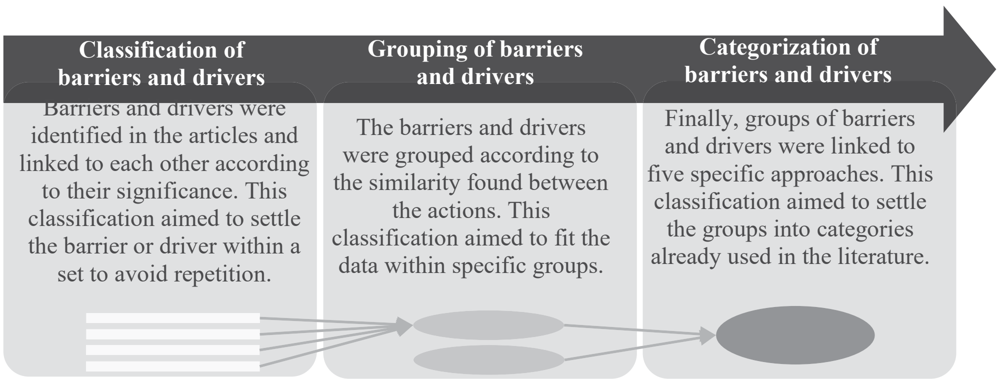

Figure 4. Components of the classification of barriers and drivers of the CE in the construction sector.

4 Results and analysis

The analysis of the results was divided into two sections: i) barriers and ii) drivers for CE. It is worth noting that some barriers and drivers may belong to more than one category or have more than one type of stakeholder.

4.1 CE barriers in the construction sector

A total of 41 barriers were identified across the five categories. Table 3 presents the categorized barriers, with their respective stakeholders and references. The categories of barriers will be analyzed in more detail.

4.1.1 Economic barriers

The economic category represented 24% of the review barriers clustered into two groups according to the similarities found. The category had a predominant governmental character. The *lack of grants* group clustered the barriers related to the lack of market investments for effective CDWM. The main barrier analyzed is the lack of marketing strategies for the reinsertion of secondary materials. This difficulty is linked to the lack of incentives for the reuse of recycled materials, and the high prices of recycled or reused materials. Besides, recycling processes require high investments and there is a lack of reward/penalty schemes related to waste management. There is a need to find subsequent uses of secondary materials, however, the recognition of the thermodynamic and recycling limits of the materials is not explicit. Thus, market forces and the value of secondary materials have emerged as a consistent barrier in the sector (Campbell-Johnston et al., 2019).

The existing market for recovered products is marginal (Akinade et al., 2019; Campbell-Johnston et al., 2019; Tomaszewska, 2020). The success of the deconstruction of buildings and the reuse of components depends on the dynamics of supply/demand for recovered materials (Akinade et al., 2019). Both the activities of a deconstruction process and those of a construction process with secondary materials require additional time and more qualified labor. Also include origin control, distribution, quality assurance, product standardization and specification, product certification, transportation, storage space, and market access (Akinade et al., 2019; Charef et al., 2019).

Challenges regarding the high availability and low costs of virgin materials and the devaluation of environmental costs in product prices were discussed by the authors. The low cost of virgin materials is one of the reasons for the insufficient demand for secondary materials on the market (Campbell-Johnston et al., 2019; Paiho et al., 2020; Tomaszewska, 2020). Besides, product prices fail to consider the environmental and social costs of manufacturing processes, undermining the benefits of moving towards circularity (Paiho et al., 2020). This context is further hampered by higher costs and lower guarantees for secondary material flows (Campbell-Johnston et al., 2019; Tomaszewska, 2020).

In the *lack of financial aid* group, the barriers related to a lack of financial incentives in the implementation of CBMs. This challenge is linked to the linear view of business models, a culture of rapid return on investments, and the aversion associated with financial risks in investing in sustainable buildings. To Adams et al. (2017), the lack of a clear initial investment or operating costs is a critical barrier to CE adoption. Investments focused on short-term operating costs go against the long payback period for circular structures and emphasize the general thinking that circular strategies involve high upfront costs (Al Hosni et al., 2020).

There is still no single appropriate economic case for the implementation of CE in the construction industry (Adams et al., 2017). Their challenges associated include the life cycle cost, lack of incentive to design for deconstruction, implementation of new partnerships and business models, lack of standards for secondary products, high costs of recycled materials, absence or weak financial incentives, and lack of manufacturers' return system, etc. Insufficient, incomplete, or poorly communicated business models and case studies are often mentioned, in addition to the lack of clarity if the project is disclosure or self-promotion (Hart et al., 2019).

Another important barrier is the high cost of developing and obtaining environmental certifications and recertifications for building materials/products. Andersen et al. (2019) emphasized the lack of market demand as one of the main obstacles to the use of Environmental Product Declarations (EPDs). This obstacle is linked to the lack of knowledge about documentation, high costs, and lack of synchronization of EPDs. The cost of developing Life Cycle Assessments (LCA), which are the basis for EPDs, makes it difficult to understand the environmental impacts caused because of the manufacture and use of a product or service.

4.1.2 Informational barriers

The informational category represented 10% of the barriers related to the lack of information and awareness about the CE principles to society in general. The category mixed issues directed at the two levels of stakeholders, internal and external, with emphasis on external issues. In the *lack of research, education and information* group, the barriers were related to negative perception, lack of knowledge, and dissemination of circular actions to the society. The lack of awareness and consumer demand is a widely recognized barrier to the implementation of the CE in the sector (Campbell-Johnston et al., 2019). In the absence of awareness, public participation, and engagement in the defense of the CE agenda and programs have low representativeness. Besides, the social and behavioral aspects of modern consumerism value the exclusivity and authenticity of products and materials (Selman and Gade, 2020). The acquisition of new products is seen as a status option, undermining the principles of recycling and reuse. Related to this is the predominant way of thinking, which tends to lean towards linearity (Campbell-Johnston et al., 2019; Paiho et al., 2020). Both existing business models and social norms encourage the generation of waste in construction.

Table 3. CE barriers and stakeholders.

Cat.	Group		Barriers	Stakeholder		References
Economic	Lack of business grants	1	High availability and low costs of virgin raw materials	E	gov.	Ghisellini et al., 2018; Hart et al., 2019
		2	Under-developed/lack of market mechanisms for recovery/reuse materials	E/I	gov./proj. pro.	Akinade *et al.*, 2019; Huang *et al.*, 2018
		3	High costs of deconstruction, separating, treating, transportation, and storage CDW	E/I	gov./proj. pro.	Akinade, *et al.*, 2019; Aslam *et al.*, 2020;
		4	High prices of recycled/reused materials/products	E	gov.	Ghisellini et al., 2018
		5	Lack of reward and penalty schemes for CDW management operations	E	gov.	Aslam *et al.*, 2020
		6	Product prices do not take environmental costs into account	E/I	gov./proj. pro.	Selman and Gade, 2020; Tomaszewska, 2020
	Lack of financial aid	7	Financial and risk aversion for circular business models	E/I	gov./proj. pro.	Charef and Emmitt, 2020; Tomaszewska, 2020
		8	Culture of rapid returns on investment and high prices for green buildings	E/I	gov./proj. pro./suppl.	Hart *et al.*, 2019; Wu et al., 2019
		9	Cost of developing products certifications	E/I	gov./proj. pro.	Andersen *et al.*, 2019; Akinade et al., 2019
		10	High investment costs of waste technologies	E	gov.	Ghisellini *et al.*, 2018
Informational	Lack of research, education, and information	1	Negative public perception (lack of communication, trust, and awareness)	E	publ.	Aslam et al., 2020; Ghisellini et al., 2018
		2	Social and behavioral aspects of modern consumerism	E/I	publ./cli.	Selman and Gade, 2020; Williams, 2019
		3	Lack of publicity and information campaigns	E	gov.	Aslam *et al.*, 2020
		4	Limited environmental management programs and facilities at academic institutions	E	publ./gov.	Williams, 2019
Institutional	Lack of strategic vision and collaborative platforms	1	Conservative, competitive, and fragmented supply chains (lack of interest and close collaboration between the sector and other sectors)	I	proj. pro./suppl.	Ghisellini *et al.*, 2018; Mahpour, 2018; Williams, 2019
		2	Lack of thinking of buying a service instead of having the ownership	I	cli./proj. pro.	Al Hosni *et al.*, 2020
		3	Lack of information about DFD, green designing, and end-of-life products	I	cli./proj. pro.	Akinade *et al.*, 2019; Cruz-Rios and Grau, 2020
		4	Lack of knowledge about circular tools (EPDs, Material Passports, certifications, etc.)	I	proj. pro./suppl.	Andersen *et al.*, 2019
		5	Insufficient application of waste hierarchy (overemphasizing recycling)	I	proj. pro./suppl.	Ghisellini *et al.*, 2018; Mahpour, 2018
		6	Lack of guidance and tools for the implementation/assessment of circular buildings	I	proj. pro.	Charef and Emmitt, 2020
Political	Lack of regulatory instruments	1	Lack of incentive and support to design for end-of-life (low pontifications for DfD)	E	gov.	Akinade *et al.*, 2019
		2	Lack of flexibility in the building codes and regulations	E	gov.	Kanters, 2020
		3	Lack of EPD international standardization	E	gov.	Andersen *et al.*, 2019
		4	Lack of producer-based responsibility system and regulatory frame to integrated resource management	E	gov.	Mahpour, 2018; Williams, 2019
		5	Lack of a waste code to guide CDWM and discourage landfilling	E	gov.	Ajayi *et al.*, 2015; Ghisellini *et al.*, 2018
	Lack of tax actions	6	Lack of a tax system and standard quality for reclaimed materials	E	gov.	Al Hosni *et al.*, 2020; Williams, 2019
		7	Lack of laws to assign a minimum percentage of CDW for reusing and recycling	E	gov.	Ajayi *et al.*, 2015; Ghisellini *et al.*, 2018
		8	Lack of land-use zoning and rational urban planning	E	gov.	Williams, 2019
	Lack of circular vision	9	Lack of national goals, targets, and legal support system with a binding effect	E	gov.	Charef and Emmitt, 2020; Ghisellini *et al.*, 2018
		10	Lack of support on research, innovation, information, and business procurement strategies	E	gov.	Al Hosni *et al.*, 2020
		11	Lack of effective supervision from the government (qualified professionals and budget)	E	gov.	Ghisellini *et al.*, 2018; Williams, 2019
Technological	Lack of integrated CDW processes, tools, and practices	1	Ineffective CDW management	I	proj. pro.	Giorgi et al., 2019; Kanters, 2020
		2	Recycling practices are thwarted by limited separation of materials, logistical barriers, and lack of process to produce easily disassembled products	I	proj. pro./suppl.	Giorgi *et al.*, 2019; Williams, 2019
		3	Lack of tools for identifying, classifying and certification of salvaged materials	I	proj. pro./suppl.	Akinade *et al.*, 2019; Ghisellini *et al.*, 2018
		4	Complexity of materials and building composition (several layers and modifications during its lifespan)	I	proj. pro.	Al Hosni et al., 2020; Finch *et al.*, 2021
		5	Lack of standardized spatial geometries and limited visualization for DfD	I	proj. pro.	Akinade *et al.*, 2019; Finch et al., 2021
	Lack of an information management system	6	Lack of effective green building design development	I	proj. pro./suppl.	Wu *et al.*, 2019
		7	Lack of quality and availability of data (privacy, trust, ownership, access)	I	proj. pro./suppl.	Selman and Gade, 2020; Williams, 2019
		8	Difficulties in understanding and developing EPDs	I	proj. pro.	Andersen *et al.*, 2019
		9	Lack of documentation of new and used building products	I	proj. pro./suppl.	Selman and Gade, 2020
		10	Lack of datasets and tools compliant for BIM	I	proj. pro.	Akinade et al., 2019; Bueren *et al.*, 2019

4.1.3 Institutional barriers

The institutional category, with 15% of the review barriers, presented the obstacles related to the stakeholders directly involved in the construction value chains. In the *lack of strategic vision and collaborative platforms* group, the cultural barriers of the sector were addressed due to the slow nature of changes and the complex and competitive supply chains. The understanding of the CE concept is a gap in the organizational dimensions. Issues such as the lack of incentives for actors towards circularity, lack of mutual interests between actors, uncertainties, and shocks in perceptions at all levels in the supply chains are the main barriers. Hart et al. (2020) indicate that the lack of collaboration and difficulties with CBMs is the main obstacle. Also, the adoption of strategic sustainability in the sector is complex due to the limited number of standardized production processes to minimize waste, or new product lines with reduced incorporated energy (Fenner and Ainger, 2019).

When considering that 33% of CDW is related to poor design strategies, greater investment is needed to improve the knowledge and skills of professionals (Aslam et al., 2020). The lack of knowledge about Design for disassembly (DfD) and EOL issues of materials and buildings is related to insufficient information on costs and methods of deconstruction, insufficient application of CDWM strategies, and lack of clarification on considering buildings as a service and not a product. Other critical issues are the lack of standards in recycling processes, and the guidance for the disposal of waste (Aslam et al., 2020). The lack of training and capacity building around issues and technologies related to CE at the individual and corporate levels hinders the transition to a more regenerative economic model (Demestichas and Daskalakis, 2020).

The establishment of tools, metrics systems, and circular guidelines must be understood as a transformational process, reflecting normative ideals to avoid inconsistencies and greenwashing (Campbell-Johnston et al., 2019). It is important to require manufacturers to be responsible for their products as soon as they reach the end of their useful life (Adams et al., 2017). Issues related to corporate responsibility have an equally damaging effect. Due to conflicting interests present in many cases among stakeholders, establishing trust and cooperation represents an important challenge (Demestichas and Daskalakis, 2020).

4.1.4 Political barriers

This category represented 27% of the reviewed barriers, which were subdivided into three groups concerned with governmental issues. The *lack of regulatory instruments* group addressed the government's lack of support for an efficient regulatory system to encourage integrated resource management and DfD. The lack of flexibility in construction codes and regulations is mainly because it is focused on the use of energy in the operational phase and does not include the incorporated energy. Besides, existing resource policies emphasized the efficient use of resources, rather than reducing the demand for resources (Hossain et al., 2020). In this sense, the adjustment of reused materials to existing regulations is an obstacle to energy performance requirements (Kanters, 2020).

The lack of a CDWM plan with a set of regulations and legislation covering all the needed steps for an adequate treatment of waste was emphasized (Hahladakis et al., 2020). Construction contracts should be adapted to incorporate the EOL phases of the components or the building, considering responsibilities based on the producer. Besides, insurers should consider the use of recovered materials in the clauses (Charef et al., 2019). The legal framework of standards, tests, and certifications that are based on virgin materials, needs to consider recovered and recycled materials and components (Selman and Gade, 2020).

These issues even consider the taxation of labor instead of the taxation of (non-renewable) resources (Paiho et al., 2020). Kanters (2020) commented on the fact that labor in Europe is much more expensive than materials, a fact that can hamper decision-making in the design and construction process that promotes circularity. The lack of adherence of the tax system to a network of recovered materials is an important barrier to the reinsertion of secondary materials in the construction value chains (Maerckx et al., 2019).

In the *lack of circular vision* group, the literature recognizes that the main barriers to CE adoption are linked to the absence of legislation and vision, the lack of government funding, as well as the lack of qualified professionals (Al Hosni et al., 2020). Government agencies have a responsibility to ensure that there are a clear vision and legislation for the implementation of CE practices. The lack of government funding for research, innovation, and investment, as well as models or a leader to implement CE principles, interferes with the acceptance and implementation of circular actions (Al Hosni et al., 2020).

4.1.5 Technological barriers

The technological category (24% of the review barriers) was subdivided into two groups concerned with the internal level of stakeholders. In the *lack of integrated CDW processes, tools, and practices* group, the lack of a construction design standard to reduce waste, low cost for CDW disposal, and inadequate urban planning were listed. This issue correlates with the lack of guidance for the effective collection and classification of CDW, immature recycling technology, and the underdeveloped market for secondary materials

(Huang et al., 2018; Kanters, 2020). Besides, the waste management market is often dominated by market players with low incentives for cooperation and recovery of high material value (Nußholz et al., 2019).

The achievement of completely dismountable and adaptable buildings presents many barriers due to the complex nature of the buildings and the designers' lack of knowledge. Architects, designers, and builders express conflicting views about DfD, have difficulty estimating and transmitting Life Cycle Costs (LCC) to their clients, and are dependent on the decisions of owners (Cruz-Rios et al., 2020). Besides, existing building designs lack sufficient information and guidance on how they can be deconstructed. Most of the buildings were not built to be deconstructed, and the performance of materials, as well as access to information on EOL materials recovery from the design stage, is a challenge (Akinade et al., 2019). The materials in buildings remain implanted for some time and at the end of the technical, functional, or aesthetic useful life, it is not defined what are the possibilities of retaining the value of the materials. Therefore, it is complex to determine multiple circular assessments that contemplate different EOL alternatives for all materials, parts, and building components (Finch et al., 2021). The widespread use of fixings, adhesives, and inherent bonding materials are the main weaknesses of conventional construction methods (Finch et al., 2021).

An additional barrier to material reuse is the lack of standardized spatial geometries, which makes it difficult to obtain enough of a consistent component or material (Finch et al., 2021). For the reuse of materials and long-term sustainability, a level of standardization is needed (Finch et al., 2021). The adoption of DfD lacks robust tools to support architects and design engineers, mainly compatible with BIM (Akinade et al., 2019), which is not yet common in EOL scenario projects. Digital methodologies such as sensors and radio-frequency identification are essential to identify reusable elements (Akinade et al., 2019).

The *lack of an information management system* was related to the lack of transparency and availability of technical data on construction elements, extending this gap to the existing modeling tools and materials database. Issues of data ownership, privacy, and business competitiveness restrict access to data from urban elements and areas (Williams, 2019). The lack of quality of the data produced can reduce the confidence in the information exchanged due to limited coverage, different data formats, monitoring, and inconsistent collection standards. The lack of collaboration between the stakeholders increases competitiveness and hinders the provision of information for the development of the sector. Problems related to capacity, especially the lack of adequate skills and training, including the limited use of

Information and communication technologies (ICTs), represent an additional barrier (Demestichas and Daskalakis, 2020).

Tools such as EPDs and materials passports (MPs) show the large amount of data that a building can generate throughout its life cycle. The challenge is to know how to deal with, structure, and store these amounts of accumulated data when mapping the elements and materials in construction (Selman and Gade, 2020). BIM can be used temporarily, but a large amount of data makes the models heavy, and new solutions must be developed (Selman and Gade, 2020). Demestichas and Daskalakis (2020) pointed out that some simulation models are incomplete and need more data and the costs related to investments in ICTs can discourage companies from adopting such technologies.

4.3 Drivers for circular economy

A total of 35 drivers were identified across the five categories. Table 4 presents CE drivers and their respective stakeholders and references.

4.3.1 Economic drivers

The economic driver's category represented 11% of the review drivers and pointed out the government as the main transforming agent. The group *incentive circular business models* sought directions for the establishment of a market (physical and digital) for secondary materials. Implementing markets with inventory control systems, product tracking, monitoring protocols and the publication of information about used materials that are or will be available is essential to make buildings a material bank. This could be a public-private partnership in which the authorities provide support for the establishment and operation (Nordby, 2019). Allowing the recovery of materials through viable return schemes (logistically and commercially) could be a symbiotic mechanism with secondary material markets.

The most important is a clear business case, where stakeholders understand commercial viability (Adams et al., 2017). The emerging data and sharing economies have been identified as an additional facilitator for CE development. In the data economy, projects and initiatives are based on CBMs that use databases to create products and services (Paiho et al., 2020). The MPs is an example of the data economy as a financially attractive business model and necessary for the management of resources in a building (Munaro and Tavares, 2021). The sharing economy takes advantage of the underutilization of offices and residential houses to provide the optimization of the use of assets, additional revenue, reducing costs for owners and operators, also increased trust between users.

4.3.2 Informational drivers

This category represented 9% of the review drivers aimed at improving CE communication, awareness, and research of the public. The category is aimed at society and the government has an important role in the implementation of these strategies. The transition to CE is a paradigm shift that requires a change in mentality and no change can be effectively implemented without consumer involvement (Tomaszewska, 2020). Only customers with specific demands to construct buildings designed for disassembly or legal requirements are realistic motivators in the current market (Selman and Gade, 2020).

The CE transition will not be accomplished without a significant research and development effort. The different governmental spheres should support companies to invest in Research Development and Innovation, promoting partnerships between research centers, universities, and companies. Intersectoral collaboration and networks will provide platforms for exchanging information, experiences, and best practices. Besides, case studies are needed to contextualize business models and provide credibility and confidence in circular approaches.

Table 4. CE drivers and stakeholders

Cat.	Group		Drivers		Stakeholder	References
Economic	Incentive circular business models	1	Establish a physical and online marketplace for material circularity	E	gov.	Adams et al., 2017; Ghisellini et al., 2018
		2	Incentive and assurance schemes for reused/recycled products	E	gov.	Adams et al., 2017; Hossain et al., 2020
		3	Encourage and exploit the financial benefits of the data and sharing economy	E/I	gov./proj. pro./suppl.	Paiho et al., 2020
		4	Explore the costs of various low waste building techniques and the potential scalability	E/I	gov./proj. pro.	Ajayi et al., 2015; Tingley et al., 2017
Informational	Improve CE awareness and research	1	Awareness through electronic media, raising CE campaign and advertisement	E	publ./gov.	Adams et al., 2017; Bilal et al., 2020
		2	Disclosure of best practice case studies, seminars, and workshops on sustainable development for public education	E	publ./gov.	Adams et al., 2017; Bilal et al., 2020
		3	More CE academic research and projects should be done by developing guidelines	E	publ./gov.	Mahpour, 2018
Institutional	Establish strategic and educational vision	1	Establish on-site inspections and audits before demolition to reduce CDW	I	proj. pro.	Aslam et al., 2020
		2	Establish a culture of compulsory sorting on-site, separate collection and treatment of the CDW	I	proj. pro./suppl.	Mahpour, 2018; Nußholz et al., 2019
		3	Encourage designers and builders to reuse CDW and prioritize upcycling rather than recycling	I	proj. pro.	Mahpour, 2018
		4	Create links between demolition contractors and stockists	I	proj. pro./suppl.	Tingley et al., 2017
		5	Benchmarking the companies engaged in the recovery and sale of secondary materials to enhance competition, supply, and diversity in offers	I	proj. pro./suppl.	Nußholz et al., 2019
		6	Develop assigned responsibilities and long-term circular value chains between stakeholders	I	proj. pro./suppl.	Hossain et al., 2020; Mahpour, 2018
		7	Training stakeholders to increase the understanding of CE and sustainability	I	proj. pro./suppl.	Hossain et al., 2020
Political	Public financial aid	1	Develop a national, regional, local action circular vision, plans, goals, and targets	E	gov.	Mahpour, 2018; Paiho et al., 2020
		2	Government incentive to kick-start the industry, subsidize or create the shared storage facility	E	gov.	Bueren et al., 2019; Tingley et al., 2017
		3	Funding for innovation, CE research and subsidize technology for CE	E	gov.	Bilal et al., 2020
		4	Circular criteria in public procurement (e.g., a minimum percentage of recycled materials)	E	gov.	Nußholz et al., 2019; Paiho et al., 2020
		5	Establish Producer-based responsibility or take-back system	E	gov.	Hart et al., 2019; Hossain et al., 2020
		6	Policy incentives, or credit in environmental assessment methods/tools	E	gov.	Bilal et al., 2020; Tingley et al., 2017
	Fiscal and regulatory actions	7	Regulatory actions for reduced GHG emission and metrics for embodied carbon in buildings	E	gov.	Hart et al., 2019; Nordby, 2019
		8	Suitable policy system that guides and supervise CDWM, including CDW reporting mandatory	E	gov.	Ghisellini et al., 2018; Mahpour, 2018
		9	Reduction of taxes on labor and an increase of taxes on the use of primary raw materials	E	gov.	Ghisellini et al., 2018; Tingley et al., 2017
		10	Tax exemptions for goods produced by secondary materials and buildings holding green certificates	E	gov.	Ghisellini et al., 2018; Tomaszewska, 2020
		11	Penalties for non-compliance and incentives for compliance with CE regulations	E	gov.	Aslam et al., 2020; Bilal et al., 2020
		12	Higher landfill charge	E	gov.	Ajayi et al., 2015; Ghisellini et al., 2018
Technological	Guidelines and tools for circular buildings	1	Early collaboration and inclusion of waste management in project sustainability tools and building control process	I	proj. pro.	Ajayi et al., 2015
		2	Better management of resource flows and end-of-waste criteria for CDW at construction sites	I	proj. pro.	Ghisellini et al., 2018; Nordby, 2019
		3	Development of symbiosis and enabling technologies to CDW management	I	proj. pro./suppl.	Adams et al., 2017; Hossain et al., 2020
		4	Development of guidance and tools for the assessment of building circularity	I	proj. pro.	Chang and Hsieh, 2019
		5	Incentive Design for adaptability and disassembly using design tools (e.g., BIM)	I	proj. pro.	Ajayi et al., 2015; Hart et al., 2019
	Integrated information system	6	Improving certification of recovered materials to reduce uncertainty and lack of trust	I	proj. pro./suppl.	Nußholz et al., 2019
		7	Mandatory application of LCA/LCC for the whole life cycle of a building	I	proj. pro./suppl.	Tomaszewska, 2020
		8	Establishment of effective and reliable ICT solutions	I	proj. pro./suppl.	Aslam et al., 2020; Hahladakis et al., 2020
		9	Creating datasets for BIM and exploring the feasibility of BIM on conducting other types of performance analysis for resource management	I	proj. pro.	Bueren et al., 2019; Chang and Hsieh, 2019

4.3.3 Institutional drivers

The main agents of the category (20% of the drivers) were the project professionals and suppliers, focusing on issues that encourage the deconstruction and recovery of building materials. An educational program that promotes the separation and collection of waste at construction sites is the first step, especially in less developed countries. Above all, the creation of partnerships and industrial symbiosis to promote circular systems supporting closed circuits and creating networks of waste and by-products of one actor that can be reused for another as a raw material (Hossain et al., 2020).

There must be in-depth and integrated teamwork between project teams, from the conceptual stage to delivery. These consultations could be implemented through workshops, industrial seminars, and collaborating companies and agencies to promote the CE agenda (Hossain et al., 2020). It is important to clarify the implications of the CE for different stakeholders through education, training, and visionary thinking, to change the attitudes and behaviors of stakeholders about the use of secondary products (Ghisellini et al., 2018).

4.3.4 Political drivers

The political drivers (34% of the drivers) stressed the role of the government to establish these changes. The group's *public financial aid* demonstrated political tools to support the implementation of the CE in construction. A long-term holistic view that declares the circular ambitions of the city or state is necessary as a starting point for any action aimed at the circular transformation. The vision must remain flexible, support experimentation, and act as a springboard for the development of a more concrete agenda (Paiho et al., 2020).

Different business models can be stimulated by public policymakers. One of the most effective methods that a government can employ to drive the growth of CBM is to use CE criteria in public procurement (Paiho et al., 2020). Cities can buy products made from secondary materials or that are designed to be repaired and reusable, encouraging the demand for circular innovations (Paiho et al., 2020). The emphasis is on legal structures, incentives, infrastructure development addressing market failures, as well as establishing an enabling environment for innovation and entrepreneurship. The Chinese government has developed a systematic approach to the promotion of sustainable buildings adopting framework policies to regulate and control the behavior of stakeholders, supporting regulations to promote the participation of construction companies through economic incentives and specific instructions, such as removing barriers related to the adoption of technological innovation, improving the environmental and energy quality of buildings (Ghisellini et al., 2018).

The *fiscal and regulatory actions* group highlighted the need for political rules to reduce the generation of CDW. The CE can be promoted through laws, policies, risk reduction (through tax collection), and strict governance (Selman and Gade, 2020). Nordby (2019) considers that the main factors for increasing the reuse of construction materials are the national targets for reducing greenhouse gas (GHG) emissions in buildings. Thus, construction-related policies should facilitate the incorporation and reuse of materials, as well as provide incentives to customer segments that value lower GHG emissions and consider circularity approaches as marketing opportunities (Gallego-Schmid et al., 2020).

The internalization of negative environmental externalities through economic instruments, such as fees and taxes, and non-economic ones (command and control measures) offers a possible solution for environmental protection. The success of the CDW internalization policies was highlighted in Hong Kong, where the amount of CDW discarded in landfills was reduced; in Europe, studies have shown that landfill taxes in the Netherlands and the United Kingdom have directed waste to recovery and recycling (Ghisellini et al., 2018).

4.3.5 Technological drivers

The technological category (26% of the drivers) is aimed at internal professionals in the construction value chain. In the *guidelines and tools for circular buildings* group, it is needed to make plans that show the use of spaces, including the application of selective and sequential disassembly planning and minimum durability requirements to allow the recovery of building components, parts, and materials with different life cycles (Maerckx et al., 2019). Better resource management will start with mandatory on-site sorting and separate collection of construction materials or the introduction of mandatory CDWM plans. This practice will also increase the symbiosis with companies committed to the recovery and commercialization of resources, to increase competition, offer, and diversity (Nußholz et al., 2019).

Circular buildings require the adaptation of construction processes to the mechanical and geometric properties of the available materials and the use of less complex materials to facilitate reuse or upcycling (Gallego-Schmid et al., 2020). The prefabrication associated with the DfD reduces the complexity of the buildings by expanding the adaptability, durability, transportability, assembly, and disassembly capacity (Cruz-Rios et al., 2020).

The group *integrated information system* presents the importance of the ICTs to create a database and tools for recovery and tracking the residual value of building materials. Gallego-Schmid et al. (2020) reinforce the need to develop and obtain access to databases with information on stocks of materials, waste and markets for reused and recycled materials, and the use of BIM to track components. Tools such as EPDs, MPs should be mandatory as the level of circularity increases in the sector.

5 Discussion and implications

The review highlighted a greater number of CE barriers and drivers in the construction sector and a shared responsibility between the government and project professionals as agents of change. The main themes were a public policy plan, CDWM, and CE awareness and communication. The following sections will deepen the discussion by relating barriers, drivers, and stakeholders in a framework that summarizes the main results of the study.

5.1 Relationships between CE barriers, drivers, and stakeholders

Figure 5 presents a framework with the main results of the study. To the left of the Figure are the results of barriers to CE and on the right are the drivers. Figure 5 can be read from the first bar, where the percentages of the three levels of construction stakeholders, external, internal, or mixed, related to each category are identified. In the sequence, the second bar identifies the representative percentage of each category of barriers, and besides, the third bar represents the percentage of groups of barriers. Finally, the groups of barriers related to each category are described. To the right of the figure, the same results are presented for CE drivers.

The framework sought to relate the 9 groups of barriers to the 7 groups of drivers to establish guidelines for CE implementation in the sector. The identification of the stakeholders in the categories indicates the role that each member of the construction value chain has in the circular transition. Next, the relationship between barriers and drivers by category will be discussed. It is noted that many barriers and drivers are interconnected, for example, the use of DfD, will reduce the complexity of buildings, reduce the cost and time of deconstruction, and the CDW generation. The circularity in the sector will work gradually as a cascade effect until it reaches the entire construction value chain.

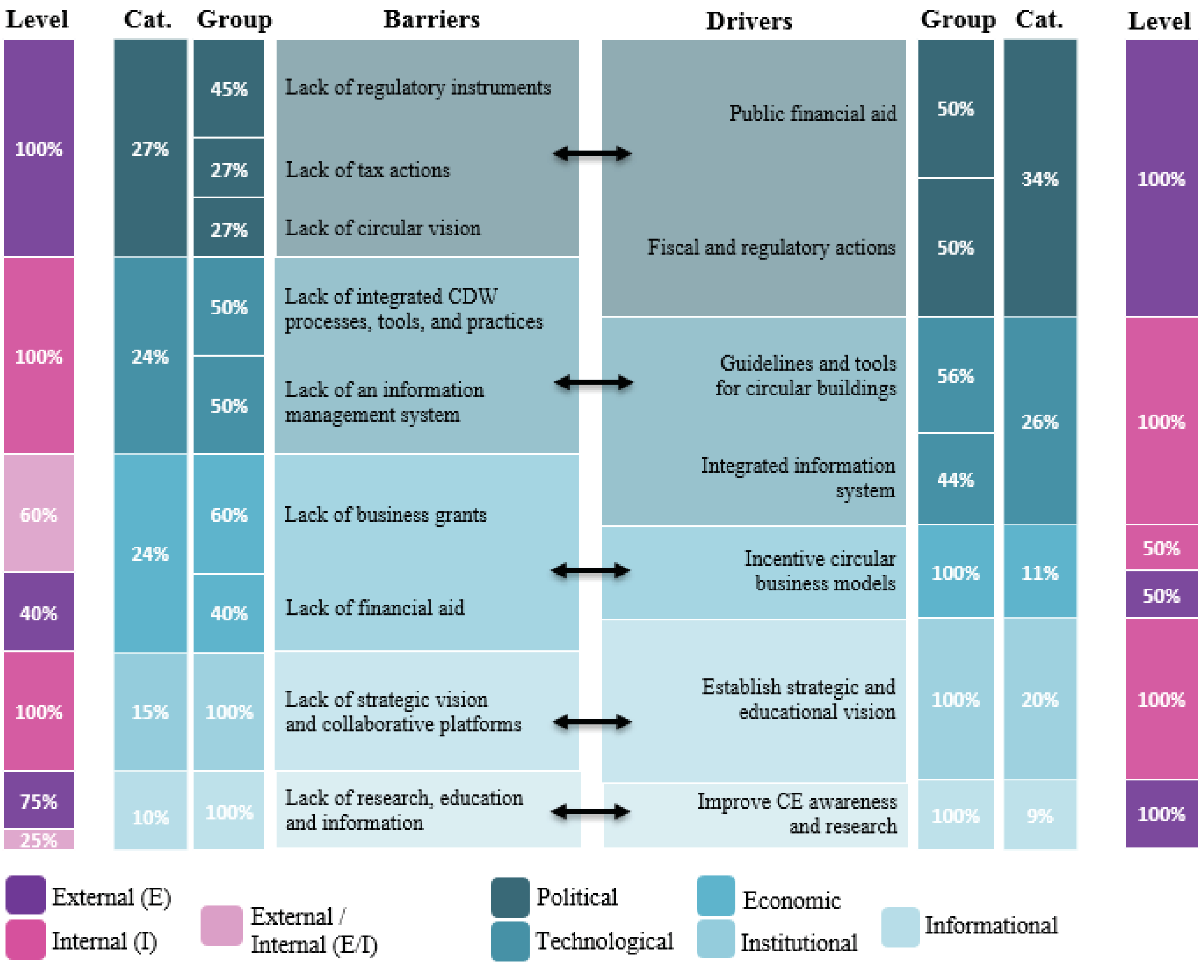

Figure 5. Framework linking current CE barriers, drivers, and stakeholders in the construction sector.

a) Political barriers and drivers

The political issues were the most representative in the review and focused on the development of a governance plan that promotes the CE. Government agencies were the agents of change identified in this category. Government regulations and fiscal actions are imperative to achieve an effective DfD and play an important role in the current national and global sustainability agenda (Akinade et al., 2019). The reuse of construction materials can reduce GHG emissions from material production, transportation, and waste management. A policy that emphasizes circular measures has synergistic potential with global climate change agreements. An increase in landfill disposal tax may also impose waste minimization activities and create opportunities to provide a Waste Minimization Fund for financially sustainable deconstruction, as suggested by Zaman et al. (2018).

Many local authorities are focused on short-term economic benefits and consider rapid industrial development to be their main political contribution, discouraging companies, and the public from reusing or recycling resources (Geng and Doberstein, 2008). Also, compliance with environmental regulations is not efficient due to a lack of budget and qualified employees. Decision-makers are regularly re-elected and do not necessarily have the ambition to establish long-term strategies for circularity or to maintain established strategies (Paiho et al., 2020). Municipal decision-making on waste and resource strategies is often fragmented between departments and other municipalities (Williams, 2019). Since material flows extend beyond city limits, and material standards and regulations are often determined at the national or regional level, it is difficult for municipal decision-makers to enact circularity without broader political integration (Campbell-Johnston et al., 2019). An integrated and unified regulatory platform to promote the CE is needed to encourage the development of sustainable technologies and products.

The importance of regulatory drivers is analogous to the role of laws and taxes in encouraging environment-friendly change, modulating the behavior of organizations, and triggering reactions in different segments of supply chains. Local government agencies can raise awareness of the benefits of circular alternatives to encourage companies to change their modes of operation. This may require the establishment of a circular management group or the appointment of a coordinator who will be able to maintain an overview of the state or city strategy (Paiho et al., 2020). A wide range of government stakeholders should be involved in the process of implementing the circular strategy. The creation of partnerships between actors in different sectors should also be encouraged, providing access to networks, organizing workshops or meetings, or establishing centers (Paiho et al., 2020). Support can also be in accessing the infrastructure and technologies available in other developed countries and from training organizations to instruct the culture of sustainability among them (Gupta et al., 2020).

b) Technological barriers and drivers

Although the literature considers technical and technological issues as relatively minor challenges (Kirchherr et al., 2018), the integration of design in circular processes is a challenge due to the lack of knowledge of the appropriate technologies and how to apply them, especially in the integration of receiving systems and reverse logistics (Campbell-Johnston et al., 2019). This emphasizes that organizations lack the technological know-how to support the implementation of sustainability-oriented innovation (Gupta et al., 2020).

The main challenge of adopting CE is to consider the EOL of components, parts, and materials during the design process. Synergies between circularity and adaptability are needed to implement the concept of circular building (Hossain et al., 2020). The use of BIM in the initial design stage, the selection of modular or prefabricated components, and integration of the LCA are essential for effective CE implementation (Hossain et al., 2020). Cruz-Rios et al. (2020) pointed out the symbiotic relationship between pre-fabrication, DfD, and product-service system (PSS) model to allow the return, repair, and remanufacturing of building materials. However, the currently underdeveloped market for recovered materials can make the cost prohibitive for reuse in new projects. Many architects only use recovered materials for reasons of aesthetics and historical value (Cruz-Rios et al., 2020).

Waste treatment needs accuracy in the separation of technical nutrients from biological nutrients to eliminate toxicity and guarantee the quality of materials returned to the value chain. Transparency in the composition of the material is essential to increase the reuse and recycling of the materials, which benefits from the use of pure materials (Paiho et al., 2020; Selman and Gade, 2020). It may be necessary to establish restrictions on the use of secondary materials. For example, it is recommended that wood materials be reused in less important applications and not for structural use (Akinade et al., 2019). Likewise, the use of identification and research technologies considering aspects of contamination or effects of aging of concrete, which can lead to deterioration and reduced useful life of structural elements, must be considered.

An information system that adopts a structured approach is necessary for decision-makers to find support to plan and manage construction resources and CDW. The use of BIM associated with DfD can improve collaboration between stakeholders, the visualization of the deconstruction process, identify recoverable materials, develop a construction/deconstruction plan, analyze performance, and simulate EOL alternatives (Akinade et al., 2019). The use of MPs is one of the main business mechanisms that will involve different stakeholders and information during all phases of the building's life cycle. Also, producers can provide and track standardized information on the environmental performance of their products and materials (Nußholz et al., 2019).

c) Economic barriers and drivers

The construction sector is slow to introduce innovations, and the lack of financial incentives related to the secondary materials market interferes with low levels of classification, the efficiency of reuse and recycling, as well as the adoption of a reduction approach to CDW. Reward measures for circular projects or penalties on waste generation rates need to be incorporated into public policies (Aslam et al., 2020; Ghiselini et al., 2018). These measures will stimulate the development of new recycling technologies to consider systematic planning of recycling facilities and the environmental compatibility of recycled products, which depend on the distances to the recycling plants (Ghiselini et al., 2018).

At the same time, the lack of structural solutions to direct fractions of the waste stream to the relevant recipients causes uncertainty in terms of the continuity of the supply of material resources. Achieving the effect of economies of scale becomes impracticable, and in many cases leads to an increase in the secondary material price (Tomaszewska, 2020). A greater understanding of the cost-benefit of applying the CE principles to each stakeholder is needed. If the real cost of consuming greenfield areas, virgin, and finite resources were paid, there would be a financial justification for investing in support systems for the reuse, recycling, and energy recovery (Willians, 2019). The lack of public subsidies for the secondary materials could be offset by the mandatory application of LCC of a building and tax exemptions for certified buildings with an ecological character (Tomaszewska, 2020).

New tax actions and financial support through public innovation and demonstration programs can help companies change their existing business approach (Nordby, 2019). Local governments can encourage circular experimentation in companies, providing appropriate spaces and funding for such activities. This can be achieved through flexible regulatory structures, support centers, concessions, or subsidies (Paiho et al., 2020). Gallego-Schmid et al. (2020) suggest the establishment of new property agreements, such as the lease of structural components which can be used in commercial and industrial installations; the development of insurance policies that better consider the risks involved, a guarantee of quality and safety of the structures; in addition to financial incentives to encourage circularity, such as taxing materials without a minimum level of recycled content. By promoting the benefits of sustainable buildings, supply chain stakeholders can overcome the current lack of market demand for these products and help the customer understand the benefits of these products, thereby increasing market competitiveness (Gupta et al., 2020).

d) Institutional barriers and drivers

Inertia and reluctance to diverge from normal business practices suggest that discussions about CE are often restricted to a company's corporate social responsibility and/or environmental divisions (Kirchner, 2018). The lack of the sector's close connection with other sectors delays the circular transition required for all sectors. For example, the real estate developer, who does not intend to own the building, can negatively influence circularity decisions of the construction, as well as the financial sector, which is mainly traditional and does not consider the EOL materials value (Kanters, 2020). Resistance to change is driven by cost and low customer demand since companies are conditioned to respond to the consumer (Kirchner, 2018; Tingley et al., 2017).

The absence of a broad consensus on what the CE looks like in the built environment is likely to prevent the adoption of circularity in the short term (Adams et al., 2017). The barriers related to lack of trust, inadequate communication between stakeholders, and issues of competence and leadership will be resolved with integrated and collaborative teamwork. A crucial role is devoted to developers and builders compared to designers. Developers must provide an environmental impact assessment document, provide solid CDWM facilities and organize meetings to acquire public and expert opinions on the proposed project. Builders must implement an appropriate design and project plan, avoid CDW, check the materials and equipment and establish safety management systems (Ghisellini et al., 2018).

Organizations need to find or create business models specific to their needs. Nußholz et al. (2019) showed the use of secondary materials to decarbonize the sector and an understanding of the interaction between policy innovation and CBMs to advance strategies with secondary materials. It is observed that larger construction companies have been more responsive to environmental protection policies and reduced ecological impacts, with organizational capacities being a strong influence in addressing sustainability issues (Fenner and Ainger, 2019).

e) Informational barriers and drivers

Despite the lack of communication and greater knowledge about circular practices being more related to government actions, the integration between the external and internal levels of stakeholders is essential to reduce the public's negative perception and expand the demand for circular buildings. Public and business actors do not have a clear idea of what a CE is, how to implement it and why it is relevant (Paiho et al., 2020). The concept of circularity can also be misinterpreted as restrictive, applying only to waste or environmental management issues (Paiho et al., 2020). Effective action is also hampered by the lack of comprehensive data on resource cycles and the absence of networks for exchanging information between stakeholders (Campbell-Johnston et al., 2019; Williams, 2019).

Since the transition requires the participation of citizens and companies' awareness-raising activities are essential (Paiho et al., 2020). These activities may include demonstrating circular projects in the city, hosting awareness events, or conducting campaigns to encourage new habits and discourage unnecessary consumption (Paiho et al., 2020). The use of social media is an engaging tool for raising awareness about a more sustainable society. Also, making circularity part of education is essential to ensure that future generations keep up with the skills needed to operate in a CE (Paiho et al., 2020).

5.2 Summary of the stakeholders' role

Table 5 presents the groups of barriers and drivers related to the main stakeholders' role in the sector. It is observed that the government has a preponderant role in the economic, informational, and political aspects of the CE implementation. Project professionals, on the other hand, have greater relevance in technological, institutional, and economic matters.

Table 5. Main stakeholders' role in implementing the CE in the construction sector.

	Stakeholders' role in implementing CE		Level internal			Level external	
Category	CE barriers	CE drivers	clients	project professionals	suppliers	public	government
Economic	Lack of business grants	Incentive circular business models		•			•
	Lack of financial aid			•	•		•
Informational	Lack of research, education, and information	Improve CE awareness and research	•			•	•
Institutional	Lack of strategic vision and collaborative platforms	Establish a strategic and educational vision	•	•	•		
Political	Lack of regulatory instruments	Public financial aid					•
	Lack of tax actions	Fiscal and regulatory actions					•
	Lack of circular vision						•
Technological	Lack of integrated CDW processes, tools, and practices	Guidelines and tools for circular buildings		•	•		
	Lack of an information management system	Integrated information system		•	•		

The implementation of circular actions is not a separate entity, but the outputs of a barrier can be input to other barriers or drivers. The CE has been applied mainly as a waste management solution. The focus of the technological and economic categories was the development of markets for secondary materials obtained from DfD structures, through the support of EPR and MP. The informational dimension emerged as a key and interrelational element for the advancement of the sector's circularity. There is a need to accelerate behavioral research, as it is people, not technologies, that are the key to embracing circularity (Pomponi and Moncaster, 2017).

The implementation of any CE initiative without a major commitment from the main stakeholders carries a high risk of failure. An effective circular plan could be achieved with inclusive and location-sensitive policies, operating from a bottom-up and top-down perspective. This would be possible by developing positive political practices with regulations that leave room for inventions, building capacity through the transfer of interinstitutional knowledge, and developing communication platforms to enable intersectoral integration. Interactive and inclusive policies are needed to ensure that stakeholders are capable and motivated enough to avoid gaps between policymaking and practice. Guidelines and principles related to public participation should be included based on demonstrations of interest by the government in concrete actions, such as in public tenders. Better communication, knowledge sharing, better-informed decisions, and better skills for all stakeholders depend on a continuously updated database of best practices.

5.3 Relevance of the barriers and drivers' categories in the CE transition

The previous discussion demonstrated the numerical representativeness of the political and technological categories. However, despite being more representative, they are not a consensus as to the most relevant for the implementation of circular actions in the sector. According to Kirchherr et al. (2018), the categories of barriers can be considered nested, and the cultural barriers determine regulatory barriers, which in turn determine market barriers; market barriers determine technological barriers. Figure 6 follows this model and illustrates the relationship between the review categories.

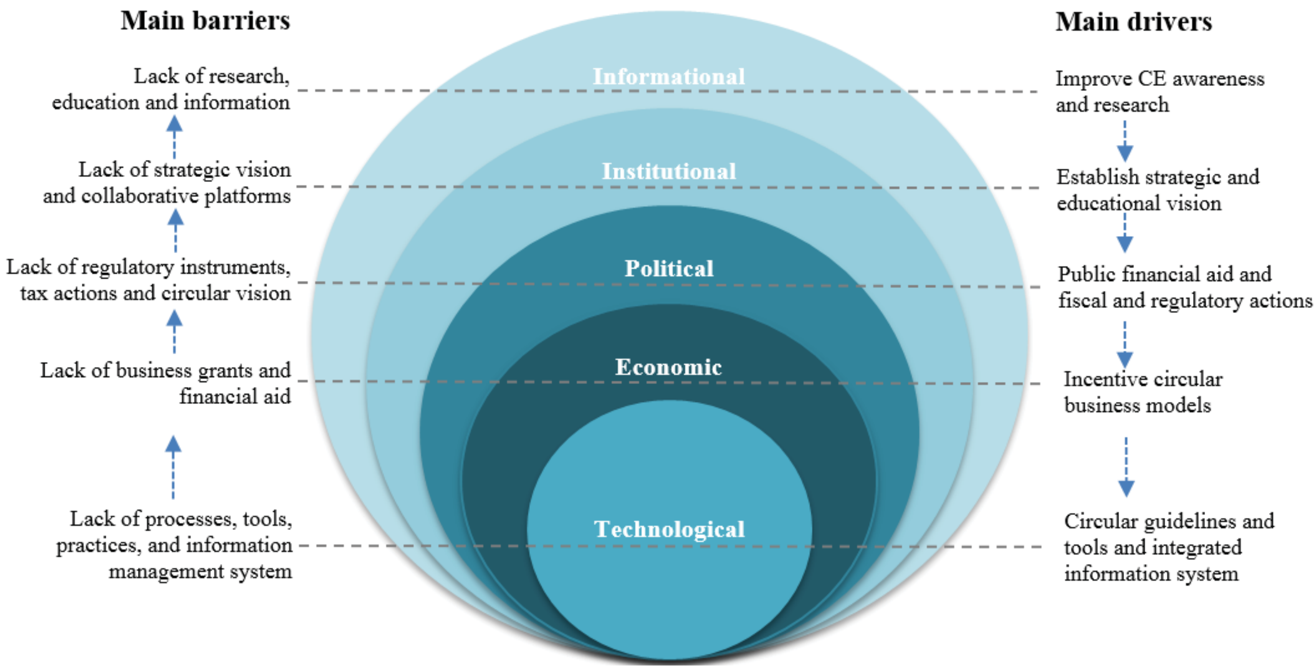

Figure 6. Relation of the categories of barriers and drivers in the CE transition.

Understanding the interrelationships between the categories and, consequently, between the barriers and drivers, will determine the main agents of change in the sector. Figure 6 shows the main groups of barriers and drivers by category. Considering the theory proposed by Kirchherr et al. (2018), informational barriers in union with institutional ones determine political barriers, which in turn determine economic barriers; and economic barriers determine technological ones. In this sense, the technical lack of processes, tools, practices, and information is linked to the lack of business grants and financial aid that promote circular issues. In turn, the lack of economic incentives depends on an efficient political system, based on regulations and tax actions that promote the circular agenda. Circular policies depend on collaborative platforms and cultural pressure from the construction industry and society. CE education and communication are the main vehicles of change in the sector.

It is interesting to note that both the institutional and informational categories were the least representative of the review. The lower representativeness of the categories may have occurred because they are issues of complex measurability and can be underestimated or neglected by the bodies responsible for the change. Besides, although the role of citizens and communities is fundamental, there is a mismatch in the way these stakeholders are included in the construction of a circular vision (Prendeville et al., 2018). Mostly, society does not participate in the formulation of public policies. Often, even clients do not have access to digital data and the collaborative process in the development of the project. These issues influence the credibility of the CE and the negative perception of sustainable development.

Communication must be segmented and have a frequency of action. Internally, companies need to establish training goals according to the level and type of information for each stakeholder in the construction value chain. Effective communication must consider the level of education and the role played by each employee. At the external level, the government needs to incorporate a CE policy linked to the issues of the environmental agenda, which is already more defined and recognized by society. A point that needs to be emphasized is the determination of the different types, means, and target audiences of communication.

Even though cultural barriers are central to circular implementation, this study highlights the lack of support, laws, and government regulations as a crucial barrier to CE implementation. However, legislation can be both a motivator and a barrier to CE adoption. As a stimulus, it can lead companies to develop circular products and reduce the environmental impacts of the product throughout its life cycle. On the other hand, the risk in top-down policies is to face problems such as the different agendas of two government organizations that confuse the actors, ignoring geographical variation, and absent or conflicting policies. Vague legislation or even the absence of legislation tends to discourage companies from adopting CE or even lead to misinterpretations.

This study does not intend to determine which category is the most important for the CE in the sector. Circular buildings are the result of the implementation of efforts in the governmental and behavioral dimensions (Pomponi and Moncaster, 2017). The joint action of the stakeholders with the government can further promote the CE development, strengthening the supervision and implementation of green buildings, actively implementing circular actions, combined with the necessary incentive measures. Paiho et al. (2020) questioned that the initial investment costs needed to switch to circular systems can be a challenge for both companies and municipalities, who may have vested interests in maintaining current linear production processes such as waste incineration companies, in addition to the risk in investing in new infrastructure. These barriers, in addition to being predominantly economic, have regulatory factors that should be considered by public policymakers.

A broad integrative CE structure is needed, with a combined top-down approach (national efforts at the informational, economic, and political categories) and a bottom-up approach (institutional, informational, and technological categories). Managing the circular transition is a matter of finding the balance between both approaches to provide a competitive advantage. As top-down approaches level and standardize circular implementation in the sector, business models are being formed through self-organized processes, which is why a market-oriented approach remains essential. The internal stakeholders are co-responsible for the change in the sector. Command and control policies motivate participation in symbiotic activities, generating economic advantage in the reuse of CDW and financial subsidies and pressures from stricter environmental standards.

6 Conclusions

This study aimed to identify the main barriers, drivers, and the role of stakeholders in the implementation of the CE in the construction sector. The study showed that the political and technological categories most influence the implementation of the CE. The political category emphasizes the need for regulatory instruments, fiscal actions, and a governance policy integrated with the sustainable and circular development agenda. Technical issues emphasized the lack of an integrated CDWM plan and an information and communication management system in internal construction chains.

The main contribution of the study is the analysis that only a joint and interdisciplinary action can promote sustainable changes in the sector. A circular building depends on a developed political-economic structure and a behavioral change in society. From the moment that effective communication about CE is implemented, supported by a flexible and collaborative governance policy with the construction value chain, a constant and gradual change will be initiated. The CE implementation will have a cascade effect, since both the directional categories of the sector (economic, political, institutional, informational, and political), as well as the barriers and drivers overlap and have a direct connection.

It was found that the sector is still linked to three major issues: lack of governance plan towards CE, an efficient CDWM program, and greater awareness and communication about circular principles. Effective CE implementation requires clarity on how circular actions can influence sustainability, supply chains, business models, and ICT systems. The CE must be adopted to select the best strategies and tools in the initial design stage. From the relationships between CE barriers, drivers, and stakeholders, the practical implications were to propose directions for future research to expand the discussion and development of the CE, seeking cleaner productions and more circular buildings.

This study has limitations that must be considered. First, the literature review was focused on academic research based on keywords. Besides, the literature sample includes only articles published in English. There would be an additional need to identify the evolution of the latest industry practices. Still, conducting a sectoral survey could validate the results or indicate the relevance of other factors in the CE implementation. In future research, it is proposed to raise CE practices for the different stakeholders in the sector. Besides, it is suggested to explore case studies that implanted the CE in CBMs, highlighting the stakeholders involved and the types of strategies adopted at the organizational and sectoral levels. Above all, conducting empirical studies will be important to carry out quantitative analyzes on the economic return, and environmental and social impacts of circularity in the construction value chain.

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PAPER A7

Design for Adaptability and Disassembly: a state-of-art review towards circular buildings

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Design for Adaptability and Disassembly: a state-of-art review towards circular buildings

ABSTRACT

Design for Adaptability and Disassembly (DfAD) is an effective method to reduce construction and demolition waste (CDW) generation, landfill loads, greenhouse gas generation, preserve natural resources and increase environmental awareness in the construction industry. However, it is an underexplored strategy due to a lack of information about projects and a set of agreed guidelines to guide the deconstruction of buildings. This study aims to understand how DfAD and other deconstruction-oriented ecodesign methods can support the sector's transition towards circularity. Through an integrative literature review, this study i) analyzed the current publications and terminologies used, (2) identified the main themes discussed, and (3) described the key criteria for integrating deconstruction in the building design stage. The results showed that the term DfAD encompasses different ecodesign strategies and that the subject is concentrated in six major thematic categories. 71 criteria were presented to guide the deconstruction of buildings, emphasizing standardization, modularization, and prefabrication of materials and components as fundamental requirements. The study highlighted the need to expand the knowledge and training of the design team, establish public policies and tax incentives, and develop tools, methods, and circular indicators to enable the implementation of deconstruction strategies for buildings.

Keywords: Circular economy; Construction sector; Deconstruction; DfAD; Building end-of-life.

1 Introduction

The construction sector is the world's largest consumer of raw materials, responsible for using one-third of the global energy and generating globally 39% of carbon dioxide emissions and 35% of landfill waste (Ajayi et al., 2015; IEA, 2019). Although more than 90% of a building's content can be reused, only 20-30% of these resources are recycled or reused at the end of a building's useful life (WEF, 2014). This scenario puts pressure on the sector to make changes in the way it plans and builds the built environment to meet market, environmental and social issues and ensure the sector's resilience, aimed at more sustainable production and consumption.

The circular economy (CE) offers an opportunity to reduce the use of primary materials and their associated environmental impacts, through different strategies that replace the end-of-life (EOL), such as reduction, reuse, and recycling of materials in the production/distribution processes and consumption (Kirchherr et al., 2017). Deconstruction is an EOL scenario that favors the recovery of construction components for relocation, reuse, recycling, or remanufacturing of construction (Kibert, 2003). The concept of Design for deconstruction, which is also known as Design for disassembly both known by the acronym DfD, appeared in the construction sector in the 1990s by ecodesign methodologies from the manufacturing industry (Macozoma, 2002; Kibert, 2003). Ecodesign or Design for Environment is an approach to developing products in line with the concept of sustainable development and life cycle thinking that directs product development towards environmental impact reductions, without compromising other criteria such as performance, functionality, aesthetics, quality, and cost (Pigosso et al., 2010).

To close material loops, DfD can be associated with Design for adaptability (DfA). An adaptable building can be modified by users to meet their constant needs, demands, and conditions (Anastasiades et al., 2020). Incorporating Design for Adaptability and Disassembly (DfAD) principles into the planning and design phase will increase the likelihood that activities during the use, maintenance, and end-of-life stages will be directed more efficiently, ensuring effective use of resources and the implementation of the CE in buildings and civil engineering works (ISO, 2020; Munaro et al., 2021).

Deconstruction is an effective strategy to reduce the generation of construction and demolition waste (CDW) and the emissions of greenhouse gases (GHG), decrease landfill loads, preserve natural resources, and increase the environmental awareness of the sector. Minunno et al. (2020) estimated that designing and building to reuse building components offsets GHG emissions by 88%. In addition, deconstruction reduces air and water pollution, emissions from heavy equipment and vehicles, and noise pollution (Tatiya et al., 2018). Kibert et al. (2003) stated that the deconstruction process creates new jobs and develops local businesses using materials diverted from landfills. Therefore, new business models can emerge with the creation of a market for recovered materials and with new market offers (Nußholz et al., 2019). For Munroe et al. (2006), deconstruction should be part of local and regional economic development initiatives, since it promotes the historical preservation of construction and building elements (Sanchez et al., 2020) and gets credits in construction assessment systems. Tatyia et al. (2018) also demonstrated that deconstruction generates lower costs than demolition.

Despite the social, environmental, and economic benefits of DfAD, less than 1% of existing buildings are fully demountable (Dorsthorst and Kowalczyk, 2002). The possibility of recovering building materials depends on how a building was designed and constructed, and deconstruction techniques are not yet common in the industry. Furthermore, information on deconstruction projects and the deconstruction process is still limited (Carvalho Machado et al., 2018). Even though many researchers have developed guidelines to allow and facilitate the deconstruction of buildings at the end of their life cycle, information is fragmented and there is no consensus on a reversible building design protocol. Not even about the different terminologies used to describe the different ecodesign methods aimed at the EOL of buildings, such as design for adaptability, design for change, and reversible building.

It is on this premise that this study seeks to explore the state-of-art of DfAD and discuss the critical criteria needed to recognize deconstruction as a strategy that must be part of the design and planning stage of the buildings. This paper seeks to answer the following question: how can Design for Adaptability and Disassembly and other building deconstruction-oriented ecodesign methods support the transition towards integration of circular economy within the construction sector? To answer the research question, three iterative analyses have been undertaken: (1) analyzing the current publications and ecodesign terminologies used in the academic literature, (2) identifying the main themes discussed on DfAD, and (3) describing the key criteria related to this strategy to be used and applied within building practice. Figure 1 shows the organization of the study.

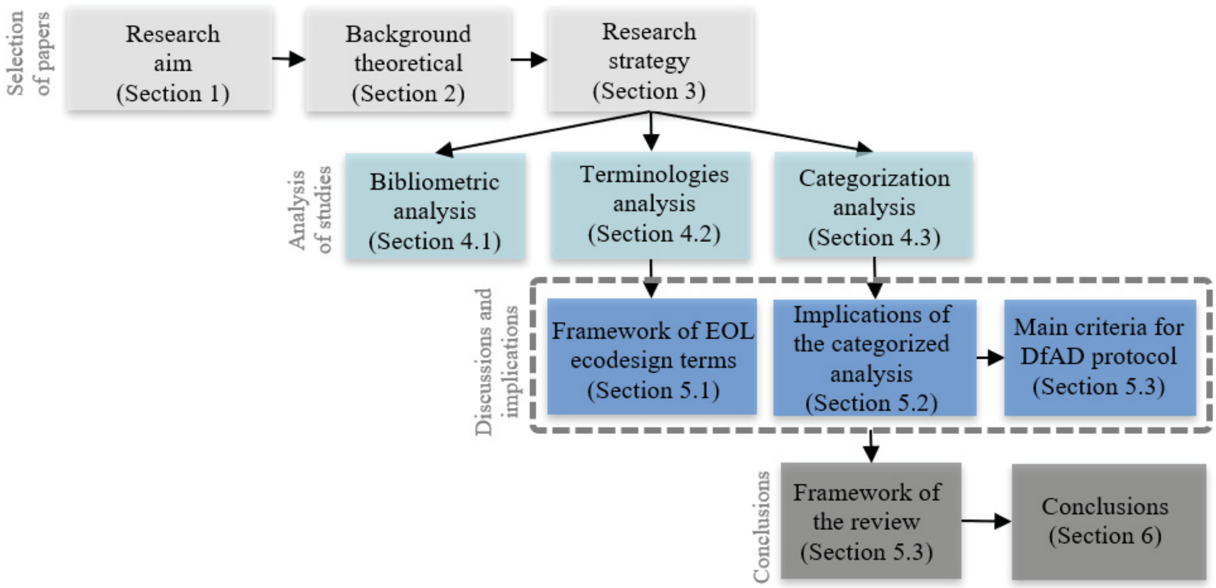


Figure 1. Organization of the study.

2 Background theoretical

Most publications have adopted the terms design for disassembly and design for deconstruction, but the terminologies of ecodesign methodologies have not yet reached a consensus in the scientific community. For the Waste and Resources Action Program (WRAP, 2009), the “design out waste” is an ecodesign method that aims to influence design decisions to reduce construction waste through five strategies: a design for reuse and recovery; design for off-site construction; design for materials optimization; design for waste efficient procurement; and design for deconstruction and flexibility. For other authors, circular strategies are independent terms. A report by the European Commission (2020) considers design for durability, adaptability, and reducing waste as approaches capable of reducing waste generation, optimizing the use of materials, and reducing the environmental impacts of projects. For Cambier et al. (2019) designers and clients need to follow 16 qualities of circular design based on three approaches: designing for longevity, disassembly, and reuse. Antonini et al. (2020) identified reversibility and durability as indicators for evaluating circular construction technologies.

Durmisevic (2019) denominated Reversible Building Design a methodology based on disassembly, adaptability, and reuse and as such determine the level of spatial, structural, and material dimensions of reversible buildings. Meanwhile, for other authors (Webster, 2007; Clapham et al., 2008; Anastasiades et al., 2020; Munaro et al., 2021), “design for adaptability” and “design for disassembly” are strategies integrated with the terminology “Design for Adaptability and Disassembly”. Munaro et al. (2021) considered DfAD as an umbrella term that encompasses different ecodesign methodologies. Moreover, different terminologies have been noted with regards to “selective deconstruction”, “demountable building”, and “circular building”.

In addition to the different terminologies used in the scientific community, the studies have different strategies to guide the establishment of CE principles for EOL buildings, and there are not yet globally recognized standard guidelines. Thormark (2001) developed eighteen design strategies based on the choice of materials, design of construction, and choice of joints and connections. According to Kibert (2003), DfD must consider 27 principles of design based on three levels: systems, product, and materials level. Nordby et al. (2007) developed a system based on 31 strategies for the recovery of materials. Sassi (2008) established criteria for the closed-loop building materials cycle. Crowther (2016) listed 27 design principles for disassembly. Akinade et al. (2017) identified 38 critical factors for DfD, grouped into stringent legislation and policy; deconstruction design process and competencies; design for material recovery; design for material reuse; and design for building flexibility. A building circularity assessment methodology based on DfAD has been also proposed by Geraedts (2016). Durmisevic et al. (2019) defined the weights for eight DfD criteria of technical reversibility accordingly to the functional, technical, and physical independence of the building/structure, as shown in Figure 2.

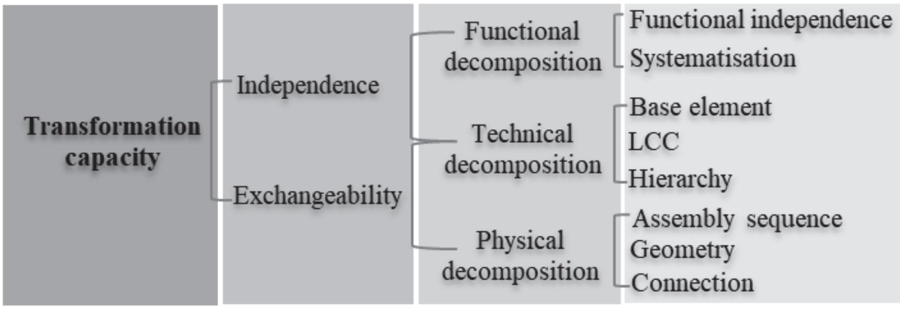


Figure 2. Reversible protocol for technical aspects of reversibility (adapted from Durmisevic, 2019).

The design aspects that influence decision making during the design of reversible structures consider:

1. Functional decomposition: subdivide the building into different independent systems and subsystems with different performances and life cycles;
2. Systematization and clustering: grouping components and elements into an independent module based on functionality, assembly/disassembly process, coordination of the element's lifecycle, and their expected usage lifecycle;
3. Hierarchical relations: minimization of the number of relationships that represent functional and technical dependencies between building elements;
4. Base element: to provide independence of elements within two clusters, each cluster must define its base element, which integrates all surrounding elements of that cluster;
5. Life cycle coordination (LCC): integration of materials concerning their lifecycle. Elements, which have a short life cycle, must be assembled last and disassembled first;
6. Assembly sequences: The sequences in the assembly represent the complexity of the structure and dependencies between building elements. Sequential assembly creates dependencies between the assembled elements, parallel sequence, instead, can speed up a build/unmount process;
7. Geometry: design the edge geometry of the product/component that allows the recovery of elements without damaging themselves or other elements;
8. Connections: use connections that allow for the separation and recovery of the elements.

3 Research strategy

The research strategy consisted of an integrative literature review with explicit and systematic review methods for data processing and analysis to protect against bias and improve the accuracy of conclusions (Transfield et al., 2003). The review followed a succession of six steps based on Torraco (2005), Whittemore and Knafl (2005), and Transfield et al. (2003), as shown in Figure 3.

1	**Problem identification**			
	How can Design for Adaptability and Disassembly and other building deconstruction-oriented ecodesign methods support the transition towards integration of circular economy within the construction sector?			
2	**Literature search**	Database (No. Articles)		
	Search strings	Web of science	Scopus	EBSCO
1	("circul* buil*" AND "circula* econom*") OR ("circul* construct*" AND "circula* econom*")	41	60	12
2	((("design* for adaptab*") AND (build* OR construct*)) OR ("adaptabl* build*") OR ("design* adaptab*" AND buil*) OR ("design* adaptab*" AND construct*))	68	123	27
3	((("design* for deconst*") AND (build* OR construct*)) OR ("deconstr* build*") OR ("design* deconst*" AND buil*) OR ("design* deconst*" AND construct*))	47	72	27
4	((("design* for disassemb*") AND (build* OR construct*)) OR ("disassemb* build*") OR ("design* disassemb*" AND buil*) OR ("design* disassemb*" AND construct*))	72	103	31
5	((("design* for modula*") AND (buil* OR construct*)) OR ("modular* build*" AND "circular* econom*") OR ("design* modula*" AND buil*) OR ("design* modula*" AND construct*))	156	267	190
6	((("design* for transforma*") AND (buil* OR construct*)) OR (("design* transforma*") AND (build* OR construct* OR "circular* econom*")))	37	50	49
7	((("design* out waste*") AND (buil* OR construct*)) OR ("design* out construct* waste*") OR (("design* waste*") AND (buil* OR construct*)))	45	62	27
8	((("design* for change*") AND (buil* OR construct*)) OR (("design* for change*") AND ("circular* econom*")))	23	40	197
9	(("build* deconst*" OR "build* disassemb*" OR "build* demount*") OR (build* AND deconst* AND "circular* econom*"))	77	82	23
10	(("flexib* build*") AND ("sustainab*" OR "circular* econom*")) OR ("flexib* build*" AND deconst*))	19	33	6
11	((("revers* build* design*") OR (("revers* build*") AND (sustainab* OR "circular* econom*")) OR (revers* AND build* AND "circular* econom*")))	31	42	12
12	(("demount* build*") OR ("demount* construct*") OR (demount* AND build* AND "circular* econom*"))	19	28	8
13	((("transform* construct*" OR "transform* build*") AND ("circular* econom*")) OR (transform* AND build* AND "circular* econom*"))	93	94	51
14	(("build* reus*" AND sustainab*) OR ("build* reus*" AND "circular* econom*"))	21	24	8
15	(("regenerat* build*" OR "regenerat* construct*") AND ("circular* econom*" OR sustainab*)) OR ("build* for regenerat*"))	12	18	13
	Total articles		**2540**	
3	**Identification of pre-selected studies**			
	Duplicate publications: exclusion of 879 articles		1661 articles	
	Analysis of title / abstract / keywords: exclusion of 1307 articles		354 articles	
	Full-text analysis: exclusion of 104 articles		250 articles	
	Final sample of the content analysis		**250 articles**	
4	**Categorization of selected studies**			
	Six categories were created in the thematic analysis. They are derived from inductive and flexible content analysis (Elos and Kyngas, 2008), according to the similarities and tendencies found in the articles.			
5	**Analysis and interpretation of studies**			
	• Bibliometric analysis • Terminologies analysis • Categorized analysis • Discussions and interpretations			
6	**Presentation**			
	A synthesis of the main criteria for DfAD was created. A framework was developed to portray the state-of-art of deconstruction design in the studies of the review			

Figure 3. Summary of the integrative literature review stages.

The first step was problem identification. This review aims to give a comprehensive overview of the academic studies on DfAD, identify the current state of the research, and existing ecodesign definitions, create a conceptual categorization of the studies, and identify the main criteria for DfAD to provide a means of describing and understanding the problem.

The second step determined the protocol developed in the literature review, based on fifteen search strings related to EOL ecodesign methods determined on a previous analysis of the literature. It was sought to capture the publications containing terms and expressions semantically different, but with the same meaning of the proposed problem. The sources of information were the academic databases Web of Science of Clarivate Analytics, Scopus of Elsevier, and EBSCO Information Services. Web of Science was selected because it can reach all indexed journals with a calculated impact factor in the Journal Citation Report (JCR), Scopus because it is the largest database of peer-reviewed papers, and EBSCO by the diversity of publications in different areas of research. The research criterion applied in the Scopus was “Title, Keywords, and Abstract”. The inclusion criteria were articles, reviews, and proceedings papers, without temporal cut and defined research area and English language.

By focusing on the review (third step) relevant sources identified were reduced from 2540 to 250 articles (Figure). The articles were selected through an initial reading of the title, followed by a careful understanding of the abstract and keywords, and finally, by critical reading of the entire article, to determine if the study fell within the scope of the review. In addition to the articles selected by the review, some gray literature publications were included to provide indications of how the problem is being discussed outside of academia.

The fourth step was the content analysis of the data to attain a condensed and broad description of the subject and the outcome is categorized to describe the problem (Elo and Kyngas, 2008). The studies were classified into six categories to fit and standardize the data within criteria for further analysis of the results. Sequentially, the data was analyzed and discussed (fifth step) through bibliometric analysis, identification of the main EOL ecodesign terms, and categorized analysis. The sixth step covers the main contributions of the study, presenting the main criteria related to the design of reversible buildings obtained from the review studies. Furthermore, synthesis in the form of a framework was developed to comprehensively portray the review. Synthesis is a creative activity that produces a new model, conceptual framework, or other unique conception informed by the author's intimate knowledge of the topic (Torraco, 2005).

4 Results and analysis

The analysis of the results was divided into three sections: i) bibliometric analysis; ii) terminologies analysis, and iii) categorized analysis.

4.1 Bibliometric analysis

Table 1 shows the main information about the articles selected in the review. The 250 selected articles were published between 1996 and May 2021, with 161 articles (64% of the review) published in 77 different journals and 89 proceeding papers (36%) in 55 proceedings, emphasizing the extension and decentralization of the subject. Most of the scientific journals have environmental issues and CE as a focus of interest. The three most representative journals were Sustainability, Resources, Conservation & Recycling (RCR), and Journal of Cleaner Production. As for the proceedings paper, the highlight was the IOP Conference Series: Earth and Environmental Science with 29 publications (33%), mainly because of the publications of the project Building as Material Banks (BAMB) conference studies, BAMB-CIRCPATH: A Pathway for a Circular Future. The articles had 1171 keywords, with the most recurrent expression being “circular economy”. The studies were developed by 550 different authors and 35 articles were of single authorship, obtaining an average citation rate of 19.58 per article. The collaboration rate between authors was 0.45.

Table 1. Main information from the literature review.

Main information	Number
Total number of documents	250
No. of articles published	161
No. of proceeding papers published	89
No. of Journals of publications	77
No. of Proceedings of publications	55
Author's Keywords	1171
Most cited keyword	Circular economy
Time frame	1996-2021
Average citations per research paper	19.58
Total number of authors	550
Authors of single-authored articles	35
Documents per author	0.45

Figure 4 shows the research methodological approach of the studies. The publications were classified according to the research approach, research aim, the procedure adopted, and data collection (Malhotra, 2012). 58% of the 250 articles selected presented a qualitative approach, 40% a quantitative approach, and 2% a mixed approach. The qualitative studies presented descriptive and exploratory research objectives, with the predominance of the bibliographic research procedure (87%), followed by case studies (23%). Studies with quantitative approaches presented descriptive and causal research objectives, and the most adopted procedures were modeling and/or simulation (68%), experiments (23%), and surveys (9%). Studies with mixed research approaches presented exploratory objectives between the survey and case study research procedures. The predominance of descriptive qualitative studies shows the sector's tendency to describe and correlate aspects of deconstruction practices in buildings, in line with exploratory studies, which aim to provide greater familiarity with the problem and make it more explicit for the community of interest. On the other hand, studies with quantitative approaches aim to validate analytical models for dismantling and reusing construction materials, and the experiments seek to observe the behavior of structures and components designed for dismantling buildings.

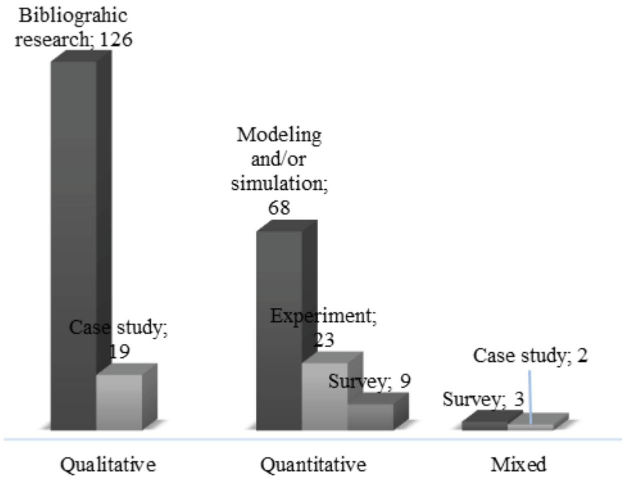
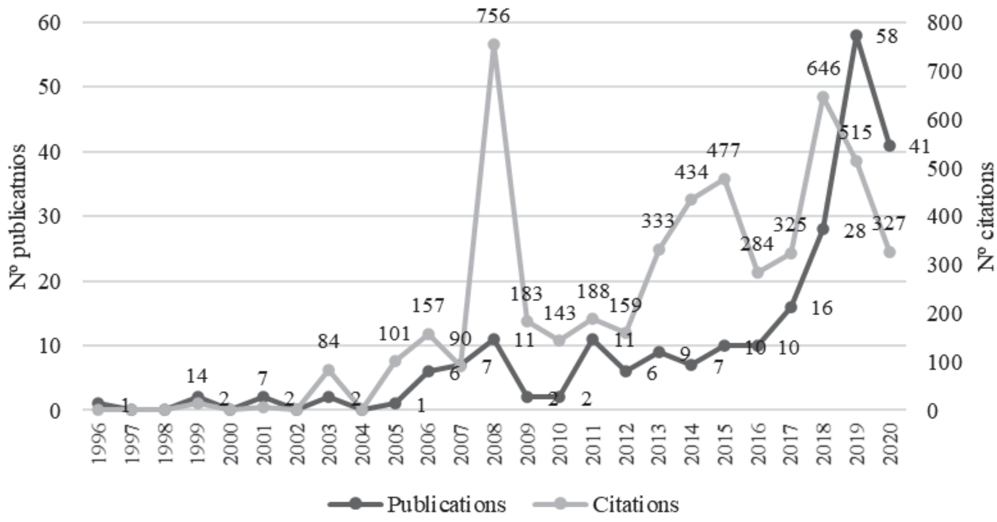


Figure 4. Research methodological procedure (number of articles = 250).

Figure 5 shows the evolution of the number of publications and citations. The DfD concept emerged in the 90s (Kibert, 2003) and the first publication presented two case studies of demountable buildings for multiple uses (Westbury, 1996). After 2010, the increase in publications remained constant over the years, a point that corroborates the developments in CE linked to the institution of the first circular law in China (Türkeli et al., 2018). In 2019, there was an increase in the number of studies due to the publication of the proceeding papers of the final event of BAMB-CIRCPATH. The last four years account for 57% of the research, indicating the interest in the adoption of deconstruction practices in the sector. Citations showed an increasing trend over the years, with a peak in 2008 due to the article by Osmani et al. (2008), which is the most cited in the review (Table) and investigates the role of architects in minimizing the generation of construction waste in the design phase. In 2018, the number of citations was also increased due to the article by Akanbi et al. (2018) which presents the development of a Building Information Modeling (BIM)-based tool to evaluate the recovery performance of components in the final stage of the building's life.



*The articles published in 2021 are not represented. **Total citations were obtained in September 2021.

Figure 5. Total publications and citations by year.

Table 2 presents the ten most cited articles in the review. Osmani et al. (2008) have the most cited article and the longest publication time on the list. The importance in terms of visibility of research by the journal Resources, Conservation & Recycling (RCR) and studies from the United Kingdom (UK) is highlighted, to develop technologies and tools to minimize waste at the EOL of buildings. The three most cited articles present perspectives from local interest groups, also with a focus on reducing CDW in the design phase.

Table 2. Most cited articles in the systematic review.

Authors	Title	Citations	Journal	Country
Osmani et al. (2008)	Architects' perspectives on construction waste reduction by design	513	Waste Management	UK
Jaillon and Poon (2014)	Life cycle design and prefabrication in buildings: A review and case studies in Hong Kong	172	Automation in construction	Hong Kong
Wang et al. (2014)	Critical factors in effective construction waste minimization at the design stage: A Shenzhen case study, China	168	RCR	China
Akinade et al. (2015)	Waste minimization through deconstruction: A BIM-based Deconstructability Assessment Score (BIM-DAS)	151	RCR	UK
Baldwin et al. (2009)	Designing out waste in high-rise residential buildings: Analysis of precasting methods and traditional construction	143	Renewable Energy	UK
Jaillon and Poon (2010)	Design issues of using prefabrication in Hong Kong building construction	141	Construction Management and Economics	Hong Kong
Akanbi et al. (2018)	Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator	131	RCR	UK
Tingley and Davison (2012)	Developing an LCA methodology to account for the environmental benefits of design for deconstruction	113	Building and Environment	UK
Akinade et al. (2017)	Design for Deconstruction (DfD): Critical success factors for diverting end-of-life waste from landfills	113	Waste Management	UK
Lehmann (2013)	Low carbon construction systems using prefabricated engineered solid wood panels for urban infill to significantly reduce greenhouse gas emissions	102	Sustainable Cities and Society	Australia

Figure 6 shows the geographical distribution of the publications according to the first author's country. Europe accounted for 54% of the research covering 21 countries, followed by Asia (28% and 11 countries). These regions accounted for 74% of the review studies. Among the 39 countries, the UK is the leading in volume (40 articles) of publications, followed by the United States of America (29 articles), and Germany (21 articles). The predominance of England studies is related to the adoption of public policies and regulatory support (Ajayi and Oyedele, 2017), and the diversity creation in the co-authorship portfolio (Türkeli et al., 2018). Large countries in terms of geographical area and economy, such as Brazil, India, and Russia, still have no relevance in the subject. It is noted that China has great academic representation in research related to the CE at the meso/macro-level (e.g., eco-industrial parks, low carbon economy) (Türkeli et al., 2018) and a smaller number of publications focused on demountable buildings.

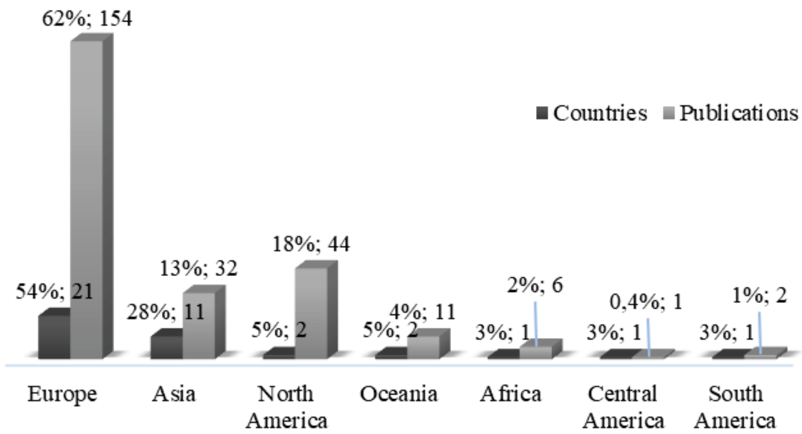


Figure 6. Geographic distribution of publications (number of articles = 250).

4.2 Terminologies analysis

The studies presented different expressions of ecodesign to relate to the subject of deconstruction building at the design stage, as shown in Table 3. The terminologies were grouped according to the focus and/or trend presented in the studies. Design for disassembly and design for deconstruction was the most used expressions in the review, representing more than 50% of the studies, and were used as synonymous expressions. Kanters (2020) incorporates the idea of reconstruction, calling the term Design for de-/reconstruction or DfD/R, adding the condition that materials and components will be re-used. The expression "Design for Adaptability and Disassembly" encompasses both the aspects related to deconstruction and the building's ability to change and, although still not widespread, this variety has been considered an umbrella concept (Munaro et al., 2022). Webster (2007) assesses that the main benefits of DfAD are the expected increase in the useful life of the construction and material reuse rates and that this methodology will increase the market value of the buildings.

The expressions “modular building”, “demountable building”, “Industrial, Flexible, and Demountable building system (IFD)”, and “deployable design” were used in studies related to the trend in the development of the industrialization of buildings. Studies that used these terms addressed prefabrication to simplify component production and effectively improve the efficiency and quality of building design and construction, accommodate functional changes over time, and meet reconfiguration or even relocation needs without demolition (Shahi et al., 2021). The focus of this set of terms is modularization in designs that is directly related to early decision making and appropriate compatibility focused on planning and coordinating construction projects (Shahi et al., 2021; Tavernier et al., 2021). However, it must be emphasized that modularity does not guarantee adaptable, or "circular" buildings (Tavernier et al., 2021).

“Design for adaptability”, “design for change”, and “adaptive reuse” were terms used in studies that addressed the changing needs of users and external factors throughout the life cycle of buildings. Understanding these changes is key to creating adaptable buildings and reducing the effort and expense involved in adding, altering, or replacing building components. In practice, however, most buildings are designed and constructed to suit their current use, while their future adaptability is ignored (Sanchez and Haas, 2018). Adaptive reuse is intrinsically linked to urban mining, retrofit activities, and the reuse of historic buildings linked to the needs of the local population (Elsorady, 2014). This group of terms reflects strategies to avoid obsolescence of buildings and ensure the comfort and satisfaction of occupants, economic and environmental feasibility, and extend the life of a building since 60% of the reasons for demolition stem from obsolescence (Ross, 2017).

“Design for reuse”, “design out waste”, and “design for construction waste minimization” were terms used in the studies that emphasized design measures capable of minimizing the waste generated by construction and demolition activities. Studies suggest that designing for standard materials size and designing for a modern method of construction, public policies, process design and competence for deconstruction, and project documentation are the main measures to mitigate waste (Akinade et al., 2017; Ajayi and Oyedele, 2018). It is significant to determine designers' levels of awareness of the fact that most waste generated at all stages of building life is largely based on design-related decisions (Osmani et al., 2008).

The expressions "Circular building", "reversible building" and "design for a Circular economy" adhere to the concepts of CE and Cradle-to-Cradle, emphasizing the closing and coupling of material loops to establish effective and efficient resource flows. DfD was considered a fundamental aspect of the circular construction project and the customer is the main actor in the possibility of reusing building materials and components from the design stage (Kanters, 2020). The studies emphasized a systemic and holistic design vision, incorporating multiple material flows and economic and social values among the sector's stakeholders. This implies that buildings and their components must be designed to retain value and meet changing needs considering the different useful lives of the components used in the building.

Table 3. List of the ecodesign methods aimed at building deconstruction collected from the literature review.

Group	Term used	Citation (No. Articles)	Definition	References
Material recovery	Design for disassembly	67	It is a method to design a transformable building that enables the systematic disassembly of the building and reuse/recycling of its parts/materials. DfD is the reversal of the construction process and results in a building designed for all the stages of its life cycle	Crowther, 1999; Thormark, 2007; Durmisevic, 2019
	Design for deconstruction	62	It is a method where a building is designed to facilitate not only adaptation and renovation but also the reuse of building materials and components. It aims to close the cycle of construction materials by including principles that allow for their deconstruction	Kibert, 2003; Kanters, 2018
	DfDA	4	In this variety, the building components can be disassembled to be replaced whenever necessary, and the building layout can be adapted whenever new requirements arise	Webster, 2007; Anastasiades et al., 2020
Industrialization	Modular building	17	Modular construction entails applying three-dimensional sections or modules which are manufactured in a precast plant before shipment to construction sites. The method avoids unnecessary demolition, and the building modules can have multiple cycles of use	Banihashemi et al., 2018; Shahi et al., 2021
	Demountable buildings	9	A demountable structure must provide flexibility to the end-user. The system must be capable of being transported in standard size units, it must be quick and easy to erect and dismantle, and it must be deployable on any site, involving fewer laborers	Westbury, 1996
	IFD	5	It is a construction method for creating flexible housing based on mass production, demountable connections, and easy adaptation of buildings	Geraedts, 2011
	Deployable design	1	Deployable structures are designed to be transportable, adaptable, flexible, easy to mount, and quick to manufacture with modular elements	Torres, 2013
Building adaptation	Design for adaptability	16	Adaptability is the ability to respond to change. The method designs buildings to facilitate physical modifications, renovations, reconfigurations, deconstruction, and reuse of its components to extend the useful life of the buildings	Gosling et al., 2013; Ross et al., 2016
	Design for change	6	It fosters future transformations and allows buildings to be refurbished efficiently and adapted effectively to meet changing users' demands, allowing the disassembling, reuse, and recycle building elements, thus closing material loops	Rajagopalan et al., 2021
	Adaptive reuse	13	It is the process of reusing an obsolete and derelict building by changing its function, meeting current standards, and maximizing the reuse and retention of existing materials and structures	Vardopulos, 2019; Shahi et al., 2020
CDW reduction	Design out waste	10	The strategy is to design the use of each material with no value intrinsic or inherent value discarding, minimizing the waste generation. According to WRAP, it is based on: Design for Reuse and Recovery; Design for Off-Site Construction; Design for Materials Optimization; Design for Waste Efficient Procurement; and Design for Deconstruction and Flexibility	Osmani, 2013; WRAP, 2016
	Design for reuse	7	It is a specific design for reuse (not recycling) and includes facilities for anticipating deconstruction. The reclaimed building components and materials can be used again, repaired, remanufactured, or recycled	WRAP, 2016; Bertin et al., 2020
	Design for construction waste minimization	1	It is a process aimed at reducing construction waste throughout the building life cycle based on the understanding of the concepts of net-zero carbon and the circular economy	Laovisutthichai et al., 2020
Resource efficiency	Circular building	10	It is a building that is designed, planned, built, operated, maintained, and deconstructed consistently with Circular Economy principles. Considers the associated dynamics of processes, materials, and stakeholders that accommodate circular flows of resources and materials	Geldermans et al., 2019; Antonini et al., 2020

Reversible design	4	A method that systematically plans the decommissioning phase of the building elements, facilitates transformation in building function and structure and allows those elements with a shorter lifespan can relatively easily be maintained or exchanged	Klinge et al., 2019
Design for a Circular Economy	1	Considers reducing, reusing, and recycling waste from a building, and better managing material resources. The method encompasses different design initiatives, such as design for modularity and off-site construction, Design for Adaptability, design for durability, Design for Disassembly, design for material recycling, and other initiatives to reduce material consumption	Ipsen et al., 2021

4.3 Categorization analysis

DfAD relates to different issues in the construction sector and the review articles were grouped into six categories, as shown in Table 4. It is important to categorize the articles to demonstrate the concentration of current efforts related to the subject and raise the gaps that need to be better clarified in the building design process. The main characteristics of each category are described below.

Table 4. Summary overview of the categorized review studies.

Ranking (No. papers; %)	Category	Description	Scope*
76; 30.4%	Design and construction principles	It explores design and construction strategies linked to ecodesign principles to facilitate the implementation of deconstruction strategies, and recovery of materials and components at the building's end of life	Architectural values; Adaptability; DfD; Building information; IFD; Modularity
50; 20.0%	Tools for DfAD	It proposes tools, methods, and assessment systems aimed at designing, measuring, and implementing strategies for minimizing waste, recovering materials, efficiently using resources, analyzing environmental impacts and the economic potential of building components	BIM; Lifecycle tools; Waste prediction; Material recovery; Environmental assessment
40; 16.0%	Components and connections for DfAD	It presents studies and experiments on prefabricated, composite, and modular structures with the use of reversible connections, reusable elements, and recyclable materials	Bolted joints; Prefabrication; Timber building; Steel-concrete structures; Push-out tests
32; 12.8%	Barriers, drivers, and guidelines for DfAD	Best practice measures about CDW management; barriers, drivers, and guidelines for designing and implementing demountable buildings and circular principles in the construction sector	Codes of practice; CDW management; Building standards; Sustainable design
32; 12.8%	Existing building stock potential	It addresses building assessment and adaptation strategies that improve existing construction conditions and extend the life of buildings and their components to minimize CDW generation	CDW; Heritage building; Material bank; Reusing; Recycling; Urban Mining
20; 8.0%	Selective deconstruction process	Studies on the selective dismantling of buildings, considering methodologies, criteria, and the use of BIM in technical, environmental, and socioeconomic issues of deconstruction	BIM compliant tools; Deconstruction automation; Adaptive reuse; Multi-objective optimization

*Review articles are in Appendix A.

a) Design and construction principles

The objective of the category was to explore design attributes and documents for deconstruction projects. The studies sought to develop a set of guidelines, barriers, and drivers capable of reducing waste during deconstructive activities. Bertino et al. (2021) identified three principles for deconstruction: 1) reduction of building complexity; 2) intelligent choice of building materials and components; and 3) access to deconstruction information. Finch et al. (2021) identified twenty circular performance criteria and highlighted three factors that limit circularity: the widespread presence of fixtures that damage components; the widespread use of chemically modified materials; and the geometric qualities of the structure's external components. Eberhardt et al. (2020) evaluated circular design strategies and found that the lack of knowledge about environmental performance and the related benefits of these strategies impedes further implementation of CE in the sector. Webster (2007) cited strategies for effective implementation of DfAD and reiterated that buildings with these characteristics will have a competitive advantage in the real estate market.

Jaillon and Poon (2010) revealed that prefabrication, combined with modular design and standardized components, saved construction time and costs compared to conventional construction. However, design concepts for deconstruction are poorly addressed in precast construction. In this sense, Sadafi et al. (2014) presented guidelines for increasing flexibility in constructions considering the use of prefabricated components, modular coordination systems, layered design, interchangeable and accessible component materials, and employing proper detailed design of fittings and connections. Anastasiades et al. (2021) discussed the importance of standardizing dimensions, components, connections, and compatibility with other building systems in the reusability of building components. They identified that protectionism from contractors who perceive standardization as a threat, protectionism from manufacturers who are reluctant to change the structure of the organization, and from designers who seem less aware of the need to implement the CE are the main barriers to DfD. Antonini et al. (2020) endorse that standardization should also cover the criteria for assessing circularity at the micro-level, highlighting the difficulty in finding circular technologies that are adequate to increase the useful life of buildings. Anastasiades et al. (2020) also reiterated the need for mesoscale circularity indicators to assess the circularity of structures.

Geldermans et al. (2019) identified circular-flexible criteria, grouped into three categories: flexibility capacity, circularity capacity, and user capacity, as essential to facilitate the circular flow of materials through buildings. Ajayi et al. (2017) concluded that good design practices require standardization and dimensional coordination of components, modern construction methods, measures for spatial flexibility, provisions for EOL deconstruction, and BIM techniques for design coordination. Project documentation, on the other hand, must be characterized by integrity and clarity, certainty, timeliness, error-free, and incorporation of a set of plans and schedules.

b) Tools for DfAD

The category comprises studies that used the paradigm of information modeling or Life Cycle Assessments (LCA) to create tools or decision support mechanisms for efficient sustainability performance at the end of the useful life of buildings. The focus of the studies was to ensure the efficient choice of materials during the project to facilitate the effective use of the material, ensure deconstruction and reduce CDW in the built environment. Since the systematic deconstruction of building components allows the recovery of more than 80% of materials (Tatyia et al., 2018).

Rajagopalan et al. (2021) detailed a method to assess characteristics such as circularity, adaptability, and reuse of building elements to provide a way to assess the benefits and constraints of circular buildings and components. Minunno et al. (2020) evaluated that a modular prototype built to be disassembled and reused has an 88% offset in GHG emissions compared to a construction focused on the recyclability of its components. Akanbi et al. (2020) developed a deep learning model to predict the number of secondary materials and waste that can be obtained from buildings at the end of their useful life.

Cottafava and Ritzen (2021) highlighted that connection types, connection accessibility, junctions, and form containment are the best indicators to predict the recovery potential of building components. Shahi et al. (2021) developed a design methodology oriented to existing residential infrastructure to meet energy performance using modular extensions. Feng et al. (2015) used algorithms in a robotic implementation that allows the autonomous assembly of modular structures on construction sites. Akanbi et al. (2018) developed a BIM-based Lifetime Performance Estimator to assess the rehabilitation performance of building structural components from the design stage. Rios et al. (2019) evaluated that the reuse of a material with high incorporated energy (a wall with a reusable steel structure) compared to a single-use alternative (wooden structure) depends on aggressive reuse rates (> 70%) to offset the environmental impacts incorporated during the production of steel. Brambilla et al. (2019) identified that the dismountable structural composite flooring system is the most ecological solution compared to conventional monolithic ones intended for demolition and recycling.

c) Components and connections for DfAD

In this category, several manufacturing principle-based approaches to erecting buildings and industrializing construction were studied. Aspects of prefabrication, open building, external production, and use of modular and standardized components were analyzed to facilitate deconstruction and encourage the reuse or recycling of materials. Ding et al. (2019) developed a finite element model that can be adopted as a tool to understand the seismic behavior and acquire cracking mechanisms of concrete structures with detachable connections. Varela and Saiidi (2019) evaluated the feasibility and performance of a bridge system incorporating plastic hinges and demountable columns. Lehmann (2013) presented the opportunities offered by using cross-laminated wood panels as a lightweight, low-carbon, and advantageous form of construction for residential buildings from 4 to 10 floors. Girão et al. (2019) explored the span-depth relationship of reusable composite beams with bolt-on connectors so that the beams can be designed more efficiently in terms of weight and shear connector distribution across the span. Eckelman et al. (2018) found that dismountable precast concrete floor systems result in higher initial energy use but have smaller impacts than traditional designs if the floor planks are reused. Reusing the boards three times reduces impacts by an average value of 60-70%. Derikvand and Fink (2021) evaluated that the use of detachable connectors with the use of screws in wood-concrete composite systems are effective solutions for the construction of structural floors.

d) Barriers, drivers, and guidelines for DfAD

The category's studies reflect that the choice of strategies to enable deconstruction requires in-depth knowledge of how the building's characteristics, together with the procedures adopted in the deconstruction process, will affect the reuse of materials and components. These strategies are intrinsically linked with waste reduction measures during the design phases, as it is estimated that 33% of construction waste can be avoided in design (Osmani et al., 2008).

Villoria Sáez et al. (2019) demonstrated that the best practice when designing building deconstruction activities is to provide a space for CDW collection, followed by planning selective demolition techniques. It is interesting to note that minimizing waste is not yet part of the core activities of the construction design process (Osmani et al., 2008). For architects, the main obstacles are the perception of waste, unknown causes of design waste, customer requirements, and ill-defined responsibilities. Legislation and financial rewards were seen as the main incentives for waste reduction practices (Osmani et al., 2008; Akinade et al., 2017). Ajayi and Oyedele (2018) found that a collaborative approach and the use of prefabrication techniques can bring the construction industry closer to industrialization, where error and waste are reduced, increasing the accuracy and integrity of the design document.

Tingley and Davidson (2011) analyzed that among the main barriers to deconstruction, the perceived risk in the specification of reused materials stands out; the lack of a market for reused materials; and the financial perception of being more expensive projects. They recommended that environmental assessment methods be revised to increase incentives for

DfD and low-carbon design throughout the building lifecycle. Kanters (2018) showed that there is a lack of a set of international guidelines on the deconstruction project; which building materials have different deconstruction potentials; that the potential of the existing building stock has not yet been exploited and that the main barriers for DfD are the lack of legislation and time and cost constraints for the design team and the client. Rakhshan et al. (2020) identified that barriers related to perception, risk, compliance, and market are very pronounced in the reuse of building components. Abdul Nabi and El-adaway (2021) showed that the most critical factors affecting the cost and schedule of modular projects are shortage of skilled and experienced workers, late design changes, site attributes and poor logistics, design inadequacy for modularization, contractual risks and disputes, lack of collaboration and coordination, and insufficient sequencing of construction activities.

e) Existing building stock potential

Reusing and adjusting future service values of unused buildings to extend lifecycles is a sustainable approach that benefits society, the economy, and the environment. According to Shahi et. al (2020), the adaptation of buildings encompasses a range of construction activities, including adaptive reuse. Studies in this category addressed the adaptive reuse of buildings as the process of extending the useful life of historic, old, obsolete, and abandoned buildings as opposed to demolition and new construction (Shahi et al., 2020). The focus of the category was to establish a comprehensive system and operational plan to assess the effects of reusing these buildings, both in changing the function of a building or some parts of the building and in recovering and reusing existing materials.

Claver et al. (2020) adapted the Analytic Hierarchy Process to relate heritage valuation criteria and spatial compatibility analysis with new uses to select activities that cause less damage to the heritage value to be conserved. Vardopoulos (2019) identified that soil conservation and the protection of cultural heritage are the two critical factors that influence local sustainable development in the adaptive reuse of buildings. van den Berg et al. (2020) when seeking to understand the conditions that lead to the recovery of a construction element, emphasized that it is necessary to (1) identify an economic demand for the element; (2) distinguish appropriate routines for taking it apart, and (3) be able to control performance until integration into a new building. Diyamandoglu and Fortuna (2015) analyzed different scenarios of reuse and recycling of building materials in reducing GHG emissions and energy consumption. The sharpest reduction in GHG emissions was in the maximum recycling scenario. The materials removed saved more energy than recycling and contributed nearly half of the resale value of the recovered materials.

The continuous development of tools and systems for registries of recovered materials was analyzed by Cai and Waldmann (2019) and Heisel and Rau-Oberhuber (2020) as a fundamental prerequisite for the implementation of the circular construction industry. Cai and Waldmann (2019) described the process of documenting materials and products used in the construction of the Mining and Urban Recycling (UMAR) unit within the Madaster platform that generates and records material passports and calculates a circularity indicator for the construction phases, use, and end-of-life.

f) Selective deconstruction process

The studies sought to provide objective and measurable systems to promote the deconstruction of the building during the design phase. To achieve this goal, the use of BIM and Information and Communication Technologies (ICT) were tools explored for facilitating transparent access to information, controlled coordination, and monitoring of deconstruction processes (Basta et al., 2020). van der Berg et al. (2021) suggested three new BIM uses for deconstruction: “3D existing conditions analysis”, “reusable elements labeling” and “4D deconstruction simulation”. Akinade et al. (2015) developed a BIM-based Deconstructibility Assessment Index to determine the extent to which a building can be deconstructed from the design stage. Sanchez et al. (2020) developed an optimization analysis for planning the selective disassembly of assets, considering the physical, environmental, and economic constraints of different deconstruction methods. Volk et al. (2018) developed a sensor-based system for acquiring building information that generates a reconstruction model and a building inventory to facilitate information gathering and planning of deconstructive processes.

5 Discussion and implications

The discussion and implications of the results were divided into three sections and sought to reflect the implications of the different terminology used in the review studies, the discussion of the categorized analyzed, and relate the main design criteria observed in the review studies to DfAD buildings.

5.1 Framework of EOL building ecodesign terminologies

It is observed in Table 3 that ecodesign methods have been studied in the sector with different terminologies and definitions. Many authors consider that these terminologies are often used interchangeably due to overlapping scopes and a lack of clarity on their appropriate uses (Pinder et al., 2017; Shahi et al., 2020; Munaro et al., 2021; Tavernier et al., 2021).

For Antonini et al. (2020) the evaluation of technologies aimed at circular construction can use as indicators of the reversibility and durability of buildings. Reversibility is the backbone of the CE and comprises the set of designs for disassembly, adaptability, and reuse (Durmisevic, 2019). Cambier et al. (2019) consider that a circular building must relate to the adaptability, durability, and reuse approaches. But it is important to note that the terms 'durability' and 'adaptability' are closely related, and both aspects need to be considered and balanced (Pinder et al., 2017; ISO, 2020). For Munaro et al. (2022) DfAD is the term that encompasses different ecodesign methods, such as the set of methods defined in WRAP, and can standardize terminologies and facilitate communication and understanding of the subject in the sector. Thus, based on the comprehensive literature review analysis the framework was developed to facilitate identifying the type of terminologies involved in EOL building ecodesign, as shown in Figure 7.

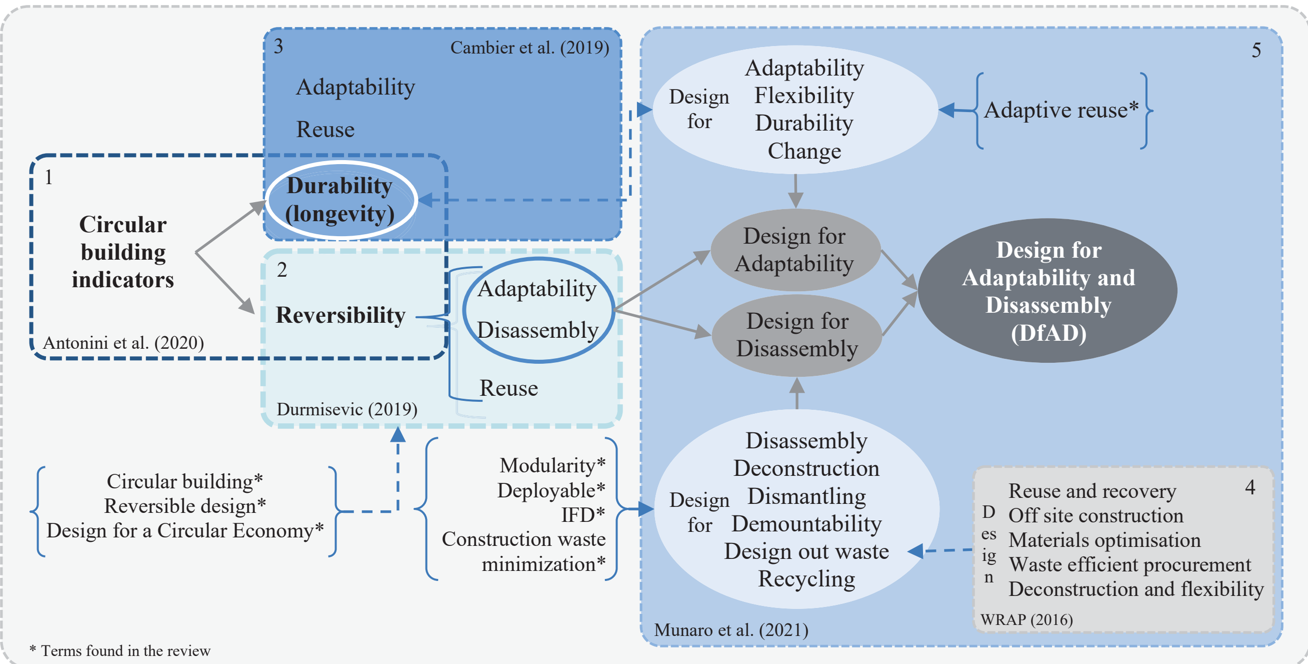


Figure 7. Framework relating different terminologies involved in EOL building ecodesign.

The framework demonstrates that many terms are synonymous or have overlapping purposes. It is recognized that the adoption of a clear and consistent definition framework can avoid the high costs arising from codes, specifications, and project descriptions that confuse these definitions (Shahi et al., 2020). Thus, the language used by professionals and their different interpretations of a project based on the EOL of the building does not yet have a consensus in the sector and can lead to misunderstandings about the project's objectives. An industry consensus regarding the definition of terms that allows for clear and consistent use of construction EOL terms is needed.

According to Tavernier et al. (2021), conceptual terminologies have frequently evolved, driven by changes in society and new procedures in the construction sector. For example, the terms deconstruction and disassembly are often used interchangeably in the literature, however, O'Grady et al. (2021) consider that deconstruction is distinct from disassembly because it refers to the removal of a building's structural elements for rebuilding as opposed to the end-of-life disassembly of a building into reusable components. Relating the terminologies, it is observed that the terms reversible (or circular) building design can be interchangeable with Design for Adaptability and Disassembly, being these two generic terms to be used in the sector. It is noteworthy that international standardization requirements such as The Standards Council of Canada (Clapham et al., 2008) and International Organization for Standardization (ISO) 20887 (ISO, 2020) have been adopting the DfAD term as a positive contribution to sustainable development.

The term "circular building" is a broad concept, and in addition to considering ecodesign methodologies, such as DfAD, it should consider other aspects capable of turning buildings into a bank of materials. Thus, in addition to a reversible design, the use of BIM in project management and coordination, the use of a materials passport to ensure the traceability and retention of value of materials and components, and the use of circular business models should be considered guided by the principles of social, environmental, and economic sustainability. Thus, DfAD is one of the requirements capable of incorporating the full potential of the circular economy principles in the sector. Clamber et al. (2019) consider 16 important qualities in a circular design, recognizing that buildings and their components are never in a final state, but part of a process, so it is necessary to rethink not only how to build, but also what to build. In this sense, the use of the DfAD term instead of reversible or circular building design may be more appropriate when considering the strategy to optimize both the service life and the design life.

5.2 Main implications of the categorized analysis

Six themes were identified in the studies, which allowed to generate an overview of how deconstruction is being applied and studied in the construction sector. The studies emphasized that modularization, prefabrication, and standardization of materials and components are fundamental requirements for the development of a circular built environment. This is mainly due to the use of mechanical and dry connections, the reduction of material waste on-site, and the ease of reusing and reusing components.

The studies expressed the absence of a definition and a protocol for a circular construction project. Choosing the right materials was considered a crucial factor, mainly due to the reduction in GHG emissions and the environmental impacts of the multiple reuses of materials. However, standard methods and tools are lacking to help architects and the design team make the right decision. The design team plays a key role in driving innovative circular architectural solutions and in integrating the different stakeholders in the sector. Thus, in addition to a collaborative design process, greater awareness of adaptable and demountable building design processes is needed.

The lack of circular indicators to assess the potential for the deconstruction of buildings and the low rate of material recovery is one of the main obstacles in the sector. In this sense, the use of the LCA is one of the main tools to assess the environmental benefits of using dismantled components and materials. However, inventories of data relating to mass and energy flows entering and leaving the various stages of the product's life cycle need further standardization to ensure greater reliability and comparability in the application of the methodology. In the process of selective deconstruction of buildings, the use of BIM stands out for its ability to store parametric models and different component data, but it requires a fully informed 3D model of the structure with a high level of development to achieve the technological support necessary for the design of disassembly.

A building planned for disassembly should be seen as a bank of materials, with documented, temporary storage and a certain financial value. Currently, both the documentation and the tracking of recovered materials lack technical and physical support. The use of materials passport and BIM in materials data management are promising tools that need a robust and integrated digital network for accessing and making information available. In addition, the physical storage of secondary materials needs to be defined and budgeted at the design stage, as well as the determination of the stakeholders responsible for the destination of each type of recovered material. It is noteworthy that the studies highlight a greater perception of risk regarding the reuse of recovered materials both from customers and from the design team itself. And the adaptive reuse of buildings is still closely linked to the regularization of energy efficiency requirements.

One of the most popular study groups in the circular building literature focuses on surveying barriers and opportunities for implementing DfAD in the built environment. The studies highlight that the lack of public policy and financial rewards has a major impact on waste reduction practices at the design stage. This suggests that the increase in fiscal measures and the introduction of reward systems for reversible projects would have greater stakeholder engagement in waste minimization practices. In addition, implementing DfAD requirements in building environmental certifications can be an alternative to raising awareness in the sector.

5.3 Main criteria for DfAD building protocol

The categorized analysis of the studies in the review highlighted the lack of a set of international guidelines on DfAD. Considering the 8 design aspects for the technical reversibility of a building, defined by Durmiservic (2019), Table 5 presents 71 criteria obtained from the review articles according to each design aspect. The criteria "Material type" and "Communication, documentation, and BIM coordination" were added to bring more details to the protocol. The objective of Table 5 is to provide a clear protocol to guide the deconstruction process, to be applied in the construction of new buildings, considering this stage as a fundamental element of the building's programming and planning.

Table 5. Main criteria for DfAD building protocol.

Criteria		References
1	Functional decomposition	
1.1	Use an open building system for flexible space management	Kibert, 2003; Akinade et al., 2017; Kanters, 2018
1.2	Minimize the number and types of components and connectors	Sadafi et al., 2014; Akinade et al., 2017
1.3	Standardize building form and layout	Ajayi et al., 2017; Ajayi and Oyedele, 2018; Crowther, 1999
1.4	Designate fixing free zones to maximum lengths of material for reuse	Tingley and Davidson, 2011
1.5	Reduce the complexity of construction and plan for using common tools and equipment	Nordby et al., 2009; Ajayi et al., 2017; Carvalho Machado et al., 2018; Crowther, 2016
1.6	Use interchangeable building components	Akinade et al., 2017
1.7	Optimize the use of interior space and improve the flow-through system layout	Sadafi et al., 2014
1.8	Dedicate a specific volume for each system	Sadafi et al., 2014
1.9	Increase system predictability	Sadafi et al., 2014
1.10	Prepare a deconstruction/demolition plan	Tingley and Davidson, 2011; Sadafi et al., 2014; Akinade et al., 2017; Kanters, 2018
1.11	Design foundations to be retractable from ground	Akinade et al., 2017
2	Systematization and clustering	
2.1	Design for preassembled components such as bathroom & kitchen pods	Ajayi et al., 2017; Ajayi and Oyedele, 2018
2.2	Design components sized to suit handling at all stages	Kibert, 2003; Tingley and Davidson, 2011; Crowther, 2016; Akinade et al., 2017
2.3	Aim for modular construction and use a standard structural grid	Kibert, 2003; Nordby et al., 2009; Crowther, 2016; Ajayi et al., 2017; Akinade et al., 2017; Kanters, 2018
2.4	Use Prefabricated components and mass production where possible	Kibert, 2003; Tingley and Davidson, 2011; Sadafi et al., 2014; Ajayi and Oyedele, 2018
2.5	Specify the use of framing techniques, drywall partitioning, and joint system	Ajayi and Oyedele, 2018
2.6	Use lightweight materials and components with dry connections	Crowther, 2016; Akinade et al., 2017
2.7	Design for steel construction	Akinade et al., 2017
2.8	Provide spare parts and storage for them	Kibert, 2003

3	Base element specification	
3.1	Increase regularity in building patterns	Sadafi et al., 2014; Akinade et al., 2017
3.2	Aim for small-scale and Eases handling and transport components	Nordby et al., 2009
3.3	Facilitate self-building and local reuse	Nordby et al., 2009
4	Hierarchical relations between elements	
4.1	Minimize the number of different types of components	Kibert, 2003
4.2	Reduce intersystem and intrasystem interactions	Sadafi et al., 2014
5	Life cycle coordination in assembly/disassembly	
5.1	Design the layers of the construction as structurally independent systems	Nordby et al., 2009; Carvalho Machado et al., 2018
5.2	Identify the design life of different elements	Tingley and Davidson, 2011
5.3	Separate the structure from the cladding and infill elements of a building	Crowther, 1999; Sadafi et al., 2014; Carvalho Machado et al., 2018; Kanters, 2018
5.4	Define the hierarchy of disassembly according to the expected functional and technical life span of the components	Nordby et al., 2007; Akinade et al., 2017; Carvalho Machado et al., 2018; Kanters, 2018
5.5	Provide access to all parts of the building and all of its components	Kibert, 2003; Tingley and Davidson, 2011; Crowther, 2016
5.6	Increase physical adjacency of access point	Sadafi et al., 2014
6	Assembly sequences	
6.1	Allow parallel rather than sequential disassembly	Nordby et al., 2007; Crowther, 2016; Carvalho Machado et al., 2018
6.2	Assemble in a systematic manner that is suitable for maintenance and allows for the possibility of replacements	Carvalho Machado et al., 2018
6.3	Use assembly/disassembly technologies compatible with common tools and equipment	Crowther, 1999; Kibert, 2003; Kanters, 2018; Finch et al., 2021
6.4	Identify a point of disassembly permanently	Kibert, 2003; Crowther, 2016
6.5	Facilitate the removal of parts that contain hazardous materials	Carvalho Machado et al., 2018
6.6	Provide sufficient information about the assembly/disassembly process	Kibert, 2003; Sadafi et al., 2014; Akinade et al., 2017
6.7	Provide adequate tolerances for assembly and disassembly	Nordby et al., 2007; Tingley and Davidson, 2011; Finch et al., 2021
6.8	Consider the logistics of deconstruction, provide replacement parts and storage facilities	Crowther, 2016; Carvalho Machado et al., 2018
6.9	Use sacrificial materials and components where wear is unavoidable and allow for their easy disassembly from the whole	Crowther, 1999
7	Interface geometry	
7.1	Create regular and standardized structural systems	Carvalho Machado et al., 2018
7.2	Design the geometry to be simple	Tingley and Davidson, 2011
8	Type of the connections	
8.1	Design joints and connections that are accessible, durable, and easily removed	Kibert, 2003; Nordby et al., 2007; Crowther, 2016; Kanters, 2018
8.2	Minimize the number of connectors and different types of connectors	Kibert, 2003; Nordby et al., 2009; Crowther, 2016
8.3	Simplify and standardize connections	Carvalho Machado et al., 2018
8.4	Use mechanical and dry connections	Kibert, 2003; Crowther, 2016; Kanters, 2018
8.5	Avoid joints and screws that affect reutilization	Ajayi et al., 2017; Carvalho Machado et al., 2018
8.6	Avoid using adhesives, resins, and coatings that compromise the possibility of reuse and recycling	Ajayi et al., 2017; Carvalho Machado et al., 2018
8.7	Avoid secondary finishes that cover connections	Tingley and Davidson, 2011
8.8	Give specifications for connections, structure, and installations	Crowther, 2016
9	Material Type	
9.1	Use natural materials and/or eco-labeled	Villoria Sáez et al., 2019; Bertino et al., 2021
9.2	Use and specify recycled, recyclable, and reusable materials	Sadafi et al., 2014; Crowther, 2016; Kanters, 2018; Finch et al., 2021
9.3	Avoid toxic and hazardous construction materials	Nordby et al., 2007; Crowther, 2016; Akinade et al., 2017
9.4	Avoid the use of adhesives, resins & coatings which compromise reuse potential	Tingley and Davidson, 2011
9.5	Avoid composite materials and make inseparable products from the same material	Crowther, 1999; Kibert, 2003; Tingley and Davidson, 2011
9.6	Minimize the variation and number of materials, parts, components, and equipment	Sadafi et al., 2014; Crowther, 2016; Carvalho Machado et al., 2018; Kanters, 2018; Bertino et al., 2021
9.7	Provide standard and permanent identification of material types	Kibert, 2003; Sadafi et al., 2014; Ajayi and Oyedele, 2018
9.8	Avoid secondary finishes to materials	Nordby et al., 2009; Crowther, 2016; Finch et al., 2021
9.9	Apply mechanical methods of water protection instead of chemical sealants and adhesives	Sadafi et al., 2014
9.10	Use of resistant materials that meet the same function with less space/weight	Llatas and Osmani, 2016
9.11	Use of building materials without packaging or provided with optimized packaging	Llatas and Osmani, 2016
10	Communication, documentation, and BIM coordination	
10.1	Design documents legible and easily read/interpreted	Ajayi et al., 2017; Ajayi and Oyedele, 2018
10.2	Design documents with incorporate site conditions and topographical information	Ajayi et al., 2017; Ajayi and Oyedele, 2018
10.3	Drawing documents free of errors and adequately coordinated/integrated	Ajayi et al., 2017; Ajayi and Oyedele, 2018
10.4	Specify project goal and adequate implementation of the sustainable building assessment procedure	Ajayi and Oyedele, 2018
10.5	Ensure design freeze at the end of the design process and involvement of contractors at an early stage	Ajayi and Oyedele, 2018
10.6	Provide updated as-built drawings	Nordby et al., 2007; Tingley and Davidson, 2011; Kanters, 2018

10.7	Provide a full inventory of all materials and components used in the building	Tingley and Davidson, 2011; Akinade et al., 2017; Carvalho Machado et al., 2018; Kanters, 2018
10.8	Use BIM to simulate the process and sequence of building disassembly and estimate the end-of-life property of materials	Llatas and Osmani, 2016
10.9	Record the data of generation, quantities, and characteristics of the waste through the BIM platform	Ajayi et al., 2017; Carvalho Machado et al., 2018; Villoria Sáez et al., 2019
10.10	Provide dissemination of knowledge and training to designers and builders of the environmental, social, and economic benefits of DfD	Nordby et al., 2007; Akinade et al., 2017; Kanters, 2018
10.11	Support research, use, and provide quantification of economic benefits of salvageability in the life cycle of buildings	Nordby et al., 2007

So far ISO 20887 is the only standard that addresses the reuse of building elements in new constructions, even though the terms DfD and DfA are already widely discussed in the scientific community (Anastasiades et al., 2021). It is observed that the criteria for a DfAD are linked to a higher level of industrialization in the sector, but manufacturers of construction materials and components need to support this change, especially considering the standardization and compatibility of connection between these elements.

It is important to emphasize that there is no point in designing circular buildings if there is still no specific direction for the reuse of recovered materials. Related challenges regarding perceived warranties, performance, quality, aesthetics, and durability of secondary materials need to be overcome by design teams and end customers. Technical challenges, including the lack of recovery routes and proper storage, hamper material recovery strategies (Munaro et al., 2020).

As soon as these DfAD criteria begin to be implemented in the sector, a systemic change in the way buildings are designed, built, and consumed will be gradually consolidated. On the one hand, it will be possible to optimize the capacity of each building to effectively accommodate the demands and needs of its users, increasing its usefulness, extending its useful life, and thus maximizing its value over time. On the other hand, it is possible to optimize the efficient management of resources of all material flows related to construction, avoiding the depletion of natural resources and the production of waste, and thus minimizing the environmental impact of buildings.

Figure 8 presents a summary of the main results obtained from the systematic review of DfAD. The framework seeks to characterize how the subject is being discussed in the academic community, provide guidelines to make deconstruction a circular practice in the construction scenario, address some research gaps to unveil new study possibilities, contribute to the strategic performance of borrowers' decision-making process and promote an approximation between the theme and the reality of the market.

	Analysis	Results	Implications
Building deconstruction	Main ecodesign terms used	Design for Disassembly Design for Deconstruction DfDA Design for Adaptability Design for Change Adaptive reuse Design out waste Design for Reuse Design for construction waste minimization Modular building IFD Demountable Deployable design Circular building Reversible design Design for a CE	- DfDA in considered an umbrella concept - "Reversible" or "circular buildings" must include, in addition to an ecodesign methodology, different circular strategies to make buildings bank of materials
	Main themes discussed	1. Design and construction principles 2. Tools for DfAD 3. Components and connections for DfAD 4. Existing building stock potential 5. Barriers, drivers, and guidelines for DfAD 6. Selective deconstruction process	1. Focus on building standardization, modularization, and prefabrication 2. Lack of circular indicators; Use of LCAs in the analysis of the environmental benefits of reversible components; 3. Importance of choice of materials and mechanical connections; 4. Adaptive reuse was focused on building energy efficiency; Perceived risk of secondary materials use; 5. Lack of legislation and financial rewards; Lack of design teams competence and knowledge for deconstruction; 6. Different methods to assess deconstruction; Predominant use of BIM.
	Main criteria of the DfAD	1 Functional independence 2 Systematisation 3 Base element 4 Hierarchy 5 LCC 6 Assembly sequences 7 Geometry 8 Connection 9 Material type 10 Building information	71 criterias to guide DfAD focusing: - standardization and pre-fabrication - simple, adaptable, and modular forms - layering of building components - parallel disasembly - mechanical and dry connections - avoid composite materials - provide traceability and documentation of the materials - supply chain integration thorugh BIM tools

Figure 8. Summary framework of the review on DfAD.

6 Conclusions

This study aimed to analyze how Design for Adaptability and Disassembly and ecodesign methods related to building deconstruction help to implement circular principles in the construction sector. Standardization, modularization, and prefabrication of components and materials were considered fundamental criteria for the circular transition of the built environment. This is mainly because off-site production reduces the generation of construction waste and requires a collaborative design and construction process.

The main barriers to DfAD implementation were the design team's lack of knowledge and training on the environmental benefits and how to design a building for deconstruction, the lack of legislation and tax incentives, and the lack of tools, methods, and indicators circular. Although LCA and BIM are essential tools for the effective implementation of deconstruction at the design stage, building certification schemes can provide guidance to the designer in terms of a series of criteria to meet and references to materials and construction methods, however, DfAD principles need to be better incorporated in certifications with careful attention to the established weights so that some criteria do not distort the project certification result.

In addition to greater awareness of DfAD, market conditions such as consumer demand and economic attractiveness are necessary for a transition towards circularity. The implementation of markets with inventory control systems, product tracking, monitoring protocols, and publication of information on secondary materials that are or will be available is fundamental to transforming buildings into a material bank. Government regulations and fiscal actions are imperative to achieve an effective DfAD and play an important role in the sustainability agenda due to the reduction of GHG emissions from material production, transportation, and waste management.

The main contribution of this study was the establishment of DfAD criteria to guide decision-making in the design stage. Circular buildings require the adaptation of construction processes to the mechanical and geometric properties of the available materials and the use of less complex materials to facilitate reuse or upcycling. The prefabrication associated with the DfAD reduces the complexity of the buildings by expanding the adaptability, durability, transportability, assembly, and disassembly capacity. The Design for Adaptability and Disassembly was the main mechanism recommended to minimize the generation of waste in construction. The practical implications were to propose directions for future research to expand the discussion and development of the ecodesign methods, seeking cleaner productions and more circular constructions.

As future research, it is expected to survey with different stakeholders in the construction sector to define weights for the DfAD criteria established in this study, as well as to point out the main barriers related to the implementation of circular building projects. Another direction of this study is to carry out a comparative analysis of different methods of modular construction, such as light steel frames, wood frames, and prefabricated concrete structures, and analyze aspects related to the implementation of the principles of circular economy in the sector.

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PART 3

Part 3 presents the main conclusions of this thesis, as well as limitations and directions for future work. In addition, it covers the references used in this document.

4 CONCLUSIONS

This study sought to explore possibilities for innovation and value creation in the built environment by associating economic activities with the circular principle of closing the cycles of materials, services, and systems in the construction sector. Through the state of art carried out in paper 1, research directions were determined for the implementation of CE-based practices in the sector that was explored in six new studies. Paper 2 presented a model of materials passport to facilitate decision-making in the design phase of buildings. The need to think about circular business models and systems was explored in article 3, which culminated in a series of examples of circular business models. Government support, crucial for the strategic action of decision-makers to introduce circular principles, was explored in paper 4. Articles 5 and 7 addressed the deconstruction strategies of buildings that favor the recovery, reallocation, reuse, recycling, or remanufacturing of building components. Finally, article 6 sought to understand the limitations and opportunities of the CE, associated with the stakeholders responsible for this transition towards circularity in the construction sector.

The results of this thesis show that the adoption of circular mechanisms is still incipient in the sector. The concentration of publications in recent years highlights the importance of the problem in the scientific community. The centralization of work in European countries and China demonstrates the result of the implementation of public policies and emphasizes that the expansion of research in other countries lacks political and governmental support. Research on CE in the built environment emphasizes the reuse of construction and demolition waste as an additive for new materials, aiming to reduce the extraction of natural resources and the environmental impacts of the construction sector. Despite efforts to develop support mechanisms in the implementation of circular practices, material flow analysis, mining of anthropogenic stocks, and design of circular materials and systems, research is still focused on reducing, mitigating, and reusing waste to increase the residual value of materials.

Realizing the potential of circularity requires a new approach to business models for all stages of the building life cycle and all those involved in the value chain, embracing changes in planning, design, technology, and economic and market approaches. The materials passport model, the methodology to create and incorporate value in business models, the different circular business models presented, as well as the ecodesign methodologies and the criteria of a reversible building design are value creation mechanisms and directions in the transition for buildings to become a material bank. In addition, they provide guidelines for creating industrial symbioses, introducing new ways to generate value and profit for stakeholders in construction value chains, as well as ensuring competitive advantage.

There are many barriers to the application of CE principles in the construction sector, especially considering the lack of shared information and understanding of the value streams of materials and services. While business is the primary means of promoting the shift to a circular economy, governments are instrumental in facilitating or constraining this transition. A systemic reformulation of the production and consumption model requires alignment between supply, demand, and policy, and governments need to shape market conditions at the national and even global levels. Policies around consumer taxation, legal frameworks, specific recycling targets, making companies responsible for products over the life cycle, implementing tax premiums for the use of regenerated resources, and building code regulations need to be reconsidered. In addition, governments also need to adopt CE in their organizations through areas such as public procurement. Circular policies depend on collaborative platforms and cultural pressure from the construction industry and society.

CE education and communication are the main vehicles of change in the sector. A restructuring of the construction value chain is needed to link existing and emerging design principles and approaches in construction, collaboratively and comprehensively, defined not by the delivery of individual components, but by the circular functionality of the entire value chain. A circular building depends on a developed political-economic structure and a behavioral change in society. From the moment that effective communication about CE governance is implemented, supported by a flexible and collaborative policy with the construction value chain, a constant and gradual change will be initiated. The CE implementation will have a cascade effect, since both the directional categories of the sector, as well as the barriers and drivers overlap and have a direct connection.

From an academic contribution perspective, the results of this study helped develop a robust and coherent scientific knowledge base about the circular economy in the construction sector. The robustness and originality of this research justify the creation of a new line of research at the PPGEC that will trigger new master's and doctoral research, as well as the creation of new isolated disciplines in the Program. This study aims to expand the discussion on the importance of circular actions and public policies and to support policymakers develop a circular plan based on a set of tools, measures, and policies to regulate resource efficiency, construction and demolition waste management, and reduction, and create a more sustainable construction sector.

4.1 LIMITATIONS AND FUTURE STUDIES

This study has limitations that must be considered. First, the studies developed were the results of bibliographic research carried out in academic databases. There would be an additional need to identify the evolution of the latest industry practices. Still, conducting a sectoral survey could validate the results or indicate the relevance of other factors in the CE implementation. In future research, it is proposed to raise CE practices for the different stakeholders in the sector. Besides, it is suggested to explore case studies that implanted the CE in CBMs, highlighting the stakeholders involved and the types of strategies adopted at the organizational and sectoral levels. Above all, conducting empirical studies will be important to carry out quantitative studies on the economic return, and environmental impacts of circularity in the construction value chain.

The research gaps identified in the articles direct new research, highlighting better clarifications about CE to stakeholders in the construction value chains, the incorporation in the design stage of mechanisms to assist in decision making, the establishment of rules for the secondary materials, the definition of criteria for the deconstruction of buildings, and the establishment of mechanisms that guarantee the maintenance of components and materials during the life cycle of buildings.

New studies can also be carried out to integrate the research of this thesis cohesively and comprehensively. It is still unclear how the transition from a linear to a circular economy might be shaped and who (market or government) will lead the transformation. It is unclear how companies will address CE issues with internal and external stakeholders in value chains. In this way, a conceptual roadmap can be developed that directs decision-makers to adopt circular tools gradually and consistently in the built environment, defining different fields, stages, and circular actions according to the organization’s objective.

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A ECONOMIA CIRCULAR NO SETOR DA CONSTRUÇÃO: TENDÊNCIAS, DESAFIOS E FERRAMENTAS EXISTENTES PARA TORNAR OS EDIFÍCIOS COMO BANCOS DE MATERIAIS

RESUMO

O ambiente construído exerce pressão sobre os recursos naturais e seu papel na transição para uma economia circular é fundamental. A economia circular (EC) propõe modelos de negócios circulares que substituem o conceito de fim de vida por redução, reutilização, reciclagem e recuperação de recursos nos processos de produção/distribuição e consumo, visando alcançar o desenvolvimento sustentável, criar qualidade ambiental, prosperidade econômica e equidade social. Apesar de estar ganhando cada vez mais destaque no meio acadêmico, corporativo e governamental, sua implantação no setor construtivo é limitada e a literatura carece de referências que esclareça os conceitos relacionados a EC e direcione a implantação de ferramentas e modelos de negócios circulares ao longo do ciclo de vida das edificações e aos *stakeholders* da cadeia de valor da construção civil. Este estudo buscou criar um referencial teórico baseado em conceitos e ferramentas baseadas na economia circular para entender as tendências e desafios relacionados a implementação de práticas circulares para que as edificações se tornem banco de materiais. Por meio de uma pesquisa de caráter qualitativo-exploratória, baseada em revisões de literatura e análise estruturada de dados, esse estudo buscou analisar (1) o estado da arte atual da EC no ambiente construído; (2) os desafios e as oportunidades de se implementar o passaporte de materiais nas edificações; (3) diferentes modelos de negócios circulares que podem ser implantados ao longo do ciclo de vida das edificações visando aumentar o valor residual dos materiais de construção; (4) as principais políticas públicas brasileiras que suportam os princípios circulares; (5) as metodologias de ecodesign que corroboram com o princípio de desconstrução das edificações; (6) as principais barreiras e oportunidades de implementar a EC na construção civil; e (7) as principais diretrizes de desconstrução das edificações que devem ser adotadas na fase de projeto. Esta tese é organizada por meio de um documento introdutório e artigos científicos que buscaram responder essas demandas de pesquisa e, coletivamente, fornecem um mecanismo amplo e coeso de conhecimento que fornecem direcionamento de ações voltadas a tornar as edificações como bancos temporários de materiais. Dos resultados, conclui-se que a EC ainda é incipiente no setor e voltada a mitigação e reutilização dos resíduos da construção civil. A demora do setor às mudanças, a falta de conhecimento e esclarecimento sobre as metodologias de ecodesign, modelos de negócios e os princípios da EC são barreiras críticas. Uma revisão sistêmica do modelo de produção e consumo das edificações requer arranjos entre oferta, demanda, política e governos voltadas à um mercado baseado no uso eficiente dos recursos. Além disso, é preciso elucidar os ganhos econômicos, sociais e ambientais que as práticas circulares irão proporcionar aos stakeholders da cadeia de valor da construção civil. Percebe-se que a esperada mudança de paradigma na forma como os edifícios são projetados e construídos será possível a partir de parcerias público-privadas que promovam a integração dos atores e o fechamento de ciclos dos materiais, fortalecendo a fiscalização e implementação de edifícios reversíveis, o mapeamento e compartilhamento de informações, aliadas às necessárias medidas de incentivo fiscais. Este estudo visou explicitar lacunas e descortinar novas possibilidades de pesquisa no âmbito científico e contribuir para o desempenho estratégico de tomadores de decisão para que introduzam princípios circulares nos modelos de negócios e nas cadeias de valor da construção civil, tornando as edificações e o ambiente construído mais sustentáveis.

Palavras-chave: Economia circular. Construção civil. Edificações sustentáveis. BAMB. Edificações circulares.

1 INTRODUÇÃO E CONTEXTO TEÓRICO

A população mundial está aumentando, juntamente com o poder de consumo e a geração de resíduos. Em um cenário em que a população das áreas urbanas cresce em 200.000 pessoas por dia, todas necessitando de moradias populares, infraestrutura social, transporte e serviços públicos, o desafio do setor de construção é imenso (WEF, 2016). O setor precisa transformar e repensar a forma como planeja e constrói o ambiente construído. Essa transformação terá efeitos sociais: ao repensar a forma de planejar, construir e consumir, reduzindo os custos de construção; ambiental: melhorar o uso de matérias-primas ou tornar os edifícios mais sustentáveis; e econômico: diminuir o déficit global de infraestrutura e estimular o desenvolvimento econômico.

Desde a Revolução Industrial, o modelo de crescimento linear adotado, ao assumir que os recursos são abundantes, disponíveis e descartá-los ao final de sua vida útil, tem levado ao contínuo esgotamento dos recursos e ao aumento do desperdício (EMF, 2015a). O setor da construção civil tem contribuído efetivamente para esse cenário, sendo o maior consumidor de recursos e matérias-primas do mundo, responsável por altos níveis de geração de resíduos, gases de efeito estufa e consumindo mais de um terço da energia total do planeta (IRP, 2017; CIRCLE ECONOMY, 2018; UNEP, 2021). Materiais e produtos de construção acabam sendo desperdiçados quando não são mais necessários para a função a que se destinam, fato que acelera a devastação dos ecossistemas, aumenta os custos ambientais e traz riscos de escassez de recursos. O setor da construção precisa evoluir para um sistema baseado na circularidade, em que edifícios e materiais de construção sejam utilizados, reutilizados, adaptados e reconstruídos, considerando a racionalidade econômica e ambiental no centro das decisões.

A economia circular (EC) é um modelo que permite repensar as práticas econômicas da sociedade e se inspira no funcionamento da própria natureza. Tem uma abordagem de desenvolvimento sustentável baseada no princípio de "fechamento do ciclo de vida" dos produtos, permitindo a redução do consumo de matérias-primas, energia e água. É inseparável da inovação e do design de produtos e sistemas. Emprega os princípios de projetar resíduos e poluição; manter materiais e produtos em uso e regenerar sistemas naturais (EMF 2015a; 2017).

A implementação de princípios circulares no ambiente construído é apoiada pelo projeto europeu *Buildings as Material Banks* (BAMB), que emprega tecnologias de informação, modelos de negócios e parcerias para reduzir custos, impactos ambientais e tornar as áreas urbanas mais habitáveis, produtivas e sustentáveis . A natureza sistêmica da EC requer que o ecossistema e seus componentes mudem. O setor da construção ainda está em fase embrionária e limitado à minimização e reciclagem de resíduos de construção e demolição (MUNARO et al., 2020). A pesquisa sistemática, incluindo como novos modelos de negócios circulares (CBMs) podem permitir que os materiais mantenham ou aumentem seus valores residuais, precisa ser mais explorada.

Este estudo busca analisar como os princípios baseados na economia circular podem ser implementados no ambiente construído, nos edifícios e nas cadeias de valor da construção para que os edifícios se tornem um banco de materiais. Propõe-se que uma edificação, caracterizada como circular, seja uma agregação temporária de componentes, elementos e materiais com identidade e registros documentados, desde sua origem até a reutilização, conectados de forma a acomodar uma função por um determinado período estabelecido.

1.1 PROBLEMA DE PESQUISA

Esta pesquisa pretende fornecer uma nova maneira de projetar e construir ambientes considerando princípios circulares na cadeia de valor da construção em uma abordagem holística e racional. Busca levantar os principais desafios e limitações do setor para reduzir o desperdício e aumentar a vida útil dos materiais de construção. Ao mapear e analisar ferramentas e estratégias baseadas em EC, visando aumentar o valor dos materiais e transformar os edifícios em um banco de materiais temporários, este estudo visa responder à seguinte questão de pesquisa:

Quais são as principais tendências, desafios e ferramentas baseadas na economia circular para a transição para os edifícios como bancos de materiais no setor da construção?

1.2 OBJETIVOS DA PESQUISA

Este estudo visa gerar um referencial teórico de ferramentas e conceitos para compreender as tendências e desafios que influenciam a implementação de práticas de EC para a transição para edifícios como bancos de materiais.

Este objetivo de investigação traduz-se em vários objetivos complementares, alguns foram identificados no início do estudo, outros foram progressivamente acrescentados ou afinados:

a. analisar como o ambiente construído aborda o estudo e as ações da economia circular;
b. identificar as barreiras, desafios e propor um modelo de passaporte de materiais com seus respectivos dados e informações visando o reaproveitamento dos materiais em fim de vida;
c. pesquisar e analisar modelos de negócios circulares ao longo do ciclo de vida de um edifício;
d. caracterizar a tipologia projetual de edifícios de reutilização reversível e adaptativo;
e. identificar barreiras e drivers necessários para direcionar a transição circular na indústria da construção.

2 ORGANIZAÇÃO DA TESE

Esta tese originou sete artigos de anais de eventos e sete artigos de periódicos. Os trabalhos dos anais foram publicados no evento final do BAMB, no Encontro Nacional de Tecnologia no Ambiente Construído (ENTAC), no Encontro Latino-Americano e Europeu sobre Edifícios e Comunidades Sustentáveis (EuroELEcs) e no SEE-U: *Sustainable Development Goals* a conferência científica global da UFPR. No entanto, neste documento foram considerados apenas os sete artigos de periódicos, descritos abaixo. A inclusão dos artigos já publicados neste documento foi verificada junto aos editores de periódicos acadêmicos, evitando assim qualquer violação de direitos autorais.

Artigo 1: Este artigo inicial fornece uma visão abrangente e holística de como o ambiente construído aborda o estudo e as ações da economia circular. Este estudo representa uma contribuição para os fundamentos teóricos da pesquisa em EC e enfatiza as lacunas de pesquisa que foram abordadas nos outros estudos desta tese.

Artigo 2: Este artigo apresenta um conceito de passaporte de materiais no contexto do ambiente construído, identificando as principais informações, oportunidades e obstáculos que esse mecanismo deve fornecer para apoiar as práticas circulares no setor da construção. O estudo atende a direção de pesquisa do artigo 1, visando auxiliar a tomada de decisão na fase de projeto de edificações.

Artigo 3: O estudo apresenta uma metodologia iterativa de criação de valor em projetos de construção e uma estrutura que relaciona modelos de negócios circulares de acordo com a fase do ciclo de vida do edifício. O estudo aborda a lacuna de pesquisa da introdução de princípios circulares nas políticas, ações e cadeias de valor do setor de construção.

Artigo 4: Este estudo analisa as políticas públicas brasileiras que apoiam a implementação da EC no setor da construção. O estudo contribui para a literatura sobre políticas públicas de apoio à EC e auxilia os formuladores de políticas na criação de um plano de política circular para apoiar a tomada de decisão e a adoção de estratégias sustentáveis no setor da construção.

Artigo 5: Este estudo analisa como o setor da construção aborda os métodos de ecodesign para alcançar a desconstrução de edifícios e estabeleceu que o método de ecodesign mais inclusivo e sustentável é o *Design for Adaptability and Disassembly* (DfAD). O estudo aborda a lacuna de pesquisa do artigo 1 sobre estratégias de desmontagem de edifícios.

Artigo 6: Este estudo analisa as barreiras, direcionadores e *stakeholders* que influenciam a implementação da EC no setor e destacou a necessidade de atuação conjunta entre governo e *stakeholders* da construção para o estabelecimento de parcerias público-privadas e comunicação efetiva e segmentada visando a transição circular no setor.

Artigo 7: Este estudo compreende como o DfAD e outros métodos de ecodesign orientados à desconstrução podem apoiar a transição do setor para a circularidade. Foram elencados 71 critérios para orientar a desconstrução de edifícios, enfatizando a padronização, modularização e pré-fabricação de materiais e componentes como requisitos fundamentais para apoiar a desconstrução de edifícios.

3 CONSIDERAÇÕES FINAIS

Este estudo buscou explorar possibilidades de inovação e criação de valor no ambiente construído, associando as atividades econômicas ao princípio circular de fechamento dos ciclos de materiais, serviços e sistemas no setor de construção. Por meio do estado da arte realizado no artigo 1, foram determinados rumos de pesquisa para a implementação de práticas baseadas em EC no setor da construção que foi explorada em seis novos estudos. O artigo 2 apresentou um modelo de passaporte de materiais para facilitar a tomada de decisão na fase de projeto de edificações. A necessidade de pensar negócios e sistemas circulares foi explorada no artigo 3º, que culminou em uma série de exemplos de modelos de negócios circulares. O apoio governamental, crucial para a ação estratégica dos decisores na introdução de princípios circulares, foi explorado no artigo 4. Os artigos 5.º e 7.º, por outro lado, abordaram as estratégias de desconstrução de edifícios que privilegiam a recuperação, realocação, reutilização, reciclagem, ou remanufatura de componentes de construção. Por fim, o artigo 6º procurou compreender as limitações e oportunidades da EC, associadas aos stakeholders responsáveis por esta transição para a circularidade no setor da construção.

Os resultados desta tese mostram que a adoção de mecanismos circulares ainda é incipiente no setor. A concentração de publicações nos últimos anos destaca a importância do problema na comunidade científica. A centralização do trabalho nos países europeus e na China demonstra o resultado da implementação de políticas públicas e ressalta que a expansão da pesquisa em outros países carece de respaldo político e governamental. As pesquisas sobre EC no ambiente construído enfatizam o reaproveitamento de resíduos de construção e demolição como aditivo para novos materiais, visando reduzir a extração de recursos naturais e os impactos ambientais do setor de construção. Apesar dos esforços para desenvolver mecanismos de apoio na implementação de práticas circulares, análise de fluxo de materiais, mineração de estoques antropogênicos e design de materiais e sistemas circulares, a pesquisa ainda está focada na redução, mitigação e reutilização de resíduos para aumentar o valor residual dos materiais.

Perceber o potencial da circularidade requer uma nova abordagem dos modelos de negócios para todas as etapas do ciclo de vida da construção e todos os envolvidos na cadeia de valor, abrangendo mudanças no planejamento, design, tecnologia e abordagens econômicas e de mercado. O modelo de passaporte de materiais, a metodologia para criar e incorporar valor em modelos de negócios, os diferentes modelos de negócios circulares apresentados, bem como as metodologias de ecodesign e os critérios de um projeto de construção reversível são mecanismos de criação de valor e direcionamentos na transição para que os edifícios se tornem um banco de materiais. Além disso, fornecem diretrizes para a criação de simbioses industriais, introduzindo novas formas de geração de valor e lucro para as partes interessadas nas cadeias de valor da construção, além de garantir vantagem competitiva.

Existem muitas barreiras para a aplicação dos princípios de EC no setor de construção, especialmente considerando que há falta de informações compartilhadas e compreensão dos fluxos de valor de materiais e serviços. Embora os negócios sejam o principal meio de promover a mudança para uma economia circular, os governos são fundamentais para facilitar ou restringir essa transição. Uma reformulação sistêmica do modelo de produção e consumo requer alinhamento entre oferta, demanda e política, e os governos precisam moldar as condições de mercado nos níveis nacional e até global. Políticas sobre tributação do consumidor, estruturas legais, metas específicas de reciclagem, responsabilização das empresas pelos produtos ao longo do ciclo de vida, implementação de prêmios fiscais pelo uso de recursos regenerados e regulamentos de código de construção precisam ser reconsiderados. Além disso, os governos também precisam adotar a EC em suas organizações por meio de áreas como compras públicas. As políticas circulares dependem de plataformas colaborativas e pressão cultural da indústria da construção e da sociedade.

A educação e a comunicação de EC são os principais veículos de mudança no setor. É necessária uma reestruturação da cadeia de valor da construção para vincular princípios e abordagens de design existentes e emergentes na construção, de forma colaborativa e abrangente, definidos não pela entrega de componentes individuais, mas pela funcionalidade circular de toda a cadeia de valor. Um edifício circular depende de uma estrutura político-econômica desenvolvida e de uma mudança comportamental na sociedade. A partir do momento em que a comunicação efetiva sobre a governança da EC for implementada, apoiada por uma política flexível e colaborativa com a cadeia de valor da construção, uma mudança constante e gradual será iniciada. A implementação da EC terá efeito cascata, uma vez que tanto as categorias direcionais do setor quanto as barreiras e direcionadores se sobrepõem e têm uma conexão direta.