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Review

Towards Sustainable Construction: A Systematic Review of Circular Economy Strategies and Ecodesign in the Built Environment

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Abstract: This review discusses the unsustainable nature of current production and consumption patterns, particularly in the civil construction sector. To address this, the circular economy model has been proposed as a solution, but the impact reduction of circular strategies (CS) is not well understood. Thus, aligning CS with ecodesign can help achieve sustainable development. We conducted a systematic review of studies on CS and ecodesign strategies (ES) in the built environment, which led us to identify 23 essential strategies, including reuse, recycling, design for disassembly, and design for life extension. This article expands on previous research by identifying 51 CS and ES, some of which are interconnected, and adopting one strategy may benefit another. The authors propose a framework based on the Plan-Do-Check-Act concept to support and manage trade-offs when selecting strategies and to facilitate a collaborative decision-making process. The framework can also help manage the effects of using these strategies on circularity and environmental, social, and economic performance, ultimately improving the construction sector's environmental performance.

Keywords: construction industry; life cycle perspective; life cycle assessment; environmental performance; circular economy (CE); ecodesign

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1. Introduction

Society is confronted with significant environmental challenges, including waste generation, extraction of natural resources, and greenhouse gas emissions. This production and consumption model is based on linear flow, and is unsustainable regarding three dimensions (economic, ecological, and social) [1]. The scientific community is concerned about the impact of human activities on the environment, and the urgency for implementing sustainable strategies has escalated, affording new production models and incorporating life cycle thinking [2].

In this context, the circular economy (CE) concept has arisen as a compelling strategy to mitigate environmental consequences while stimulating economic development [3]. CE plays a role in transforming societies through a resource-efficient model [4]. The model aims to slow down natural resource use and waste production while boosting the economy, retaining the economics of the extracted materials for a long time [5].

The transition toward the CE presents both a new challenge and an opportunity to pursue sustainable industrialization [6]. This process necessitates a comprehensive, multi-level shift that includes technological advancements, novel business models, and stakeholder collaboration [7]. It is particularly pronounced in energy- and materials-intensive industries [3]. The built environment is one such industry, responsible for 40% of the total energy demand, 44% of the material used, and generating 40–50% of global greenhouse gas emissions [8]. The Circular Economy Action Plan highlighted these types of industries and sectors due to their remarkable potential for innovation, aimed at reducing their significant environmental impact and resource consumption [9].

Thus, integrating CE principles into the construction sector offers the potential to enhance sustainability and depart from the industry's historical patterns [10]. However, despite its promise, the application of CE principles in the building industry has only recently emerged and poses unique challenges. This evidence is primarily due to the complex nature of composite structures in buildings and infrastructure, which are typically designed for long-term use and undergo multiple life-cycle phases compared to other products [4,5].

The CE implementation presents an additional challenge as it can either serve as a tool for sustainable development or contribute to the "sustainable" degradation of the planet by focusing solely on more efficient resource utilization without addressing overall degradation [11]. This issue is particularly significant in the construction sector, where there is a lack of studies examining the impacts of employing circular strategies (CS) and establishing the feasibility of multiple life cycles for different building and infrastructure materials. Hence, the inclusion of life cycle thinking and the consideration of environmental performance at the design stage emerge as the most effective approaches to tackle this issue [12].

The design stage has a key role in mitigating environmental impacts and maximizing product value throughout multiple cycles [13]. Designers must adopt strategies that prolong the lifespan of products, minimize material requirements, facilitate repair and resale, enable product upgrades, embrace modularity and remanufacturing, promote component reuse, and explore end-of-life options [14].

Ruiz-Real et al. [15] identified three key trends in CE research: eco-innovation, ecodesign, and waste management. However, other studies from the construction sector indicate that many studies have primarily focused on waste recycling and minimizing waste in new buildings [16]. This approach concentrating on end-of-life solutions is insufficient for a successful transition to the CE [11], and other CS encompassing the entire life cycle must be studied [6]. Thus, ecodesign is crucial as a driving force for implementing CE practices [17]. It involves integrating environmental considerations into product design and development in order to enhance performance throughout the entire lifecycle at as many stages as possible.

As mentioned before, the CE model has been proposed as a solution for the current environmental degradation, but the impact reduction of CS is not well understood. Moreover, designers can apply ecodesign strategies (ES) to develop projects with advanced solutions for all lifecycle stages. Thus, aligning CS with ES can help achieve sustainable development and the transition to a circular model in the construction sector.

In recognizing the significant connection between the CE and ES in the building sector and the reduced number of studies on this topic, we propose conducting a comprehensive and interdisciplinary review of CE applications, enhancing our understanding of sustainable development, with specific emphasis on the integration of ES and CS. This review is conducted in the academic field and grey sources.

In the present work, aiming at a holistic and general analysis of all available strategies for the civil construction sector, we consider a comprehensive approach to the built environment. Thus, we will consider, for the present work, that the built environment is the space or occupation structure that was developed by man, considering all scales (material or system to compose such spaces, buildings, and cities) and different project stages (new, existing, retrofit, temporary, and others).

However, some strategies are inadequate for all situations without a prior analysis of existing constraints, regulations, policies, and protocols. One example is historic buildings, which need an in-depth analysis of the environmental and circular benefits of applying the strategies and their effects on heritage and memory preservation. Another example would be temporary buildings in extreme weather conditions, where designers must prioritize functional requirements.

Furthermore, the authors propose a framework based on the Plan-Do-Check-Act concept to support managing trade-offs and facilitating a collaborative decision-making process when selecting strategies. The framework can also help manage the effects of using these strategies on circularity and environmental, social, and economic performance, ultimately improving the construction sector's performance.

2. Circular Economy in the Construction Sector

The CE model serves as a facilitator for sustainable development, and the construction sector holds significant potential for transitioning towards this new consumption and production paradigm [18]. We analyzed previous systematic literature reviews to provide an exploratory overview. The summary contents of each article are in Supplementary material Table S1.

The literature that combines these two topics has experienced significant growth in recent years [19–21], highlighting concerns regarding the transition from a linear to a circular model [20]. Circular practices, such as recycling, prefabrication, and material reuse, lead to lower carbon emissions compared to traditional construction methods [4]. However, these studies tend to be fragmented, primarily focusing on barriers and examining isolated phases within the supply chain [21]. Moreover, there is a lack of standardized and integrative methods, as well as practices that encompass multiple stages [20,21], and there is a need for CE models specifically tailored to the construction industry [22].

Munaro et al. [21] reviewed 318 articles and identified that "circular economy" is the term that leads in the number of citations, followed by the collocations "sustainability or sustainable construction/development/materials" and "recycling aggregate/material/concrete".

The construction industry encounters a challenge in understanding the advantages of implementing the CE and considering the impacts of materials, components, and product end-of-life within the product design process, given the limited availability of specific studies and practical applications in this field [19]. Therefore, a comprehensive and multidisciplinary review of CE applications is crucial for comprehending the intricacies of sustainable development in this domain. Such a review supports the development of effective policies and planning practices and aids decision-makers in determining the concrete steps they should take [23].

Moreover, designers hold a pivotal role in the transition to the CE due to their authority in making decisions regarding material sourcing, the use phase, end-of-life destinations, and reuse and recycling rates [4]. These decisions significantly impact the circularity and waste generation of a building project [24].

Furthermore, Marruci et al. [25] suggest that designers incorporate a holistic analysis of the entire life cycle and seek to integrate different tools that enable the reduction of environmental impacts, social justice, economic effectiveness, and means of producing circulars. To assess and improve building performance, the life cycle assessment (LCA) method has been widely accepted. The LCA can help users to understand the environmental challenges of the entire life cycle, identify the critical points, and start solving them through an ES [26,27].

To spread the combination of LCA-based ecodesign, it is desirable to adapt design instruments, such as architectural drawings, to accommodate these principles [28]. Thus, building information modeling (BIM) is gaining prominence because it improves information-sharing, transparency, and the early identification of inefficiencies, enhances flexibility, and incorporates environmental requirements at the beginning of design [5,29]. Moreover, BIM can be integrated with LCA to quantify materials and architectural elements for life cycle inventory (LCI), integrate environmental information to BIM as a design tool, and develop an automated process based on LCI data and software [30]. This section shows that implementing the CE in the construction sector requires substantial efforts, and multiple design strategies will be necessary to facilitate this transition [31] because buildings are currently not designed for recycling or value recovery [32]. Furthermore, CS can enhance other strategies because they are not separate entities, as the output from one process may be the input for other processes [23].

3. Method

A method with two stages is conducted as shown in Figure 1. The first stage is a systematic literature review in three search engines: Scopus, Web of Science, and Science Direct. We selected these databases because of the indexed international journals, the multidisciplinary studies, the collection size, and their relevance in the academic field. The question that our study must answer is "How can ecodesign and circular design strategies influence CE adoption and reduce environmental impacts in the construction sector?".

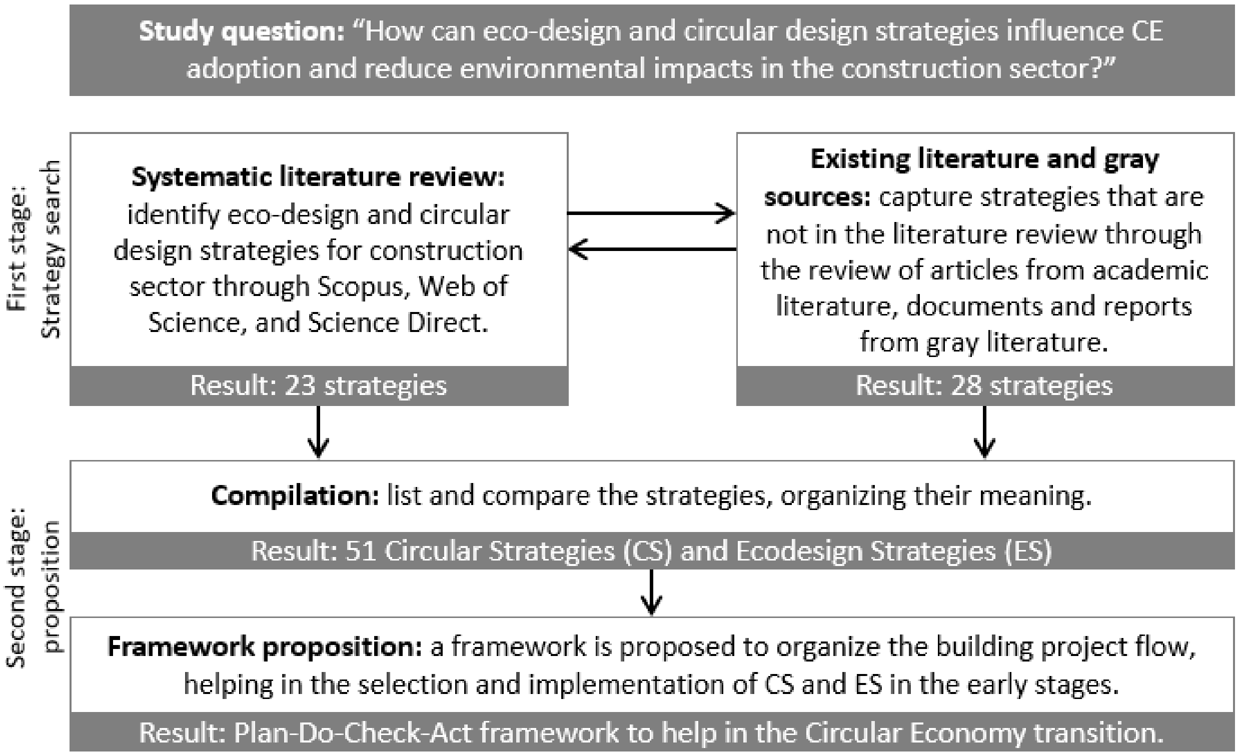

Figure 1. Method overview with objective, stages, and main results.

The search terms selected are: (i) built environment, buil*, and construction; (ii) CE, and circular design; (iii) ecodesign, ecodesign, and eco design; (iv) strategy, case, technique, method, and framework. These keywords are combined in two different strings, as illustrated in Figure 2. The search fields analyzed are title, abstract, and keywords.

During the analysis some criteria are established:

- The results are filtered by the type of document (peer-reviewed articles), source type (only published studies and journal articles), main subject area (related to building and construction), and language (only English);
- Articles that are not related to the built environment/building were excluded;
- Publications must contain at least one building design and construction strategy.

All searches were performed on 10 January 2023 and the first database, comprising 734 papers, was obtained. We removed 139 duplicates and rejected 526 papers by abstract review. We eliminated the articles that were not aligned with the research theme, did not address CS or ES, or did not comply with any criteria established in the review protocol. In this way, many articles only mentioned the EC or ecodesign theme, but did not explore the relationship with sustainability or strategies. A total of 69 peer-reviewed journal articles were included for analysis. The analysis was summarized into three categories:

- Current overview and trends (metadata information): document title, year, authors, country, publication source, author keywords, and study type.
- Built environment characteristics: scale (city, building, system, and material) and assessment tools (environmental, social, and economic sphere).
- CE and ecodesign relation: barriers, benefits, and concept.

Also, we reviewed the existing literature, encompassing articles from academic literature, documents, and reports from gray literature.

In the second stage, we compared the strategies (CS and ES) from the systematic literature review with the ones from the existing literature. Thus, they are listed, compared, and the related meaning of each strategy is organized.

Afterward, we proposed a framework to organize the building project flow, helping to select and implement CS in the early stages. The proposed framework can incorporate environmental performance into the built environment using CE and ecodesign principles.

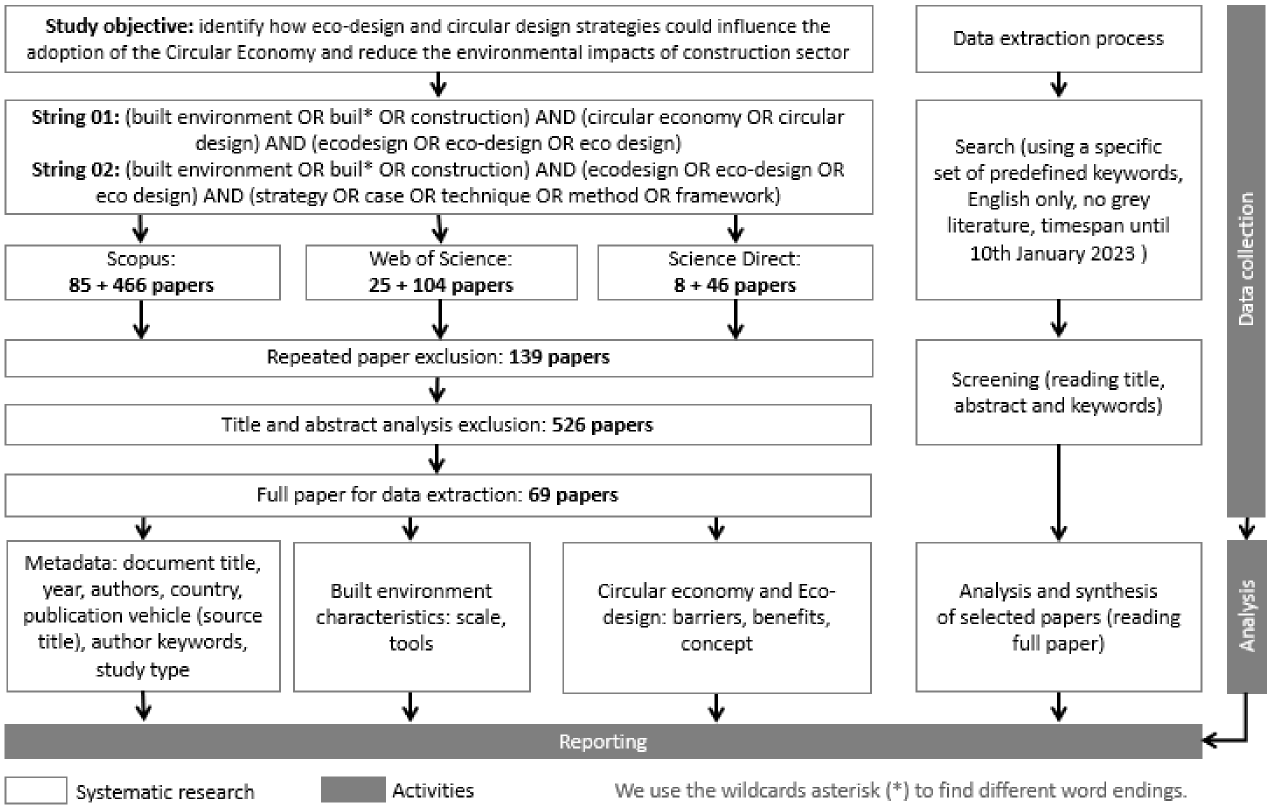

Figure 2. Scheme of the systematic literature review protocol.

4. Results and Discussion

4.1. Systematic Literature Review

As previously presented, 69 studies are considered relevant for further analysis. Supplementary Material Table S2 provides the study purpose and some results of each article.

4.1.1. Current Overview and Trends

Metadata analysis is crucial for providing an overview of publications and identifying research gaps and trends. Accordingly, we present the data of the analyzed articles, including the document title, year, authors, country, publication source, author keywords, and study type.

The first aspect of the metadata analysis focuses on the number of publications over the years, as depicted in Figure 3. The integration of ecodesign and CE is a relatively new field of study, with a notable increase in the number of articles published since 2017. The highest number of published studies per year was observed in 2021 (20 papers). These findings indicate that the combined approach of ecodesign and CE has significant potential for further exploration in the built environment, particularly in fostering a transition to the CE that encompasses environmental and social considerations associated with this transition.

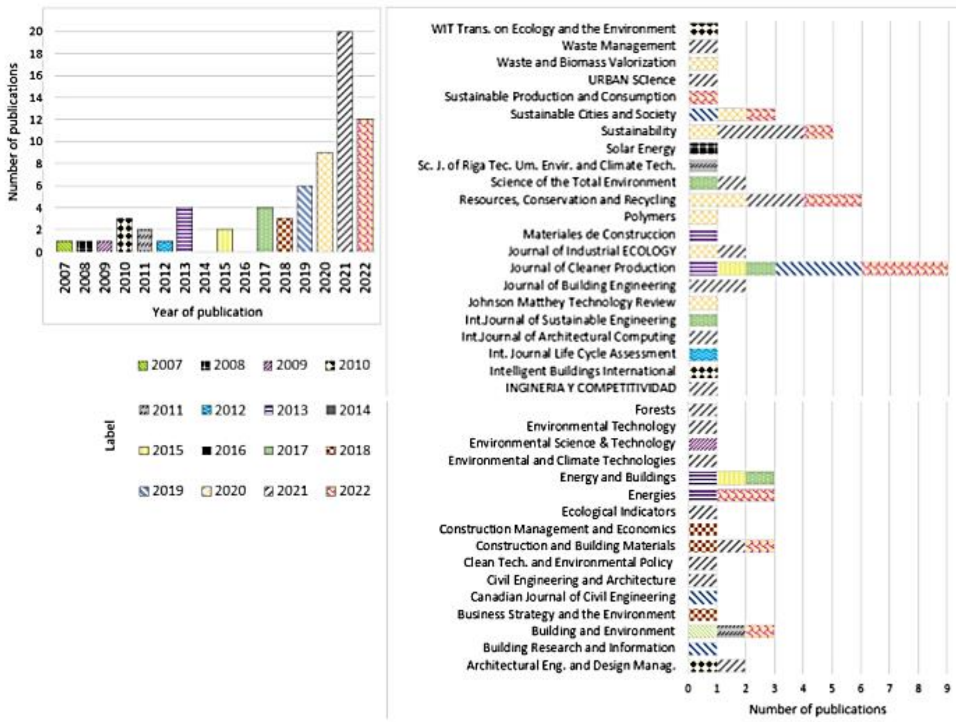

Figure 3. Number of publications by year and sources of publication by year.

The second analysis is about the publication source, and the articles are distributed into 38 journals. Figure 3 shows that the most important publication source is the *Journal of Cleaner Production* (nine articles), followed by *Resources, Conservation and Recycling* (six articles), and *Sustainability* (three articles).

The journals *Building and Environment*, *Construction and Building Materials*, *Energies*, *Energy and Buildings*, and *Sustainable Cities and Society* have each published three articles. All the other journals published one or two articles on the subject, indicating fragmentation. This result is also identified by Marruci et al. [25].

Another relevant assessment is about the year and source of publication relation. In the *Journal of Cleaner Production*, the articles are concentrated on 2019 and 2021. On the other hand, the journals *Sustainability* and *Resources, Conservation and Recycling* have more publications between 2020 and 2022.

Considering the authors' and co-authors' affiliations, the highest number of contributions comes from Europe, where the United Kingdom accounted for 12 articles, followed by Spain (10 articles) and Italy (10 articles). Europe has the most publications in this area. This can be explained by the long adoption of CE and the sustainability policy process by the European Union [4]. In North America, Canada has the highest number of publications (nine articles) and in Asia, China (four articles). The results are in Figure 4.

The keywords found according to their occurrence are summarized in Figure 5. Among 206 terms, "life cycle assessment" leads the number of citations (35 citations), followed by "circular economy" (25 citations), "ecodesign" (22 citations), "building" (11 citations), and "sustainability" (10 citations). Expressions such as disassembly, deconstruction, adaptative reuse, recycling, reuse, and design for the environment reiterate the research on CS to mitigate environmental impacts. Many terms appear only once and are grouped into eight groups: environmental topic; strategy; technology or techniques; material or constructive system; LCA; construction sector; standards and rules; and others.

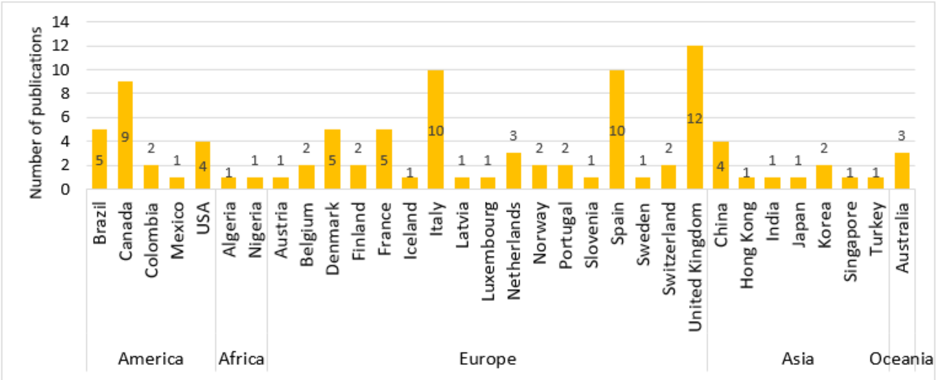

Figure 4. Geographic locations under study.

The last metadata evaluation refers to the research procedure. The most predominant is the case study (39 articles or 56.5%), followed by theoretical and conceptual studies (11 articles), survey (7 articles), modeling (6 articles), and review (6 articles). Most of the case studies used LCA to assess the application of ecodesign principles in mitigating the project's environmental impacts, by evaluating systems, materials, or the building as a whole. Many authors also combined two procedures (21 articles). The combination of case study research methods and modeling (seven articles) is the most representative, followed by theoretical and conceptual studies aligned with the case study (six articles), modeling and theoretical and conceptual studies (three articles), and survey and theoretical and conceptual (two articles). Other search method combinations appear only once.

We identified trends and indicated some gaps through metadata analysis. The search for the theme is recent, with significant growth in recent years but a concentration in European countries. In this way, there are opportunities to broaden the discussions to new contexts, identifying CE barriers in developing countries, which may have different construction techniques and other business models in the civil construction sector. The variation in the results may be insignificant and not considered, or there may be significant divergence related to social factors (such as the qualifications of the workforce or the environmental awareness of the designers) and technological factors (such as machines and techniques capable of assisting in the deconstruction at the end of life). The aspects mentioned are just some factors that may interfere with differences in context. More studies must test them to be more accurate about decision-making and to develop specific and adequate benchmarks for different contexts.

There is fragmentation in the publication's sources, but these numerous journals are opening space for the theme due to their relevance to achieving sustainability. The keywords and the study type indicate that many studies sought to identify the relationship between CE and sustainability, LCA, and ecodesign through case studies of one or a few strategies. In this sense, future studies must expand investigation about how to propagate the strategies into different materials, systems, buildings, and contexts. Besides the potential, we need more evidence about viability, new business models, production means, standards, and others. Furthermore, regarding the study types, the number of surveys is lower. Thus, there is a gap for more discussions that seek to capture the perception of other stakeholders in the civil construction sector (such as builders and suppliers) about CE, barriers, advantages, applied practices, and challenges to the transition.

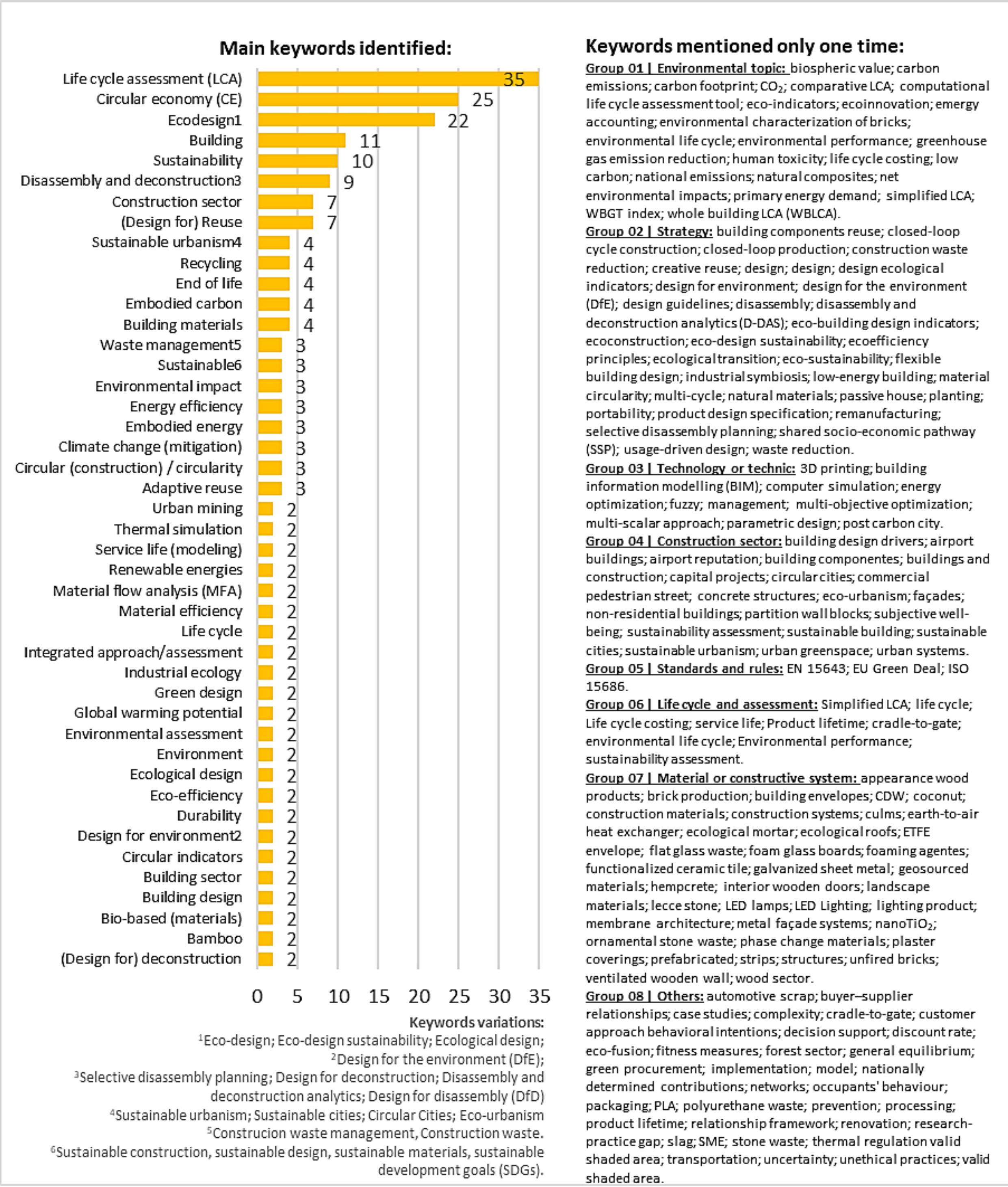

Figure 5. Keywords identified in the systematic literature review.

4.1.2. Built Environment Characteristics

In this subtopic, we compile information from articles referring to characteristics of the built environment as scale. Thus, we classified them according to the topics covered: city, building, system, and material. Furthermore, we verified which spheres are addressed, from environmental, social, and economic. In general, there was always at least one sphere under analysis, but there were cases in which more than one was covered.

The building characteristics analysis entailed checking the study scales and using assessment tools (Figure 6). Regarding the scale, the studies focus mainly on buildings

(28 articles; 40.6%), followed by materials (19 articles), constructive systems (14 articles), and cities (8 articles). The topics investigated have a balanced distribution over the years. However, there is a concentration of studies related to buildings in 2020 and 2021. Furthermore, studies on city scales have only gained momentum in the last three years.

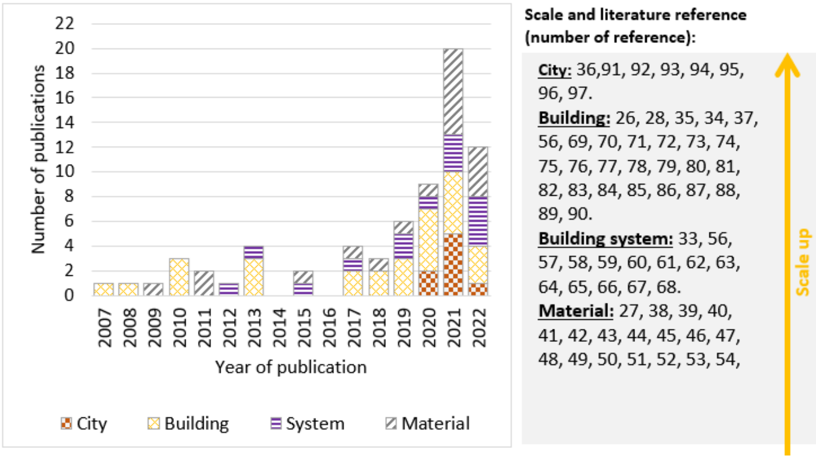

Figure 6. Study scale identified in the literature review.

The implementation of the investigated strategies is evaluated mainly in the environmental sphere (61 articles; 88.4%), where 42 articles apply or cite the LCA, 5 perform a thermal simulation [26,33–36], and one calculated embodied energy and carbon [37].

It is important to highlight that a majority of the articles did not conduct a complete LCA. Some studies consider only the cradle-to-gate system [38–46], while others address the cradle-to-grave approach [28,47–55]. In contrast, few studies have assessed more than one life cycle [56–59], existing urban stocks renewals [60], reuse scenarios [61–63], and credits for potential reuse, energy recovery, or recycling of materials in subsequent product systems [64].

The disseminated use of LCA is because it offers a systematic approach to quantifying environmental impacts. In addition, other studies used the LCA to help in the process of comparing environmental aspects and potential impact associated with materials options [41–43,45–47,51,54,56,61], building types [65], and modular building with strategies for the end-of-life (disassembly and reuse strategies) [66].

Moreover, one study applied the consequential LCA of circular wall assembly alternatives, acknowledging the time dependence and closed-loop nature of those design alternatives [67], and one carried out an attributional LCA of oriented strand boards [68], where the data of wood screening residues were allocated according to the mass of residues and the mass of wood included in the OSB. Di Capua et al. [57] considered an economic allocation of 50% for seeds and 50% for straw in the initial phase of the analyzed life cycle of hemp cultivation. On the other side, Joensuu et al. [58] compared three different methodological approaches (extending the system boundaries; partitioning and dividing by use cycles; and component-specific service life approach) to depict the impacts of different choices, mainly in design for deconstruction components. Cascione et al. [56] used a cradle-to-cradle LCA to compare the circular wall panel with other prefabricated wall panels, and they used economic allocation to distribute impacts in multi-product processes, like sheep's wool insulation. And Rezende Leite et al. [43] made a cradle-to-gate LCA to compare the environmental performance of mortars made with sand and cement replacements, and mass allocation is necessary to deal with multi-functionality.

Two studies have employed a new approach that adapts LCA to incorporate circularity [69,70]. In one study, CE-LCA was utilized to assess and compare various circular design options for two building components: a kitchen and a renovation façade [69]. A workflow was developed to facilitate an LCA-based evaluation, enabling the comparison of environmental impacts among alternative design variants while keeping the construction system and material selection open [70]. Furthermore, regarding the environmental sphere, Lamé et al. [71] evaluated different ecodesign tools in the construction sector: complete LCA, screening LCA from The EeBGuide Project, Quality Function Deployment for Environment (QFDE), ecodesign Pilot from Vienna TU, and ESQCV.

In the economic sphere, nine articles investigate economic performance, where three articles calculate the cost, and the other six articles investigate the theoretical and conceptual part of this sphere. Buyle et al. [67] applied an LCC study, Sanchez et al. [72] used the cost information for destructive disassembly from the national database RSMeans®, and Ali et al. [44] calculated the annual cost per year based on primary data from the industry. In contrast, Jugend et al. [73] studied conceptual and methodological economic aspects. Moreover, Vakili-Ardebili and Boussabaine [74] investigated eco-drivers in building design. Lu and Schandl [75] derived the land-use-change-related GHG emissions by coupling the Global Trade and Environment Model (GTEM-C) with the Global Biosphere Management Model (GLOBIOM). It provides the outputs of land-use change and the related GHG emissions considering gross domestic product (GDP), population, and carbon price path. Bourgeois et al. [76] introduced an ecodesign tool that facilitates the integration of circularity and sustainability of building renovation projects, enabling the evaluation of solutions using Environmental Product Declarations (EPDs), LCA-based calculations, and life cycle cost information.

Only two articles investigated the social sphere, mentioning social requirements and not applying or measuring them. The limited number of studies that address the social sphere was also identified by other authors [19,77].

We verified, through the analysis of built environment characteristics, that there is a concentration of studies on the building scale, while the city scale is still gaining space. In this sense, future studies must expand the discussions on this scale, including a systemic approach in resource management and highlighting the opportunity to share and cycle resources between nearby buildings, with different typologies, but mainly industrial.

Furthermore, buildings can function as material banks, and designers need to address resource management because these stored materials may be used in future cycles of new buildings. Therefore, it is important to explore how to manage such resources at the societal level, rather than just focusing on the building's owner. In this regard, BIM technologies can be key for planning buildings and structures, and for managing resources throughout the entire life cycle. BIM modeling software for buildings has made significant advancements, but further improvements are required to optimize and integrate such software with LCA techniques, especially on larger scales like neighborhoods and cities.

There is great interest in the environmental sphere, mainly in the LCA technique application. However, many studies do not develop environmental analyses for multiple life cycles. In this sense, it is worth exploring some topics:

- How to use the CS and ES in more than one life cycle;
- What the effects are of combining these strategies;
- How to guarantee the technical quality of materials throughout the cycles;
- What the turning point is between keeping a product in the same function and migrating to downcycling;
- What economic or organizational changes encourage the use of non-virgin materials, among other points.

There is also a need to investigate LCA modeling regarding allocation decisions, system expansion, and potential benefits of the strategies. At the scale of cities, future studies must expand the investigation into LCA inventory management, calculating environmental impacts, and seeking to decarbonize the economy.

There is a need for further investigation in the economic sphere because there are a limited number of studies addressing this area. Thus, future studies can investigate new business models, residual values in non-virgin products, fees for extraction and disposal, standardization of processes, and others. In addition, we recommend more analyses on the financial viability of CS and ES because they can assist the transition to CE. The economic information can be used by stakeholders in the decision-making process to compare the benefits and means of return on investments, considering the entire life cycle and possible subsequent cycles. Another noteworthy aspect is the impact of the CE on society, encompassing the emergence of new job opportunities, business models, and the dynamics of reverse logistics.

The social sphere is the least addressed, but we emphasize that it should be considered in future studies, with investigations focused on the benefits of reducing resource extraction in land use change, the effects of reducing waste disposal, impacts on health, urban mining, and consumpt+ion patterns, among other factors.

4.1.3. Circular Economy and Ecodesign Relation

Ecodesign principles involve integrating environmental considerations into product design and development. This approach aims to minimize primary resource consumption, optimize production and distribution, extend the product's lifespan, reduce the use of hazardous materials, increase the utilization of recycled materials, and enhance the ease and efficiency of waste treatment [78]. Ecodesign, also named design for environment (DfE), green design, or environmentally conscious design, is a strategic design practice that aims to create sustainable solutions by adopting a life cycle perspective [27,79].

Furthermore, the eco-building design aims to fulfill the customer's expectations and considers the relationship and interactions between site context and building functions in the early stage of building assets [80]. The ecodesign process in buildings is considered organic, non-linear, and holistic to fulfill technical, functional, and technological requirements and human needs while minimizing negative impacts on the natural environment [81]. These definitions make ecodesign a viable technique for use in circular economy applications.

In the transition to a more sustainable society, standards and regulations are key enablers for building ecodesign and can help to understand competitive advantage [71]. However, even with this legal incentive, there is a gap in the ecodesign integration into the design process, and in the daily practice of designers [79]. The authors link this to the lack of the environmental information needed in the early design stages, the required expert knowledge in the environmental assessment of products, and the need for efficient and feasible methods.

At the end of the life of buildings, the challenge of separating different materials and the lack of awareness show the need to bring about changes in building design to favor the disassembly process and avoid hasty disposal in landfills and/or incinerators [50]. More studies are required to explore reversible connections, durable materials to enable disassembly, building component reuse, the costs, and the effects on performance rates (for example acoustic) [67]. Finally, resistance from builders and owners can still occur when they have the alternative of reusing materials, because of uncertainties related to the material quality and the absence of methodologies to categorize them [77].

The application of ecodesign principles brings different benefits. The most widespread is the ability to reduce the product's environmental impact considering the whole life cycle. The other benefits are cost reduction, stimulating innovation, business opportunities, implementing improvements in quality, and improving the public image [79]. Also, it makes it possible to compare alternatives, considering initial costs and future costs for maintenance and waste management, and facilitate decision-making [26,82].

4.1.4. Comparison of Ecodesign Strategies (ES) and Circular Strategies (CS)

Among the articles reviewed, the ES mentioned are clustered into 23 categories, highlighting "Reuse of buildings and materials" (36 articles), "Studying alternatives" (24 articles), "Design for disassembly" (21 articles), "Recycling" (21 articles), and "Design for life extension" (16 articles). In contrast, the strategies that are less cited are "Green Public Procurement" (two articles), "Product Service System (PSS)" (two articles), and "Eco-fusion" (one article). The complete list and definitions are in Table 1.

Table 1. Building design strategies from the literature, their definitions, and occurrences.

Strategy	Definition	Source	Occurrences
Dematerialization or reduction of the amount and diversity of materials used	The substitution of a product by a nonmaterial alternative with the same utility for users, or material reduction.	[49,52,60,70,73,75,79,83]	8
Design for disassembly or reduce the end-of-life waste	Designing products to be simple and safe to disassemble, that can contribute to waste reduction during the end-of-life phase and facilitate the reuse of components in subsequent cycles. An effective and feasible selective disassembly plan is related to the product's durability, versatility, simplicity, available information, and others.	[21,37,48,52,56,57,61,62,64,66,72,73,77–80,84–88]	21
Design for ease of product maintenance and updating	Design to reduce the cost and difficulty of maintaining, repairing, updating, and replacing components during the life cycle. Some characteristics that help are modularity, easy disassembly, compound materials, and type connections. Maintenance can postpone renovation needs and extend the building's lifetime.	[60,73,77,79,80,87,89,90]	8
Design for flexibility and adaptability	Design to accommodate changes in future use and adapt to available materials. Such design actions should prioritize secure usage, affordability, low maintenance, and extend the lifespan of buildings, components, or materials.	[21,47,61,65,66,69,70,72,77,80,81,85,88,91]	14
Design for improving the production	Design to improve environmental performance during the production phase considering the reduction of waste, control of water in use, avoiding hazardous substances, and others.	[40,41,53,60,63,75,78,79,85,87,90,92]	12
Design for life extension	Design to prolong material and product lifetime through the inclusion of durability, reliability, ease of maintenance, and optimizing quality. Other strategies like design for reuse, disassembly, and remanufacturing can contribute to life extension.	[21,39,47,59,60,64,69,73,79–81,87,90,92–94]	16
Design for modularity and demountable parts	Design to optimize the valorization of materials at the end of their service life by designing demountable and reusable building elements. It also includes the study of modularity, connections that reversibly resist multiple assemblies, and existing buildings as materials banks.	[57,67,69,78,83,85,87,88,94]	9
Design for recycling	Design to facilitate the recycling process: using only one or a limited number of materials in products; using materials that can be recycled by the available technology; avoiding materials that are challenging to separate; limiting and avoid the use of hazardous materials; providing disassembly plans to sort materials.	[21,49,56,69,77,79,85–88,90,94]	12

Table 1. *Cont.*

Strategy	Definition	Source	Occurrences
Design for remanufacturing	Design to disassemble and recover a product or component. It enables the extraction of reusable parts from a used product and their incorporation into the construction of another product. By implementing this process, design components and products can be utilized across multiple lifecycles, resulting in waste reduction, minimized reliance on virgin materials, and the establishment of a closed-loop reverse logistics process. It must be aligned with other factors, such as assembly plans, buybacks, reverse logistics, managing product take-back timing, and others.	[73,77,78,92]	4
Design for reuse	Design to facilitate reuse with the minimal treatment of the material, low energy consumption, and targeting higher value retention options. Thus, it includes actions to ease deconstruction as standard dimensions, modular coordination, safety guarantees, correct joints, and others.	[21,44,57,60,61,65,69,77,78,85–87,90,94,95]	14
Develop standard of products, use phase or maintenance	To facilitate the circularity of materials, develop standardized sizes, fittings, assembly and disassembly processes, and maintenance routines.	[27,50,52,53,69,85]	6
Eco-fusion	Design to enhance the interplay among multiple scales of the built environment. This practice-based concept aligns ecodesign and eco-planning to achieve sustainable development at multiple scales (macro, meso, and micro).	[92]	1
Green public procurement	The process to include environmental performance in public procurement. The criteria inclusion can cover the end-of-life options, percentage of wastage, toxicity levels, and others.	[78,85]	2
Improved energy efficiency	Designing to promote energy-efficient construction techniques, which involves utilizing high-efficiency equipment, integrating renewable energy systems, and reducing thermal demand for heating and cooling.	[39,46,49,55,74,79–81,88,90–93,96]	14
Passive-house design and building simulation	Designing with a bio-climatic approach involves incorporating elements such as high-performance windows, heat recovery ventilation, effective air tightness, high insulation levels, and local renewable energy generation into low-energy building projects. The building simulation checks the performance and can verify if the buildings have nearly or net zero energy/emissions.	[26,35,55,60,71,74,80]	7

Table 1. *Cont.*

Strategy	Definition	Source	Occurrences
Product service system (PSS)	Model where the manufacturers retain ownership of their products and take them back after use, for value recovery and redistribution. Thus, users pay for services solutions rather than products.	[27,73]	2
Recycling	Design to reprocess the waste in order to obtain secondary raw materials. It is the least sustainable option in CE, because the materials are downcycled, reducing the quality of the second-life product.	[28,40–44,50,52,64,66,73,75,78–80,84,85,89,90,92,97]	21
Regenerative design	Design to enhance the use of natural and biodegradable resources, aiming to improve and regenerate the natural capital.	[36,48,51,57,58,69,73,79,83,85,97,98]	12
Reuse of buildings and materials components	Promote component reusability in the construction process, allowing them to be utilized in their previous function or repurposed for a new one in subsequent processes.	[27,33,37,39,40,45–47,49,50,52,55,56,59–61,63–67,69,72,73,75,79,80,83–86,89–92,97]	36
Sharing of products and services or industrial symbiosis	Collaborative relationships facilitate the exchange of energy, services, information, water, or materials within a specific geographic area (regions, provinces, or countries).	[37,46,73,78,83]	5
Study solutions for transport	Explore solutions and scenarios for low environmental impacts such as avoiding the use of fossil fuels, prioritizing local products and materials, choosing and combining modal types, and others.	[27,38,50,52,79,91]	6
Studying alternatives or improved material design	Design to achieve the most environmentally friendly option for a function or material through goals such as reducing the weight and volume of products, prioritizing materials with lower embodied energy/water, and others. Also, investigate the hotspots of a process and develop solutions to reduce environmental impacts.	[28,34,38–42,45,48,51,58,70,71,76,79,85,87,88,91,93,96–99]	24
Use of renewable energy and decarbonization of supply chain	Design to use renewable energy, sources are regenerated or naturally replenished (biomass, geothermal, solar, hydro, wind, and biofuels), to generate electric power, heating, cooking, water heating, and as fuel for transport.	[28,52,68,73,74,91,93]	7

Analyzing the relationship between the year and the strategy, as shown in Figure 7, the most cited strategies between 2020 and 2022 are "Reuse of buildings and materials", "Studying alternatives", "Design for disassembly", "Design for flexibility and adaptability", "Design for life extension", "Design for reuse", and "Recycling".

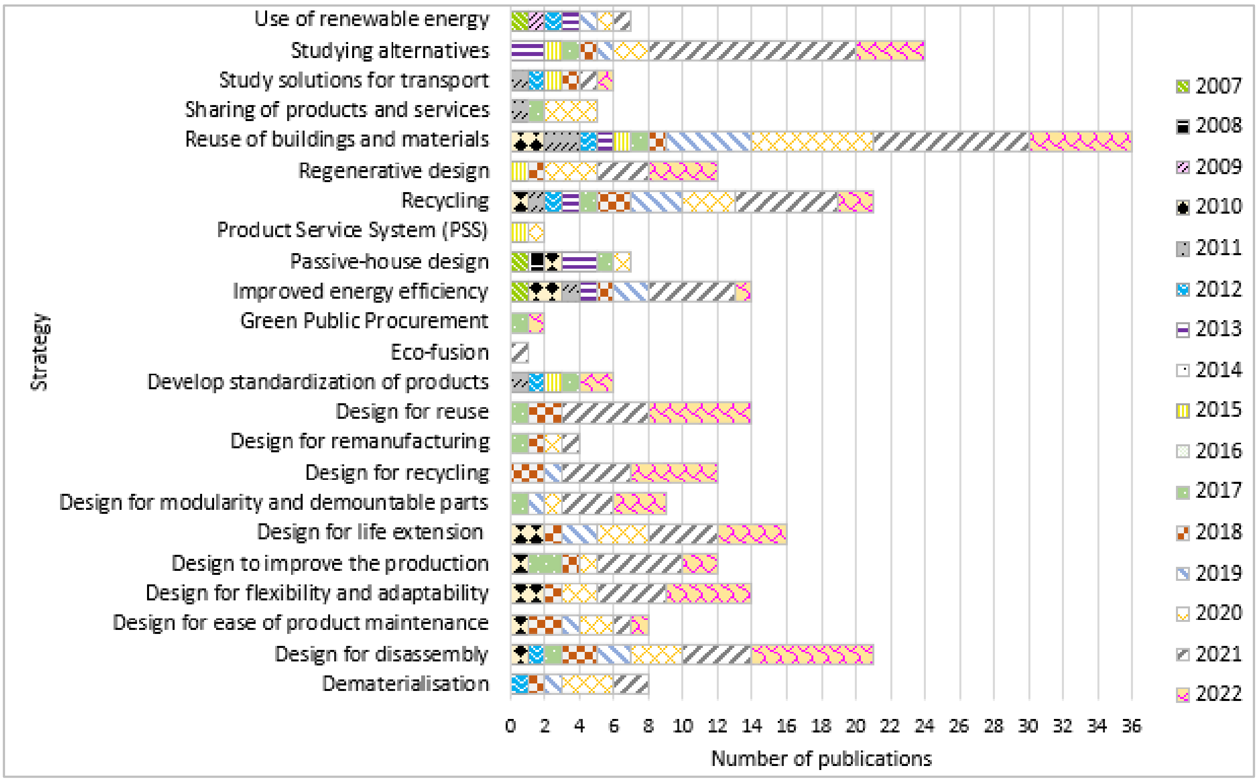

Figure 7. List of ES to implement CE by year.

Furthermore, the most recent ecodesign studies address a wider range of strategies. Until 2010, the studies were focused on investigating the "Use of renewable energy", the "Passive-house design", and "Improve the building energy efficiency", seeking to optimize the performance of buildings and their components and reduce environmental impacts. After 2010, the articles also investigated ways to extend the service life ("Design for life extension"), use material in more than one cycle ("Design for disassembly", "Reuse of buildings and materials", and others), standardize inputs and processes aiming at the exchange between suppliers and end-of-life managers ("Develop standardization of products", "Design for modularity and demountable parts", and others) and encourage new business models ("PSS" and markets for second products and remanufacturing). The analysis emphasizes that the life cycle perspective and circularity incorporation in the ecodesign process can facilitate the transition from a more circular and less environmentally impactful construction sector.

CS is defined in the scientific and gray literature. Thus, to compare the ES found in this study with the existing literature on CS, we analyzed four articles from the academic literature and seven documents and reports from the gray literature (see Table 2). The list with strategy definitions from the grey review is in Table 3.

Mhatre et al. [100] found 26 strategies with a research focus on recycling construction materials, end-of-life management techniques for resource recovery, and evaluating environmental impacts of CE adoption. Additionally, the authors identify some strategies that can lead to adopting CE on a large scale, such as bio-based materials use, ecodesign, and green procurement. A hierarchy of preference among CE implementation needs to be established, prioritizing the environmental impact reduction and considering the specificities of the context.

Table 2. Comparison of the building design strategies from the present literature review with other existing literature.

		Existing Literature											
		Academic Literature				**Gray Literature** [3]							
Strategy	**This Systematic Literature Review** [4]	**Adams et al. [101]**	**Benachio et al. [20]**	**Eberhardt et al. [31]**	**(Mhatre et al., [100]** [1]	**CIRCUIT [102]**	**De Schoenmakere and Gillabel [103]** [1]	**EMF [104]**	**IHOBE and Basque Ecodesign C. [105]**	**ISO/TR 14062:2002 [106]** [1]	**Open Systems Lab [107]**	**Zimmann et al. [29]**	**Total**
Dematerialization or reduction of the amount and diversity of materials used	x	x		x	x					x	x	x	7
Design for disassembly or reduce the end-of-life waste or selective disassembly planning	x	x	x	x	x	x		x	x	x	x	x	11
Design for ease of product maintenance and updating	x	x	x					x	x	x			6
Design for flexibility and adaptability	x	x	x	x	x	x		x			x	x	9
Design for life extension (durability)	x	x		x	x	x	x	x	x	x	x	x	11
Design for modularity and demountable parts	x		x	x			x	x	x	x	x	x	9
Design for recycling	x				x		x	x	x	x	x		7
Design for remanufacturing	x		x		x					x	x	x	6
Design for reuse	x		x			x		x		x	x	x	7
Design to improve the production	x	x	x		x					x	x	x	7
Develop standardization of products or to use phase and maintenance	x	x		x							x	x	5
Eco-fusion	x												1
Green public procurement	x	x			x								3

Table 2. *Cont.*

Strategy	Existing Literature												
		Academic Literature				Gray Literature [3]							
	This Systematic Literature Review [4]	Adams et al. [101]	Benachio et al. [20]	Eberhardt et al. [31]	(Mhatre et al., [100] [1]	CIRCUIT [102]	De Schoenmakere and Gillabel [103] [1]	EMF [104]	IHOBE and Basque Ecodesign C. [105]	ISO/TR 14062:2002 [106] [1]	Open Systems Lab [107]	Zimmann et al. [29]	Total
Improved energy efficiency	x							x		x			3
Passive-house design and building simulation	x												1
Product service system (PSS)	x		x		x		x	x				x	6
Recycling	x	x	x		x	x	x	x			x	x	9
Regenerative design	x				x			x		x		x	5
Reuse of buildings and materials components	x	x	x	x	x			x		x	x	x	9
Sharing of products and services or network-based or industrial symbiosis or collaborative relationships	x			x	x	x	x				x	x	7
Study solutions for transport	x												1
Studying alternatives	x	x	x	x	x			x			x		7
Use of renewable energy and decarbonization of supply chain	x				x							x	3
Accessibility [2]				x									1
Cascading materials [2]					x								1
Circular supplies [2]					x						x		2

Table 2. *Cont.*

	Existing Literature												
		Academic Literature					Gray Literature [3]						
Strategy	**This Systematic Literature Review** [4]	**Adams et al. [101]**	**Benachio et al. [20]**	**Eberhardt et al. [31]**	**(Mhatre et al., [100]** [1]	**CIRCUIT [102]**	**De Schoenmakere and Gillabel [103]** [1]	**EMF [104]**	**IHOBE and Basque Ecodesign C. [105]**	**ISO/TR 14062:2002 [106]** [1]	**Open Systems Lab [107]**	**Zimmann et al. [29]**	**Total**
Co-location [2]												x	1
Customization/made to order [2]					x		x				x		3
Delivering services remotely/home delivery systems [2]							x					x	2
Design for functionality optimization (multiple functions, automated control) [2]					x		x			x			3
Design structures with internal circular resource cycles [2]												x	1
Developing urban planning instruments [2]						x							1
Development of material passports [2]			x					x					2
Digital technologies and flexible design methodologies [2]							x	x			x	x	4
Eco-labeling/product labeling/socially responsible consumption [2]					x								1

Table 2. *Cont.*

		Existing Literature											
		Academic Literature				Gray Literature [3]							
Strategy	**This Systematic Literature Review [4]**	**Adams et al. [101]**	**Benachio et al. [20]**	**Eberhardt et al. [31]**	**(Mhatre et al., [100] [1]**	**CIRCUIT [102]**	**De Schoenmakere and Gillabel [103] [1]**	**EMF [104]**	**IHOBE and Basque Ecodesign C. [105]**	**ISO/TR 14062:2002 [106] [1]**	**Open Systems Lab [107]**	**Zimmann et al. [29]**	**Total**
Energy recovery [2]					x								1
Layer independence [2]				x									1
Local production on demand [2]							x						1
Material storage [2]			x	x									2
Materials exchange portal (optimize supply and demand) [2]						x		x					2
Off-site construction/prefabrication [2]		x	x	x							x	x	5
Open-source design platforms [2]					x						x	x	3
Reduction of building complexity [2]										x	x		2
Short use [2]				x									1
Take-back schemes and reverse logistics [2]		x			x	x		x	x			x	6
Taxation, tax credits, and subsidies [2]					x								1

Table 2. *Cont.*

Strategy		**Existing Literature**											
		Academic Literature				**Gray Literature** [3]							
	This Systematic Literature Review [4]	**Adams et al. [101]**	**Benachio et al. [20]**	**Eberhardt et al. [31]**	**(Mhatre et al., [100]** [1]	**CIRCUIT [102]**	**De Schoenmakere and Gillabel [103]** [1]	**EMF [104]**	**IHOBE and Basque Ecodesign C. [105]**	**ISO/TR 14062:2002 [106]** [1]	**Open Systems Lab [107]**	**Zimmann et al. [29]**	**Total**
Urban mining [2]			x			x							2
Use adequate of land [2]										x			1
Use of a tool to evaluate the state of materials (adopt a global system perspective) [2]			x				x			x			3
Use of water management practices [2]			x										1
Virtualization [2]					x			x					2
Total	**23**	**25**	**14**	**17**	**13**	**16**	**6**	**22**	**12**	**20**	**18**	**10**	**-**

Notes: The x is used to indicate whether the reference has information on the listed strategies. [1] The reference lists strategies that are related to several sectors, not only for the construction sector. [2] The full strategy description is presented in Table 3. [3] Gray literature consists of non-academic publications from organizations such as consultancy firms and policy institutes, which provide practical examples and insights. [4] In the Systematic Literature Review column, the number of citations is not considered; thus, if the strategy was cited at least once, it will appear in the table.

Table 3. Ecodesign strategies list, definition and source.

Strategy	Definition	Source
Accessibility	The goal of accessibility is to enhance the design of assembly/disassembly, simplify maintenance, optimize material recovery at the end of its useful life, and increase flexibility in systems, including dismountable and reconfigurable facades. This approach is also referred to as "open design" and allows for convenient access to the connections between components.	[31]
Cascading materials	The process to insert components and materials into different uses after their end-of-life to extract energy or other characteristics from the resource. It creates a cyclical flow of materials, extending the life of these resources. However, it is a downcycling process because resource quality declines, dissipation occurs, and entropy increases.	[100]
Circular supplies	When the supply chain is based on a closed-loop production that keeps products or materials in use for more time. Some actions to reconfigure the linear to circular supply chain: replacement of material inputs derived from virgin resources with bio-based, renewable, or recovered; product design; manufacturing; and reverse loops. Some benefits are avoiding premature disposal, lower levels of virgin resource consumption, and increasing the efficiency and productivity of the process.	[104,108]
Co-location	The co-location strategy examines the demand for area-specific quantities of activities and proposes the optimization of use by sharing spaces. This approach can be implemented in various contexts, such as housing, where it involves accommodating more people within a smaller footprint through co-living; at work, by making more extensive use of offices and workplaces around the clock via co-working; and in the consumption of goods, by sharing facilities, products, and vehicles.	[29]
Customization/made to order	Strategy based on meeting needs through product modifications and accessibility, because it provides user satisfaction and can reduce waste minimization and ecological footprint. This strategy can be combined with modularization (customization at the end of the production chain) and 3D printing technology (customized by demand or prototyping). On the other hand, uncontrolled customization can affect the repair and remanufacturing because products are too different, producing higher environmental impacts.	[103,104,108]
Delivering services remotely/home delivery systems	The process of providing remote services involves leveraging the power of IoT to track the location, status, and quality of products or services, and to remotely control them. This is made possible by embedding sensors and smart monitoring devices, which can anticipate issues and perform maintenance tasks automatically. Additionally, continuous monitoring and remote services offer several benefits, including increased efficiency, reduced waste, and prolonged lifespan of the infrastructure.	[29,103]
Design for functionality optimization	Design for functionality optimization aims to create products that integrate multiple functions, leading to a rise in product complexity and a decreased need for materials. This approach allows for the consolidation of several products into a single item, as seen with smartphones. Nevertheless, augmenting product complexity and incorporating diverse material mixtures can cause products to be incompatible with existing recycling systems.	[103]

Table 3. *Cont.*

Strategy	Definition	Source
Design structures with internal circular resource cycles	Design structures with internal circular resource cycles means designing the building's operating stage by predicting the circularity of inputs such as water (water capture, filtering, and treatment), organic waste (composting and use in gardens), independence in energy production, and the adoption of other actions aimed at minimizing externalities and environmental impacts.	[29]
Developing urban planning instruments	Cities employ diverse standards and procedures to promote sustainable construction, yet there is a dearth of precise and detailed data that can inform the development of circularity benchmarks, targets, and interventions. If such data were systematically collected and made accessible through open databases, governance and planning efforts could better support waste management, carbon footprint analysis, circularity, and related objectives. Enhanced data collection and aggregation are essential to this end.	[102]
Development of material passports	A Building Material Passport is a set of information and indicators to increase transparency about the material or system characteristics, aiming to value and maximize its use. That information allowed the choice of less impactful building materials, tracking building resources, and improving end-of-life management (reuse of materials, different life cycles, suppliers, and others).	[20,104]
Digital technologies and flexible design methodologies	Digital technologies and flexible design methodologies aim to leverage technology and innovative design to reduce uncertainty, optimize building and asset performance, minimize waste production, reduce primary material use, repurpose infrastructure use, and more. For instance, laser scanning enables the quick creation of precise 1:1 models, infrared surveys allow for non-destructive building diagnostics, and 3D printing and the Internet of Things (IoT) can enable the creation of new sustainable solutions. Another example is digital material passports, which can help with the identification, traceability, and management of materials throughout their lifecycle. Moreover, these solutions are digital, facilitating remote use and collaboration among stakeholders, and driving transformative changes in the way construction projects and processes are structured.	[29,103,104,108]
Eco-labeling/product labeling	A process based on environmental rules that allow product comparison and aid in decision-making processes. This strategy develops information standardization for consumers and compliance with the standards of products or services, also promoting environmentally friendly products and the resources circularity.	[100]
Energy recovery	A process to convert non-recyclable waste materials into usable heat, electricity, or fuel. This downcycling strategy happens through combustion, gasification, pyrolysis, anaerobic digestion, or landfill gas recovery. It must not be prioritized before other circular strategies, but it is helpful for enjoying the unused potential energy sources while minimizing dependence on conventional energy sources.	[100]
Layer independence	The layer concept acknowledges that building materials and components have varying lifespans and should be regarded as distinct layers. This approach simplifies the management of operations, maintenance, material recovery, space adaptability, and end-of-life recovery.	[31]

Table 3. *Cont.*

Strategy	Definition	Source
Local production on demand	Process where the supply chain is closer to the end-user because of the manufacturing versatility and decentralized production, while keeping the global digital aspect. It is possible because of technologies such as additive manufacturing, which can produce objects with complex geometries from digital models layer-by-layer, ease customization and on-demand production. Examples of this are 3D printing and laser cutting machines.	[103]
Material storage	The building materials bank concept posits that buildings serve as long-term repositories of materials, both for the duration of their useful life and as temporary constructions. This approach safeguards materials stored within the building from degradation over time and reduces the risk of intermediate retention that could harm the materials. Moreover, it enables the assessment of the circularity of existing buildings and assists in identifying the optimal solutions for renovation.	[20,31]
Materials exchange portal	The materials exchange portal is an online marketplace designed for materials released from building and infrastructure stocks. This technology-enabled platform facilitates the exchange of used building materials between individuals and organizations interested in giving away, selling, or buying such materials.	[102,104]
Off-site construction/prefabrication	Prefabrication, or off-site construction, involves moving the building process out of the physical construction site and into a controlled factory setting. This approach strives to promote the recovery, reuse, and recyclability of materials, optimize construction time, streamline assembly and disassembly projects, and enhance adaptability.	[20,29,31,101,108]
Open-source design platforms	Open-source design platforms are web-based platforms that enable designers to share their designs with other designers and users. This allows other designers to customize, adapt, or even construct buildings themselves. As open-source design gains popularity, architects, engineers, and designers must shift their mindsets.	[29,100]
Reduction of building complexity	Simplifying building complexity can be achieved at various levels and seeks to alleviate the challenges related to construction, maintenance, and end-of-life deconstruction. By employing complexity reduction strategies, it is possible to minimize losses, enhance efficiency, and improve product circularity. To accomplish this, it is essential to limit the use of unique materials, components, and techniques, and to label parts with numbers or colors to simplify the assembly process. Another approach is to prioritize the production of highly complex parts in industrial environments with advanced technological control and rigorous technical standards.	[106,108]
Short use	The short use concept stands in contrast to the design for durability concept, as the building is constructed solely for its designated purpose and a set duration. Consequently, material, product, and performance choices are tailored to this specific timeframe. A prime example of this approach is the Queen Elizabeth Olympic Park in the UK, which was constructed to host the Olympics and subsequently dismantled for alternative uses.	[106]
Take-back schemes and reverse logistics	Take-back and reverse logistics are part of extended producer responsibility programs designed to encourage the collection of used products at the end of their life cycle and facilitate closed-loop material systems. Reverse logistics employs techniques such as remanufacturing, refurbishment, repair, reuse, or recycling to recover and process materials and products after they have been consumed. Incentivized return policies serve to stimulate the flow of materials and products throughout the supply chain.	[29,100–102,104,105]

Table 3. *Cont.*

Strategy	Definition	Source
Taxation, tax credits, and subsidies	The government and other public entities can apply taxation to encourage or discourage practices, materials, processes, and others. In addition, taxes can determine how products are developed, utilized, and managed along supply chains and across cycles to ensure user safety and reinforce circular economy solutions. Examples are: higher prices for fossil-based products; higher taxes to kilometers driven to make transport over larger distances more expensive; taxes on landfilling and incinerating recyclable construction and demolition waste; taxes on primary materials for building materials; and tax incentives for PSS.	[100]
Urban mining	Urban mining involves the comprehensive quantification of materials embedded in the existing built environment (material stock), enabling material flow analysis and predictions about the outflow of materials during demolition. Urban mining may be informed by the analysis of historical demolition and refurbishment rates to anticipate when secondary materials may become available. Proper disassembly and inventory-taking can facilitate the reuse of these materials in new buildings.	[20,102]
Use adequate of land	This strategy avoids inadequate soil use and reduces pollution production through the optimized use of infrastructure resources and local materials required for the product.	[106]
Use of a tool to evaluate the state of materials	Examples of tools or techniques are life cycle assessment (LCA), carbon footprint, material flow analysis (MFA), life cycle cost assessment (LCC), and others. These tools evaluate the state of materials during production, lifespan, and end-of-life. Thus, a lifecycle perspective is adopted, preventing decisions based only on a single environmental criterion or lifecycle phase.	[20,103,106]
Use of water management practices	Water management practices enable the circulation of water and nutrients in the building operation phase. It is based on consumption reduction (adoption of efficient products and devices), loss reduction (monitoring losses in buildings, installation of circulation and return circuits), reuse (like of effluents from baths and washbasins for discharges in toilets), recycling of wastewater (re-introduction of water at the beginning of the circuit after treatment), and resorting to alternative sources (like rainwater harvesting or the use of saltwater).	[20]
Virtualization	Design to dematerialize and to create a virtual version of resources, flows, models, or business. Some technologies help in virtualization, such as cloud storage of data, easy access, use of artificial intelligence (AI), and the creation of virtual models of buildings and cities.	[100,104]

Eberhardt et al. [109] noticed that commonly found strategies in the literature include material selection, assembly/disassembly, and adaptability, which are primarily focused on material reuse and direct reuse of buildings. The authors emphasize the importance of designing and constructing strategies that differentiate between different buildings, components, and material groups.

An online survey conducted in the United Kingdom assessed the construction industry's awareness of the CE [101]. The survey identified 13 strategies currently being implemented and recommended additional incentives to facilitate a successful transition.

Furthermore, Benachio et al. [20] created a table with 17 known CE practices organized by life cycle stages. The end-of-life was the stage that most appeared in the articles, followed by the project design, and the phase that was least covered was the use phase.

Among the references in the gray literature are ISO/TR 14062:2002 of Environmental Management, which describes concepts and current practices related to the integration of environmental aspects into product design and development [106]. Another reference that addresses strategies more broadly is the report *Circular by design: Products in the CE* [103], which mentions 13 strategies. The book of ideas [105] investigates initiatives to use ecodesign to foster CE and identifies six strategies. On the other hand, the report published by ARUP [29] analyzes the strategies already implemented in real case studies, correlating the data with the RESOLVE Framework [13] and the different layers of the building (System, Site, Structure, Skin, Services, Space, Stuff).

The most recent report included in the study is from the Ellen MacArthur Foundation, which investigates the key sectors for a more circular and less impactful recovery in a post-pandemic context [104].

Finally, information on two practical initiatives was included. The first is the Circular Construction in Regenerative Cities (CIRCuIT), which aims to bridge the gap between theory, practice, and policy through the dissemination of demonstrative data, case studies, and events [102]. The second initiative is the WikiHouse project, an open-source design platform that incorporates digitally-manufactured building systems with high-performance and customized user needs [107].

As presented previously, in the systematic literature review, we found 23 strategies, and, in the gray documents, we found another 28 strategies. Thus, the total number of strategies is 51. The comparison of them enables us to identify that a number of strategies from the gray sources extrapolate those found in the literature review, and, in each document, the number of strategies addressed ranges from 6 to 25. Among the most common strategies are: "Design for life extension" and "Design for disassembly (. . .)", which are present in 11 documents; "Reuse of buildings and materials components (. . .)", "Recycling", "Design for flexibility and adaptability", and "Design for modularity and demountable parts", which are present in 9 documents.

Among the identified strategies, the ones seeking efficiency, reducing consumption, reuse, recycling, and remanufacturing continue to be the most widespread and explored. Previous studies have shown that these strategies can effectively minimize material costs, reduce waste generation, and meet the demands of new customers and population growth [13]. However, exploring only these strategies might not be sufficient to bring about circular buildings. Thus, further studies are needed to investigate other strategies listed in this study, seeking to identify the benefits and challenges linked to each one.

The description of the strategies also indicates that many of them are correlated, and the application of one may favor the application of another. However, managing the trade-offs of strategy choices to achieve circularity and adequate environmental performance can be confusing. Eberhardt et al. [108] highlighted that the strategy choice was often based on intuition since there is a gap in the strategies' environmental performances and related benefits.

There are different recommendations for the strategy choice: consider the longevity and initial lifetime of products [19]; extend the value and useful life of the resources used [21]; enable future adaptations, including expansion or deconstruction [29]; and others. Furthermore, the strategy could bring different results because of buildings' typologies, components, and material groups and how they are used in their life cycle [31]. The authors also pointed out that insufficient knowledge about strategies' environmental performances risks inappropriate selection and potential rebound effects with higher environmental impacts. To reduce this gap between theory and practice, efforts must be made to identify the needs of designers and the necessary adaptations in the ecodesign process [71].

Moreover, designers wishing to use ecodesign must be supported by simplifications in the method and effective recognition of the sustainability approach's complexity and importance [90]. Advances in the development of open-source methods can provide early feedback on design decisions and help designers to drive circular building design [110]. Moreover, the integration of creative problem-solving activities, such as the ecodesign process, can help in the translation of customer demands into innovative and sustainable solutions [111].

4.2. Framework

The choice of strategies must be made on a case-by-case basis, within the temporal, spatial, and cultural study contexts [1]. Thus, the framework proposition aims to organize the building project flow, helping to select and implement CS and ES in the early stages, as illustrated in Figure 8.

The proposed framework is based on the Plan-Do-Check-Act concept, recommended by ISO/TR 14062 [106] for environmental management, because improvements and iterations are continuous and must be constantly reviewed. Also, the number and complexity of interactions among actors in the CE create complicated management of trade-offs [112], which require a holistic and collaborative view of the decision-making processes of strategies.

In the first stage, Plan, the objectives (environmental, social, economic, and circular) are established through the initial environmental assessment. It can be carried out using data from previous studies, benchmark databases, EPDs, or materials passports. Moreover, in this stage, the following can be considered: the main hotspots to be improved, the defined scale of action, and creating the dashboard criteria. The scales are classified as follows. The macro scale refers to cities and neighborhoods, the meso scale to buildings, and the micro scale to assemblies and components [113]. The creation of the dashboard involves correlating relevant aspects, such as material consumption, energy usage, water consumption, waste production, and pollution, with the different phases of the life cycle.

In the second stage, Do, two activities take place. The first one is the definition of the design strategy, based on the results of the dashboard, considering technical and biological cycles and the long-term building lifecycle. After that, efforts should be made to develop communication (internal team and final user) and the alignment of consumer preferences, choices, and behavioral patterns. To ensure effective communication, it is recommended to follow the characteristics of the framework proposed by Lofthouse (2006) [114]: guidance; information; visual; inspiration; dynamic access; non-scientific language; and education.

The second activity refers to the implementation of the selected strategy or strategies through the simultaneous modeling of the building model and the life cycle. The combined assessments allow stakeholders to define the feasibility and desirability of design strategies and to check the environmental building performance and circularity. The use of BIM helps in the integration of different stakeholders in these processes and digital technologies.

In the third phase, Check (and monitoring), the results of Stage 2 with the Stage 1 objectives are compared, checking the reduction of the environmental impacts from selected strategies. Monitoring must take place throughout the entire lifecycle (first and others) and the results obtained by each strategy must be reported, as well as the relationship of the strategies with the behavior of users. Such data can be obtained from the BIM models of the processes under analysis and will also serve as a data source for future benchmarks.

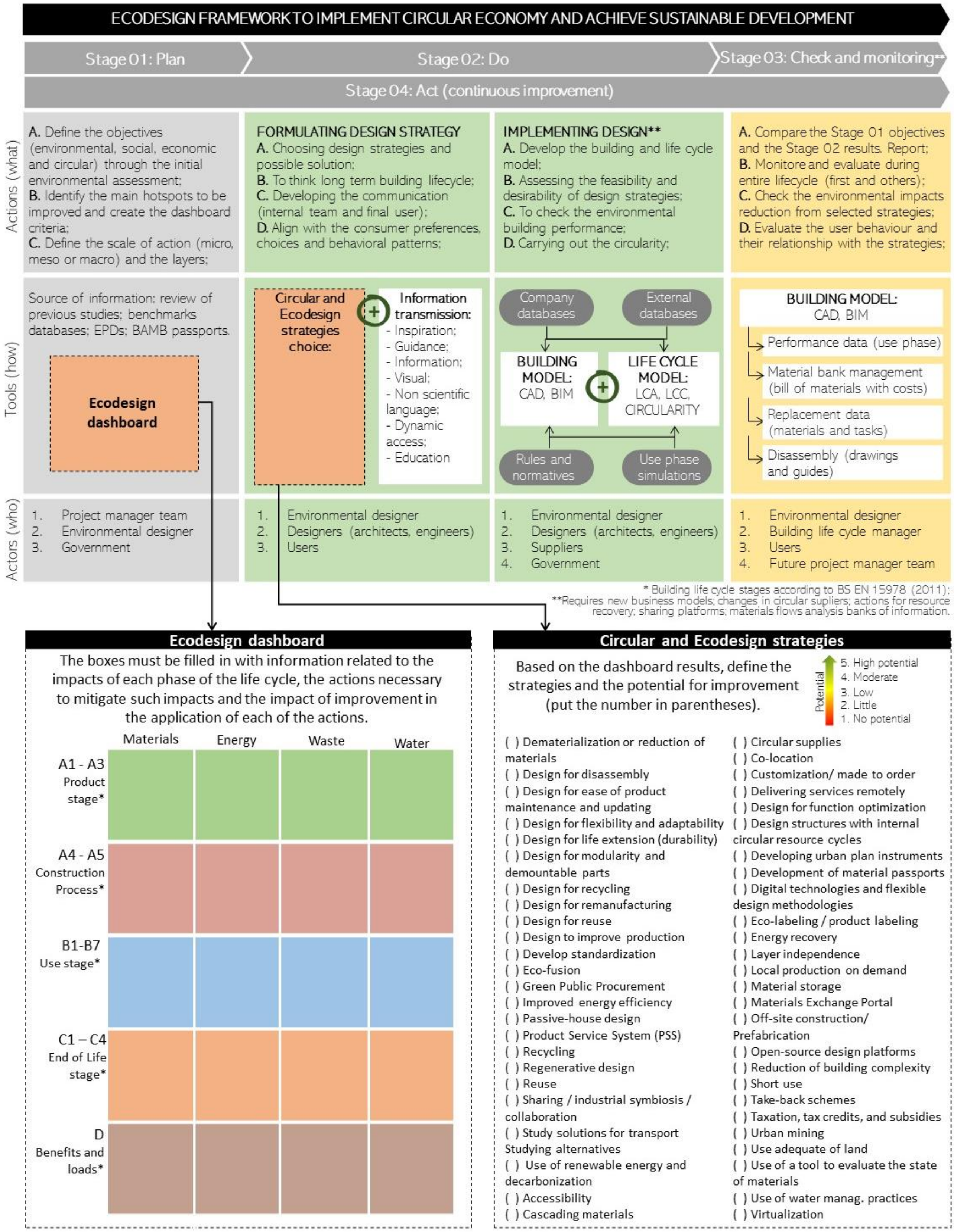

Figure 8. Ecodesign framework to implement CE and achieve, check and monitor sustainable development.

In the fourth phase, Act, the results of the framework application must be reported, as well as its difficulties and new variables that must be considered in the ecodesign process for implementing the CE.

The proposed framework allows the management of trade-offs of competing objectives (such as economic and environmental) that need to be considered simultaneously in an integrative manner [17]. Furthermore, we developed the structure based on ecodesign and PDCA principles, which allow the organized development of new ideas, the exploration of new alternatives, and the search for continuous improvement in the design flow.

Finally, the proposed framework helps in the CE transition because:

- It allows a collaborative view of the decision-making processes in the initial phases of the project;
- It helps identify environmental hotspots and aligns with previously employed strategies (benchmarks);
- It facilitates management throughout the life cycle and can connect with new life cycles (bank of materials, deconstruction, and cycling, among others);
- It facilitates the mapping of information and the construction of a database for new projects;
- It guides on the integrated use of the LCA environmental assessment technique and BIM modeling software;
- It assists in checking the impacts of the use of CS and ES regarding circularity, environmental, economic, or social spheres.

5. Conclusions

The CE theme has grown exponentially in recent years in different sectors. The analysis of existing reviews on CE in the construction sector indicates that there is awareness of the urgency of adopting the principles of the model. However, there is fragmentation in the approach to the theme. Furthermore, there are still uncertainties related to the impact reduction of many CS, and an in-depth analysis of how they can affect environmental performance is required.

This study provides a comprehensive analysis of ecodesign and CS in building construction. The identified strategies, together with the proposed framework, can serve as a useful guide for stakeholders to improve the environmental performance of the built environment and increase circularity. We included 69 articles in the review and identified 23 strategies. The findings indicate that the most cited strategies are reuse, recycling, design for disassembly, design for life extension, studying alternatives, and improved energy efficiency. However, new strategies have also emerged in recent literature, indicating the ongoing evolution of the field.

The comparison with grey literature allows the identification of new strategies, totaling 51. Further studies are needed to investigate the benefits and challenges linked to each one, and how the strategies are correlated in the search for better environmental performance and circularity. Furthermore, the investigation of ES is also relevant since the CS primarily aims to increase circularity, while ecodesign ensures the mitigation of environmental impacts and a holistic view of the project.

We proposed a framework based on the Plan-Do-Check-Act concept to streamline the management of trade-offs when selecting strategies. This framework enables a collaborative approach to decision-making processes for strategies and effectively manages their impact on circularity, as well as environmental, social, and economic performance.

By embracing a life cycle perspective and integrating circularity into the ecodesign process, the civil construction sector can play a pivotal role in driving the transition toward a more sustainable CE. This study enhances our understanding of the potential of CE in the construction sector and offers valuable insights into the implementation of circular strategies and ES practices, thereby contributing to the attainment of sustainable development goals.

We list some recommendations for future work aiming to continue discussions in this area: (i) check the economic viability of the application of CS and ES and compare it with traditional practices; (ii) apply CS and ES in different case studies and, preferably at different scales, to verify the relationship between increased circularity and reduced impact; (iii) examine the effects of combining strategies and determine if there are specific building types, materials, or construction systems to which they are better suited; (iv) analyze whether there is a particular strategy that should be prioritized or that offers greater environmental benefits based on the stage of the building, whether it is existing, historic, new, temporary, or other; (v) check how the context can affect the application of CS and ES and which factors should be analyzed carefully; (vi) determine how to communicate the levels of circularity (or possible paths) and its benefits to decision-makers; (vii) determine how to automate the inclusion of strategies in modeling software such as BIM, facilitating the inclusion of the practice in the routine of design offices.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings13082059/s1, Table S1: Summary contents of review articles about Circular Economy (CE) in the construction sector; Table S2: Study purpose and key results of each article analysed in the literature review.

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