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Review article

Circular economy in construction - findings from a literature review

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ABSTRACT

The paper aims to enable a comprehensive definition for a Circular Economy (CE) that will support its effective introduction in the building and construction sectors. According to the European Commission (EC), the building sector in 2020 accounted for 40 % of the primary energy demand in the European Union (EU) and 37 % of its greenhouse gas emissions. Thus, the sector can play a crucial role in decarbonisation and hence in achieving a zero-emissions future in response to climate change. A CE aims to harmonise economic growth with environmental protection and is based on the concept of closing the loop with minimal practical waste as in a natural ecosystem. The adoption of CE concepts is therefore seen as a feasible response to climate change through the deployment of more sustainable construction processes that significantly reduce the need for natural resources by maximising recycling and reuse. However, and despite the recognition of the potential of a CE in relation to sustainability issues, the adoption of a CE model within building and construction sectors is challenging because of the wide range of aspects and priorities which are reflected in the diversity of definition resulting in a narrow and limited adoption. There are currently many definitions of CEs as related to building and construction in the literature, creating confusion and preventing effective implementation.

The study presented here intends, using a comprehensive literature review as its basis, to define the key domains of a CE on which to align a concise and accurate definition that will enable effective application in the building and construction sectors. The research also aims to identify current research gaps and barriers to contribute to the future of CE research in the building sector and thus drive the implementation of CE projects to mitigate the effects of climate change and support the achievement of the UN Sustainable Development Goals (SDGs) by laying the foundations for a novel and forward-looking approach to circularity based on properly established, defined and understood principles of CEs.

Abbreviations

C2C Cradle-to-Cradle
CE Circular Economy
DFA DFD Design for Assembly Design for Disassembly
EC European Commission
EEA European Environmental Agency

(*continued on next page*)

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(*continued*)

EMF Ellen MacArthur Foundation
EPD Environmental Product Declaration
EREP European Resource Efficiency Platform
EU European Union
FSOC Financial Stability Oversight Council
GHG Greenhouse Gas
GlobalABC Global Alliance for Buildings and Construction
IEA International Energy Agency
LCA Life Cycle Assessment
OECD Organisation for Economic Co-operation and Development
BMP Building Material Passport
UNEP WorldGBC United Nations Environment Programme World Green Building Council
WEF World Economic Forum

1. Introduction

For decades, science has been describing how the Earth has been becoming increasingly warmer as illustrated in Fig. 1 and has put forward various scenarios of varying degrees of complexity as to the impact of these changes. There is now a consensus that a causal relationship between human activity and rising temperatures is driving increasing numbers of extreme weather events around the world [1]. This can largely be attributed to the overconsumption of fossil fuels over time and the prevailing linear economic model that drives current business practices.

The economic and social costs of environmental effects associated with human activities are often overlooked, despite these activities being widely recognised as a major cause of resource depletion, climate change and social inequality. Thus, the 2021 '*Climate Transparency Report*' by the Financial Stability Oversight Council [2] reveals that the economic losses associated with extreme weather events have increased by 86 % over the past decade to $129 billion per year, and that these losses impact primarily on vulnerable peoples and communities and developing countries. These increased losses are largely due to the increasing frequency and intensity of extreme climate events such as hurricanes, floods and forest fires, which are themselves associated with climate change.

The physical effects of climate change will have far-reaching consequences for human well-being and the economy. Rising temperatures will lead to lower productivity and crop yields, while higher sea levels and extreme weather events will cause damage to infrastructure and ecosystems. Economic estimates of these consequences are frequently generalised and fail to account for the unequal distribution of costs, which disproportionately affect the poorest and most vulnerable communities. There are also unforeseen and potentially catastrophic tipping points in the climate system that could cause serious economic and societal problems as emerges in the research of Dietz et al. [3] and reported by the Grantham Institute – Climate Change and the Environment. The 2021 Financial Stability Oversight Council report also underlines the importance of countries implementing the Paris Agreement and achieving Net-Zero emissions by the middle of the 21st century to minimise the long-term impacts of climate change.

According to the International Energy Agency as reported by Mathioulakis in '*Aspects of the Energy Union: Application and Effects of European Energy Policies in SE Europe and Eastern Mediterranean*' [4,5], the built environment has long been a significant contributor to high resource consumption, as illustrated in Fig. 2. In Europe, as outlined in the European Commission's "*Clean Energy for All Europeans package*" [6–8] the buildings and construction sector are currently responsible for 37 % of global operational energy and process-related CO2 emissions. published by the UN Environment Programme (UNEP) and the Global Alliance for Buildings and Construction (GlobalABC) shows that by 2050, half of all buildings will be new constructions. To transition to a low-carbon sector, significant advancements in projects, innovation, and financing are needed to achieve a net-zero trajectory by 2030. The report by the GlobalABC also highlights that energy demand from buildings contributes to one-fifth of emissions, with even a 1 % increase in emissions being equivalent to more than 10 million additional cars. In addition, the EU has a significant number of older buildings, with 35 % being over 50 years old while almost 75 % of the current building stock is considered as energy inefficient.

Surprisingly, only 0.4 %–1.2 % of the EU building stock is renovated each year [6], and, according to the IEA [9], this will need to increase by 3 % each year to achieve universal net-zero carbon status by 2050. This goes beyond residential homes. The Global Status report for Buildings and Construction [10] emphasises the need for major renovations of commercial buildings such as offices, hospitals, factories, warehouses, and educational institutions in order to achieve a 40 % decrease in energy usage. The research emphasises that present retrofitting initiatives fall well short of what is necessary, citing limited financing and barriers to implementing retrofitting technologies such as high upfront costs, lack of incentives, disruption to ongoing operations.

Achieving a sustainable built environment therefore requires a rethinking of the resources that the planet can sustainably produce. This need for urgent behavioural change is illustrated by Earth Overshoot Day [11], the nominal date on which it is estimated that the year's resource consumption exceeds the Earth's capacity to replenish these resources by the end of the year. This date has been constantly moving forward and for 2023 was taken as 2 August, further evidence of the depletion of planetary resources. As a CE aims to mirror nature's circular economy, the adoption of a CE concept by the building and construction industries could make an effective

[1] Direct emissions are from the use of coal, oil and natural gas in buildings. Indirect emissions are from the generation of electricity and heat used in buildings.

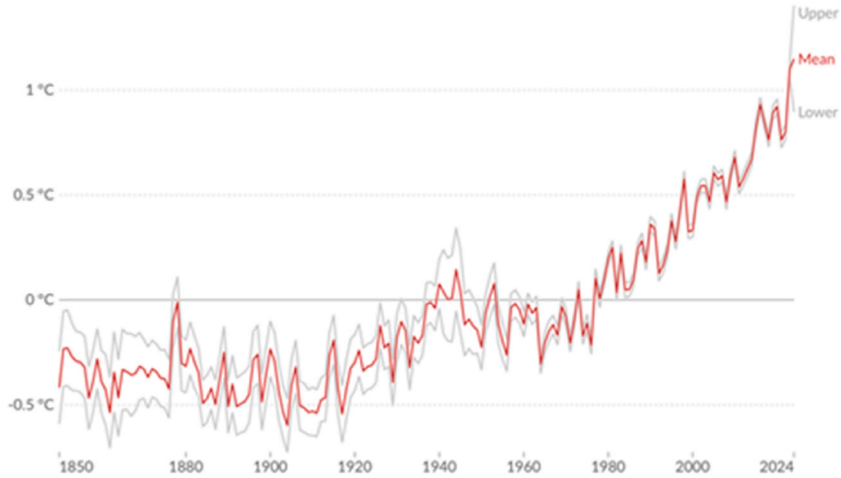

Fig. 1. The average land-sea temperature anomaly.
Data source: Met Office Hadley Centre (2023) https://ourworldindata.org/grapher/temperature-anomaly

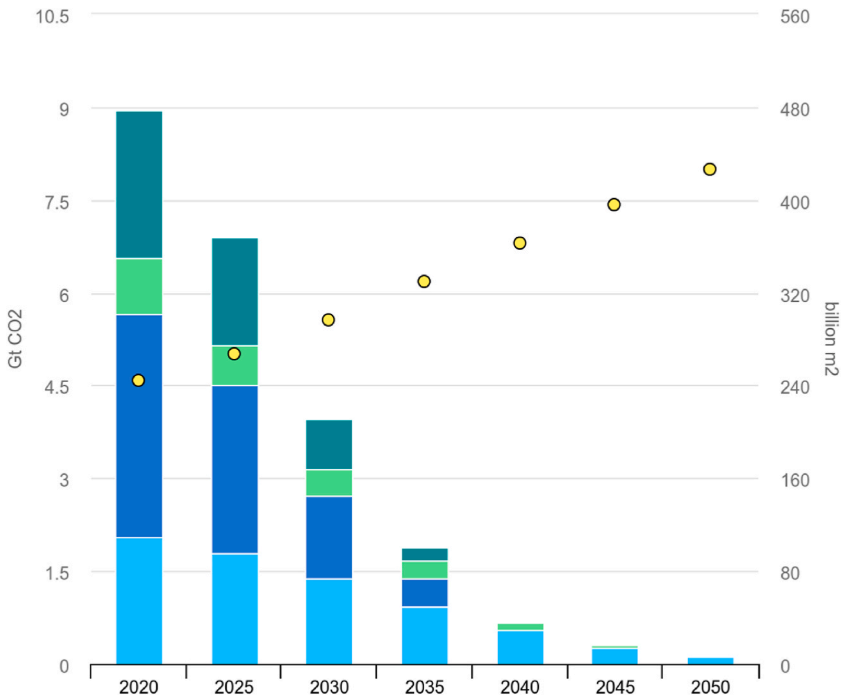

Fig. 2. Global buildings sector CO2 emissions and floor area in the Net Zero Scenario, 2020–2050.
Sources: Data from IEA's Net Zero by 2050: A Roadmap for the Global Energy Sector.[1]

contribution to combating climate change and achieving the UN Sustainable Development Goals [12].

How to translate CE principles into practice and to ensure their large-scale adoption by the building and construction industries is therefore an important element of the research. Another is to investigate if there is currently an agreed, understandable, and comprehensive definition of a CE for the building and construction sectors that encompasses all key sustainability areas relating to environmental, economic, and financial, social and technological issues. The research thus aims to identify the key features of these areas on which based a novel framework, here taken to be a supporting structure around which the CE can be built, developed, assessed, and monitored, to support the effective adoption of the CE. A review of the existing literature was therefore conducted to determine the current state of research and to identify the associated gaps in this research to determine what paths to follow to achieve sustainable, circular buildings and a Net-Zero carbon built environment.

2. Research methodology

The first aim of the literature review was to identify existing definitions and related backgrounds associated with achieving a sustainable CE in the building and construction sectors to understand how to meet the complexity of CE objectives in ways that are compatible with achieving circularity for sustainable buildings. The first step was therefore to identify the state of the art in terms of current definitions, initially for a general CE and then with specific reference to the building and construction sectors.

2.1. Research process

This section explains how the methodology of the study was designed to evaluate the literature review, initially regarding the general concept of a CE and the principles on which it is based, its origins and therefore its definition. Establishing the original concepts and historical development of the idea of a CE is crucial to understanding whether existing definitions effectively encompass all dimensions of the CE, as well as where these existing definitions originated.

A literature review was decided upon as the research methodology as it represents a transparent, repeatable, and updatable process [13] structured as follows.

a) the research questions were clearly defined;
b) the aim and scope of the review were determined;
c) the inclusion and exclusion criteria were established for the selection of relevant studies and are transparently reported, as are the processes used for data extraction and synthesis;
d) the search strategy was developed and executed on two electronic databases (Scopus and Web of Science), as well as through manual searches of reference lists;
e) the search strategy and literature review process were documented, allowing for replication and update of the study to find further eligible material;
f) the study was conducted in accordance with accepted criteria and guidelines, including the PRISMA flow diagram of Fig. 3, which enhances the transparency and replicability of the literature review.
g) the results of the literature review were summarised and synthesised, highlighting the key themes and knowledge gaps in the literature. The findings are presented in a narrative format supported by tables and figures. The findings are discussed and recommendations are made for further study in this field.

A representation view of the methodological approach used is given in Fig. 4.

This approach is based on the argument by Briner & Denyer [14] that the review process should adhere to the following principles: (1) perform a methodical review; (2) present a transparent process; (3) be repeatable and updatable; and (4) summarise and synthesise the major theme of the research. Table 1 demonstrates how this approach is applied in this study.

2.2. Review process

A literature review was conducted to identify the current state of research and identify existing gaps and barriers to the adoption of the CE and of its future development. Relevant literature published between 2010 and 2023 was considered. The start date was chosen as the European Commission included a description of the CE concept in its 2015 communication '*Closing the Loop – An EU Action Plan for the Circular Economy*' [15], which forms a part of the EU's Circular Economy Package. A time period of 5 years before this EU document was thus used to include background papers.

The literature search was conducted using the complementary databases Scopus and Web of Science using specific sets of keywords and strings related to the CE concept as derived from the papers themselves so that the analysed publications contain keywords selected to obtain publications covering the broader notions of the CE concept. The keywords and search terms used are listed in Table 2, along with the number of returns associated with each of these.

The searches returned an initial total of 570 publications. This number was then reduced to 128 by comparing the title, abstract and keywords with the scope of the study and removing non-relevant topics and duplicates. In addition, returns in which CE was not related with the building and construction sectors and/or in which the proposed solutions were contextualised to specific case studies in a particular location or nation were eliminated. Finally, 49 papers were selected from the databases to which a further 6 from other studies cited in the 49 selected articles and from grey literature were added, for a total of 55 articles.

Here, grey literature [16] refers to literature that is not disseminated through conventional and traditional channels such as academic journals or books. This includes reports, dissertations, conference proceedings and government documents. Grey literature has the advantage of providing data that may not be found in published papers, especially as journal publication tends to favour positive results, leading to publication bias [17]. Grey literature can include studies with invalid or negative results that might not otherwise be published, providing a more comprehensive and unbiased view of research in a particular area. It can also disseminate research findings that do not meet the criteria of a journal, such as preliminary studies or niche research. The inclusion of grey literature in overviews and analyses improves both scope and reliability, as a broader range of sources is included. Overall, grey literature helps to reduce publication bias, increase the reliability of scientific reviews and create a fair presentation of research findings.

Considering that the concepts of a CE were developed to a significant extent through grey literature, papers from grey literature were also collected and identified a priori as meeting the scope and selection criteria of the research. The available grey literature was

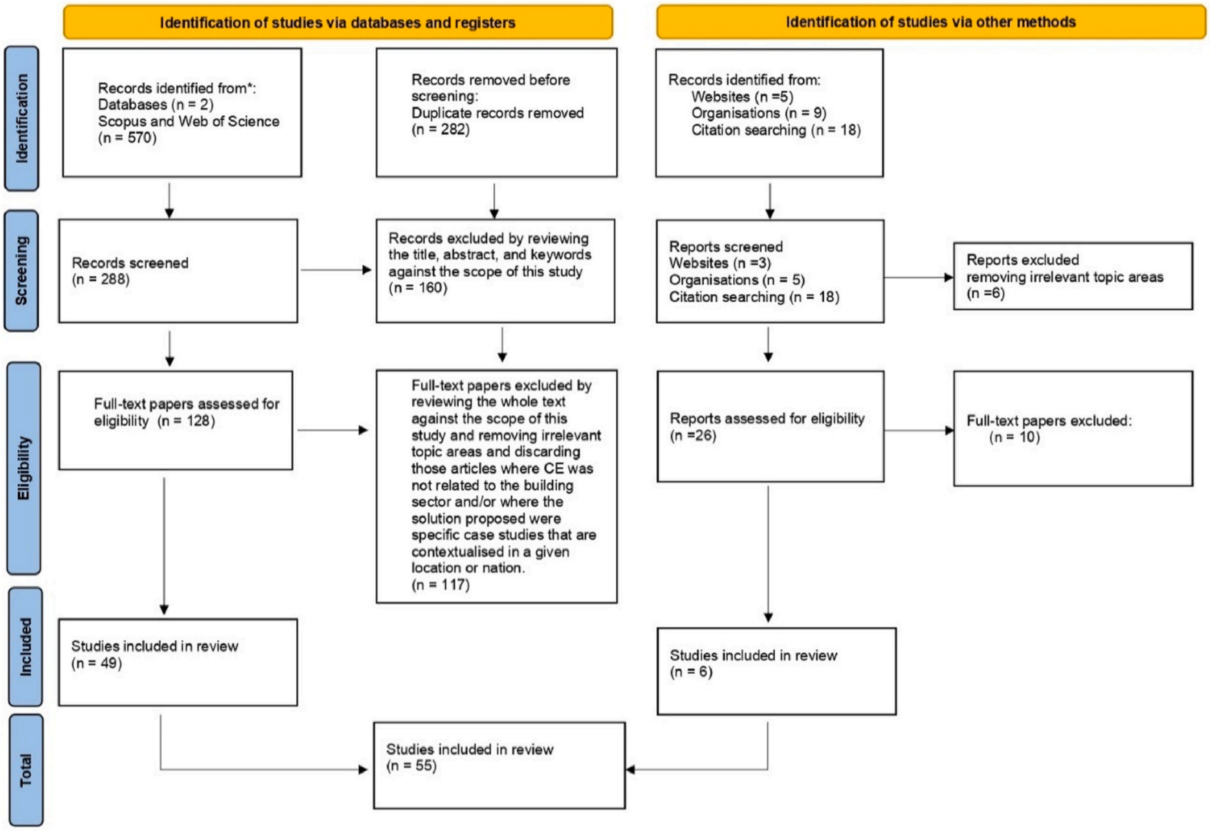

Fig. 3. PRISMA Flow Diagram for the literature search as carried out and reported.

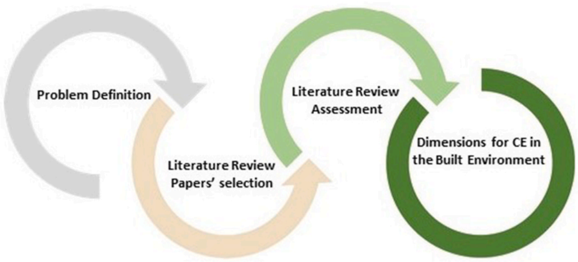

Fig. 4. The methodological approach of the research.

Table 1
Research process development.

Steps	Research Process
Scope	How does CE meet the complexity of the policy and be coherent to achieve circularity in respect of sustainable buildings?
Question definition	Is there a need for a comprehensive definition of a CE in the built sector?
Objective(s)	a. Identify the current state of research.
	b. Establish the gaps and barriers to the adoption of the CE and its future development within the building sector.
Selection criteria	Identification of papers relating to the CE concept and its application in the building sector.
Strategy	Data basis and grey literature.
Screening	Not matching the selection criteria.
Eligibility	Selected papers studied by authors.
Results	Findings from the selected papers.

Table 2
Keywords, search terms and numbers of papers returned.

Search Terms	Papers Returned
circular economy AND built environment OR building sector	203
circular economy AND built environment OR building sector AND NOT circular AND economy OR building environment AND construction sector	188
(TITLE-ABS-KEY (circular AND economy) OR TITLE-ABS-KEY (building environment) AND TITLE-ABS-KEY (construction sector))	139
(TITLE-ABS-KEY (circular AND economy AND framework) AND TITLE-ABS-KEY (circular AND economy AND indicator) AND TITLE-ABS-KEY (built AND environment))	12
(TITLE-ABS-KEY (cradle to cradle) OR TITLE-ABS-KEY (circu* building*) OR TITLE-ABS-KEY (low environ* impact*) AND TITLE-ABS-KEY (construction sector))	28
Total	570

analysed to determine what had already been done at the market and policy levels, using publications such as European Commission reports [15,18–20], Organisation for Economic Co-operation and Development (OECD) reports and material from the International Energy Agency (IEA) [1,4], the World Economic Forum (WEF) [21], the United Nations Environment Programme (UNEP) [8,22], the Ellen MacArthur Foundation (EMF) [20,23–25]' and the Financial Stability Oversight Council (FSOC) [2].

3. Content analysis and interpretation

This section reports on the content analysis of the selected papers to establish the state of the art concerning the CE concept. This content analysis is divided into two phases: (1) examining the theoretical concept of CE, its origin and principles, and their historical development to support an understanding of the concept of a CE, and (2) analysing existing definitions of a CE for the built environment to assess the extent of adoption of its principles in that environment.

3.1. CE theoretical concept

A CE represents a fundamental alternative to the conventional linear economy model based on the '*take, make, dispose*' approach to production and consumption which assumes that natural resources are abundant, readily available, easy to obtain and inexpensive to dispose of. As a result of this linear model, in the early phases of industrialisation when neoclassical economic theory prevailed, industrialised and industrialising nations did not consider the limitations of natural resources. This theory no longer seems applicable [26] and, in contrast, a CE aims at a regenerative approach to minimise resource use, waste emissions, water consumption and energy use [28,29]. This is achieved primarily by slowing down, closing, and reducing the consumption of energy and raw materials. Achieving a CE can be carried out in part by extending the life of materials while maintaining their quality, further supporting the conservation of resources and energy [30]. Thus, the CE concept is proposed as a concept that has significant potential to contribute to solving the negative consequences of human intervention in the environment and related problems such as resource depletion, climate change, pollution, and public health [30–32[33]]. It is now also increasingly accepted by governments as it combines economic growth with environmental protection and the optimal use of resources [34].

The CE component in Fig. 5 thus aims to avoid the loss of economic and environmental value as much as possible and to operate within the ecological limits of the planet by producing more efficiently and consuming less. This also requires a move away from the linear model to reconcile materials production and consumption with minimising the use of natural resources.

The need to save raw materials through more efficient production models [35] is not a recent concept, but one that originally emerged in 1989 during the economic crisis that followed the embargo on Chinese goods after the Tiananmen Square protests of that year, and which was later reaffirmed by the rise in raw material prices in the 2000s. Moreover, in recent years, the increasing frequency of climate change-related events has emphasised the need to shift production processes from the usual linear to a circular path [36,37]. The CE concept has also gained prominence in conversations about industrial growth as a strategy for tackling environmental problems [21,38] and promoting sustainable development, and at its core represents an entirely new way of thinking about how to do business and how to produce and consume. According to the World Economic Forum's [134] report '*Towards the circular economy: Accelerating the scale-up across global supply chains*', it is estimated that a transition to the circular model will save one trillion US dollars[2] in material costs alone over the next ten years, with both environmental and economic benefits [28].

3.2. Origin and principles

Recognising a CE as a viable alternative to the linear model, an examination of the genesis of the CE principles and their development was conducted to better understand the meaning and potential of the concepts contained within the words *'circular economy'*. This assessment was necessary to understand the consequences and interrelationships of the main principles of the Circular Economy when applied to the built environment and to assess the availability of a universally accepted definition.

[2] 1 trillion US dollars in 2014 translates to approximately 1.3 trillion US dollars in 2024.

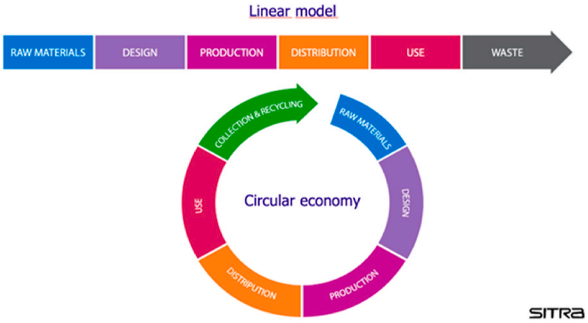

Fig. 5. Linear vs Circular economic models.
Source: https://www.sitra.fi/en/

The term '*circular economy*' emerged in the 1988 publication '*The Economics of Natural Resources*' by Kneese [38]. These same principles are also expressed in a slightly different form and context as the '*Triple Bottom Line*' of Planet (environment), Profit (economic) and People (social), or the 3Ps, as put forward by Elkington in 1994 [40,41] and set out in Fig. 6. From this viewpoint, the significance of a holistic approach that considers environmental issues in addition to economic growth was stressed.

At first, it might seem odd that the concept of '*circular economy*', which focuses on the cycle of resources [42] and proposes a model based on reusing, repairing, remanufacturing, and recycling existing materials and products, emerges from an economic rather than environmental perspective [30]. This is in large part due to the United Nations Environment Programme ([133]) definition of the green economy as one that results in '*improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities*' [8].

> "*The definition of the green economy places economic value on natural resources since they are finite in availability and vulnerable to human usage.*" [39]. Thus, the CE begins to be seen as a potential solution for long-term sustainable economic growth [41], according to the United Nations Environment Programme.

Another assumption underlying the concept of a CE is that of fair access to resources in the present and future as was stated in the well-referenced 1987 Brundtland Commission Report '*Our Common Future*' in which sustainability is defined as '*meeting the needs of the present without compromising the ability of future generations to meet their own needs*' [44]. This concept was emphasised by Ghisellini [26] who assumed the CE a solid basis for considerably changing the present business model by focusing on regenerative eco-industrial growth, as well as enhancing well-being by restored environmental integrity. These same principles are again expressed in a slightly different form and context by Elkington in the *Triple Bottom Line* concept [40,41]. In this latter case, the significance of a holistic approach that considers environmental issues in addition to economic growth was stressed.

> The term '*circular economy*' is thus associated with the natural ecosystem. The idea that materials production and energy use should become as circular as natural ecosystems was proposed in the 1966 article '*The Economics of the Coming Spaceship Earth*' by Kenneth E Boulding [27] [26,34], in which he explains why we should be in a '*cyclical*' production system and thus in a '*circular economy*'. This relationship with the natural ecosystem is illustrated in the European Commission Directive 2008/98/EC, which recognises that human activities, particularly in the form of design and the pursuit of progress and

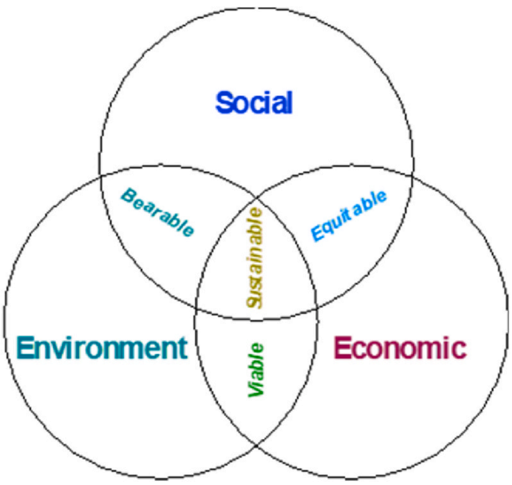

Fig. 6. The triple bottom line.

> prosperity, affect the natural balance in ecosystems. This directive recognises that the pursuit of industrial progress and economic growth, as practised to date, has led to conflicts with environmental sustainability and the conservation of natural resources. It is now clear that the current '*take-make-dispose*' linear economic model produces not only negative effects on the environment, but also causes social and economic inequalities worldwide. *The* 2008/98/EC Directive presents the European Commission's efforts to address this conflict and promote a more sustainable approach to industrial activities.
>
> Lazarevic & Valve [30] suggested a concept based on the balance of the ecosystem as follows: '*the industrial ecosystem would function like an analogue biological ecosystem*'. *This* highlights the relationships between and interdependence of, the different components within an industrial system, in a manner similar as to how species and organisms interact within a biological ecosystem.

The concept of a CE is now envisioned as an economic paradigm that will support more sustainable growth and a more fair and peaceful society [26], even if other components, particularly the social dimension, are not usually included [43].

3.3. The current definitions

This section aims to demonstrate that, while the CE concept requires addressing environmental, social, and economic concerns, there is a proliferation of CE definitions based on specific factors that make the CE concept vague and unclear. In doing so, more detailed CE definitions are investigated to better understand why the existing CE definitions are ineffective in embracing the CE model.

The 1987 Brundtland Commission Report was a landmark publication by the United Nations World Commission on Environment and Development. Investigating the interrelationship between human activity [26] and the environment and the subsequent implications for economic and environmental policy was a role [12,44] of this Commission and resulted in the definition of sustainability quoted in the previous section [42]. Although this is essentially a definition of sustainable development [40,45,46] the Brundtland Report emphasised the relationship between the use of resources and the consequences of failing to guarantee that future generations have equal access to these same resources. The concept of sustainability introduced in Brundtland's statement is thus closely intertwined with the idea of CE development.

> Therefore, to better understand the context it must be remembered that etymologically, the term '*sustainability*' comes from the Latin verb sustineo (sub-teneo), with the double meaning of '*hold, hold up, don't drop, keep in its position, make sure that a certain thing lasts or subsists*' or '*taking on, carrying on, hold on, taking on himself the commitment*'. On the one hand, the term implies the protection and continuation of whatever exists now and must be preserved for and in the future, while on the other, it means support and the assumption of responsibility. Two worlds intersect in this duality of meaning: the world of the object (the world, nature) that lasts and is conserved, and the world of the subject (humanity first and foremost) accountable or co-responsible for the world's preservation [47]. In the etymological root of the word sustainability thus lies the principle of resource justice.

The Brundtland report's sustainability argument laid the foundations upon which the concept of the Triple Bottom Line was based and from which three domains of intervention emerge: namely social, economic, and environmental, all of which should coexist in harmony [43]. Ghisellini confirmed that the CE comprises establishing cleaner production processes inside businesses, fostering more responsibility and knowledge among producers and consumers, therefore the use of renewable technologies and materials to support these efforts performs a critical role [26].

However, linking social, environmental, and economic dimensions together is of itself not sufficient to create a circular environment. The research described here also addresses the technological dimension of circularity because these play a critical role in the creation of a circular environment in the building and construction sectors.

Despite this, it is observed that few of the studies reviewed take a comprehensive approach encompassing the social, environmental, economic, and technical dimensions of a CE. Typically, only one of these is emphasised, most commonly the environment. This is due to the complexity of CE adoption, the interests and priorities of stakeholders, political imperatives, and the lack of integrated frameworks that will facilitate the integration of all dimensions of CE. As a result of this fragmented approach, CE adoption is often simplified in terms of resource consumption, waste, and emissions production [43]. The environmental issues are often addressed most forcefully as the CE concept has a heavy emphasis on reducing waste and minimising resource depletion. These are areas where it is easier to provide metrics, for instance in respect of waste management as waste can be measured quantitatively through collection and disposal data, whereas reuse, repair, and recycling involve more varied and complex processes that are harder to track and measure accurately [48].

One of the most commonly referenced definitions of a CE is that introduced by the Ellen MacArthur Foundation in 2012 which states that "*A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the end-of-life concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse and return to the biosphere, and aims for the elimination of waste through the superior design of materials and products, systems, and business models*" [23,30,49]. The CE system envisaged in this report is as illustrated in Fig. 7 and establishes a CE as restorative with the aim of maintaining the function of products, components, and materials while preserving their value [28,38].

To many, the Ellen MacArthur Foundation's definition of CE is acceptable as it considers both environmental and economic factors, though technical implications and social dimensions are neglected [35,50]. This definition of CE relies on the notion of ensuring that production and consumption systems contribute to long-term development, such as decreasing waste and pollution, reusing and recycling products and materials, regenerating natural systems, and other challenges connected to a sustainable lifestyle. According to the Ellen MacArthur Foundation's report '*Towards the Circular Economy: economic and business rationale for an accelerated transition*'

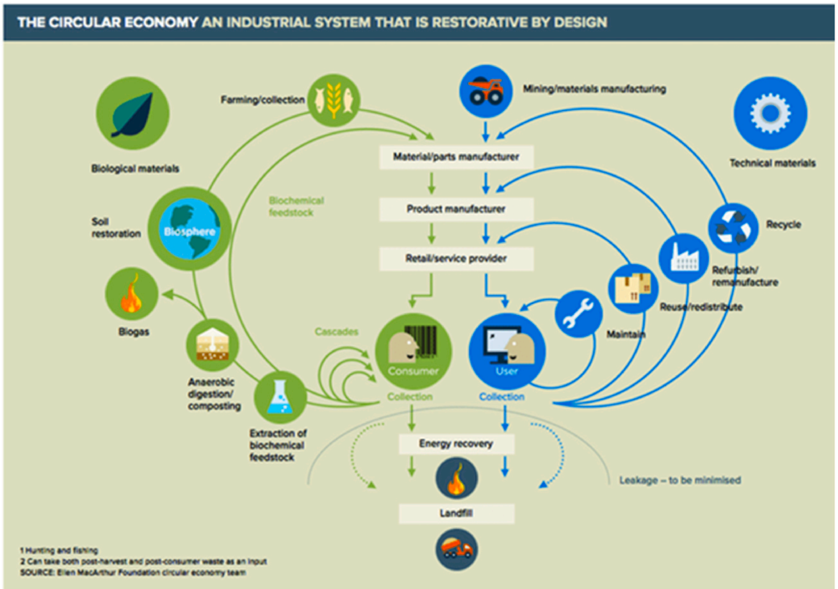

Fig. 7. A Circular Economy is an industrial system that is restorative by design.
Source: Ellen MacArthur Foundation circular economy system diagram (February 2019) https://www.ellenmacarthurfoundation.org/

published in 2012, companies might decrease their waste production while increasing resource optimisation, resulting in a more sustainable and circular economy. This definition of a CE also has the added benefit of emphasising design, which recognises that sustainable and circular solutions rely on mindful design decisions such as design for longevity and durability, design for disassembly and recyclability.

In recent years the CE concept has gained momentum within the EU, as documented by the '*Circular Economy Package*', presented on December 2, 2015, by the European Commission where the CE is defined as '*an economic model based inter alia on sharing, leasing, reuse, repair, refurbishment and recycling, in an* (almost) *closed loop, which aims to retain the highest utility and value of products, components and materials at all times*' and on March 4, 2018, the European Commission presented a report on CE's implementation [15]. Nevertheless, the EU legislation has not as yet established a legal definition of '*circular economy*' [30]. In the Action Plan '*Financing Sustainable Growth*' published by the European Commission in 2018 [18], which includes targets, ecological definitions and commerce and business investors' obligations, the concept of a '*circular economy*' is defined as: '*maintaining the value of products, materials and resources in the economy for as long as possible and minimising waste, including through the application of the waste hierarchy as laid down in Article 4 of Directive 2008*/98/EC *of the European Parliament and of the Council*' [19].

Despite this increased interest in the CE model at the European level, the definitions reported above fail to fully embrace the CE concept as they neglect social issues and environmental impact, both of which need to be included within a broader vision. Climate change tends to impact most severely on poorer neighbourhoods and vulnerable peoples, worsening current social, economic, and health inequalities. A CE approach should reduce environmental impact and resource scarcity but also improve human well-being and social equity. Thus, the social dimension should be included more clearly in the CE definition. The key problem with this sectorial approach is thus that there is no general agreement on what constitutes an effective CE model and this acts to prevent its effective adoption.

Creating a closed-loop system for the CE model, such that materials used in the manufacturing process can be reused or recycled indefinitely mimicking the eco-system in nature is a theoretical concept based on changing the approach to the ways in which products are designed and manufactured. This approach relies on the '*cradle-to-cradle*' concept, which argues for the design of products to close the loop, as advocated in the CE model. The EMF report warns that it is impossible to avoid all waste [23] due to the inefficiencies in recycling processes, the limited durability of materials and components, and the presence of residual and hazardous waste that cannot be easily recycled or safely reused as well as consumer behaviours and habits. However, this approach aims to eliminate, as far as possible, the concept of waste by ensuring that, wherever possible and practical, materials derived from a product have value and can be returned to the production cycle. Incorporating the cradle-to-cradle concept into the design phase requires a shift in mindset from the traditional linear economy model, where products are made, used, and then to a large extent simply discarded. Instead, the focus is on designing products with materials and manufacturing processes that allow for easy disassembly, recycling, and reuse. Despite the concept emphasising the significance of the design process, it nevertheless focuses primarily on products and materials.

Another important element of the CE concept emerges through the so-called 3Rs of '*Reduce, Reuse and Recycle*'. This is a concept relating to the efficient use of resources [34], that enables the '*return*' of materials and resources when considering the lifecycle of a product for reuse or remanufacture in other products, consuming less energy while generating less waste, pollution and emissions [34]. The *Reduce-Reuse-Recycle* concept is a sequence of statements as to how to properly manage waste, assuming that disposal is part of the

CE model focusing on optimizing returns by modifying previous waste management strategies.

Top priority is generally given to *Reduce*, which aims at reducing the amount of raw material used and the associated waste generation. *Reuse* and *Recycle* are then intended to give waste material additional opportunities for use before final disposal [29]. The potential of a CE extends beyond simply recycling materials to save raw materials. Indeed, its main value lies in its ability to promote reuse, maintenance, and remanufacturing, thus prolonging the lifespan of products [35].

Following on from the 3R concept the 5R concept of *'Reduce, Reuse, Recycle, Recovery, Remanufacturing'* has been introduced [50, 52], adding two further stages of waste management. The first of these is *Recovery*, which is the process of recovering or converting materials that can no longer be recycled into energy sources or ecologically beneficial materials by investigating other applications or repurposing opportunities to prolong their lifespan and prevent them from ending up in landfills. Implementing advanced waste conversion technologies that can extract valuable resources from non-recyclable materials and investigating creative ways to repurpose them, such as upcycling them into new materials or turning them into raw materials for other industries is another strategy that can be used to decrease the amount of waste that ends up in landfills. The second, *Remanufacturing*, is a specific type of recovery process that involves disassembling used products, inspecting, repairing, and reassembly them to create like-new products. The remanufacturing process has the benefit of obtaining products that are typically held to similar standards as new products and are often considered as good as new.

Additionally, implementing stricter regulations and incentives to promote proper disposal and encourage the use of more sustainable materials can also help reduce the amount of non-recyclable materials ending up in landfills.

Finally, the 6R concept of '*Reduce, Reuse, Recycle, Recovery, Remanufacturing, and Redesign*' aligns with the *Cradle-to-Cradle* (C2C) concept [51] as an attempt to achieve a closed-loop system as set out by Refs. [35,53] and presented in Fig. 8.

Here, each material used in a product is intended to be both safe and functional, while also providing resources for future generations of goods and products. Thus, materials are considered as a system nutrient and are intended to circulate safely and productively throughout the system. Overall, the benefits of considering materials as system nutrients and focusing on their safe and productive circulation include environmental conservation, economic opportunities, improved product performance and social responsibility.

3.4. *The CE concept in the building and construction sectors*

To align the building and construction sectors with an essentially closed-loop system and thus to a CE model, Lazarevic and Valve [30] suggested the following concept that points out the importance of the design phase for both products [54] and buildings '*Durable mixed-use building design in a modular way with recyclable and non-toxic materials*'. Emphasis is then on the production of energy rather than consumption to reach as nearly as is possible a closed water, nutrition, material and energy cycle. This concept is crucial because it involves a range of different elements including energy, water, and materials, emphasising the need for a multidisciplinary approach. Benachio [28] reported that Sanchez and Haas [55] suggested '*that projects that use Circular Economy should have distinct phases in the design stage, with decision gates and planning methods*', highlighting the importance of the design process as well as the stakeholder engagement in the process.

As it has been suggested by Lieder and Rashid [35], design approaches should be based on a service-oriented perspective, rather than a product-oriented mindset as this will enable environmental impacts to be reduced while economic success is maintained. Such a service-oriented business model is based on providing access to functionality or services such as leasing or pay-per-use, whereas the traditional business model is centred on the sale of products. As a result, the service-oriented model enables optimisation of resource consumption and extension of the life of a product through innovative recovery and remanufacturing technologies while retaining product value. However, the potentials of product design in combination with these new circular business models are as yet

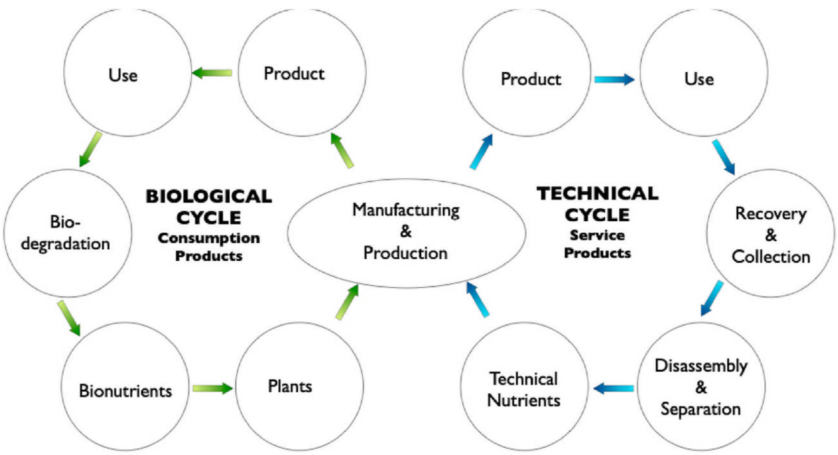

Fig. 8. Cradle 2 Cradle concept.

insufficiently assessed [20].

Concerning the technological dimension, the implementation of advanced technologies can enable more efficient resource utilisation, waste management, and recycling processes, thereby minimising environmental impact. This involves developing and adopting technologies that support sustainable production and consumption patterns. Thus, a more sustainable future requires new perspectives on consumption based on responsibility incorporating innovative technologies and new economic and business models that support resource efficiency and effective solutions.

Despite the recognition of their significance and the emphasis on population, consumption and the interaction between them, innovative technology is not adequately addressed by all stakeholders of the value chain of the building and construction sectors [55]. Yet integrating technological advancements along with social, economic, and environmental considerations is essential for achieving a circular economy. By leveraging the power of technology, a more sustainable and efficient system can be created that ensures economic growth and well-being, minimises waste, optimises resource usage, and tackles environmental challenges. Addressing the currently inadequate adoption of technology in the building and construction sectors requires a multi-faceted approach involving awareness, financial incentives, collaboration, and research and development efforts.

The incorporation of new technologies into CE development necessitates the consideration of wait times, which can in part be evaluated using the NASA Technology Readiness Scale (TRL) for technology assessment. At level 6 (TRL 6) a technology has a fully functional prototype or representational model. A TRL 7 technology then requires that the working model or prototype be demonstrated in its environment. At TRL 8 technology has been tested and '*qualified*' and is ready for implementation into an already existing technology or technology system [57]. A technology would need to be at least TRL 7 to have an impact in the next 5–10 years as a technology typically takes from 25 to 40 years to develop from concept to full commercial implementation [58]. Since economic progress relies on technical innovation and has a significant influence on the environment, people's habits, and wealth, it is vital to address economic, social, and environmental dimensions, as well as technological ones, together. It is therefore critical to assess the present level of technology and its potential to combine with the environment, social issues, and economic opportunity. This comprehensive approach will help unlock the potential of technology to enable the establishment of a CE in the building sector.

Generally, therefore, it is found that the discussion around CEs tends to focus on the need to reduce the environmental impact of economic activity by closing the materials loop. In this context, financial and social issues may often be viewed as secondary. However, this is a limited and flawed perspective, as a CE is, by definition, an economic model that seeks to balance environmental, economic, social, and technical objectives [59]. Neglecting financial and social considerations may potentially have unwanted consequences, such as an unequal sharing of benefits from CE adoption, with limited or no benefits for the most vulnerable in society. In the 2020 paper '*Addressing the Social Aspects of a Circular Economy: A Systematic Literature Review*' Padilla et al. [60], have revealed that neglecting financial and social issues has a detrimental effect on vulnerable groups such as low-income groups, the elderly, and migrants because they may not be able to afford to buy into CE initiatives. These issues have to be resolved by transitioning to a CE model, as not doing so may result in increased social inequality.

Focusing specifically on the social consequences of CE development, Avelino [61] discovered that ignoring financial and social issues implied that only a subset of stakeholders within the CE adoption process will benefit from CE practices. Aguilar-Hernandez et al. [62] in the article '*Macroeconomic, social and environmental impacts of a circular economy up to 2050: A meta-analysis of prospective studies*', argue that focusing on just environmental impact without considering financial and social dimension can lead to an unsuccessful transition of CE processes because it may increase inequalities and prevent social integration. The case study by Mies and Gold [63] confirms the importance of considering the social implications of the adoption of a CE model in developing countries. These findings taken together suggest that CE adoption needs to consider the financial well-being and social inclusiveness of communities. Geissdoerfer [56] focus on the socio-economic implication of the adoption of a CE model in the European Union and find that neglecting economic and social dimensions acts to prevent effective adoption.

All these studies emphasize the need for inclusive policies that consider the needs and capacities of all stakeholders, particularly those who may be socially or economically vulnerable. Failure to do so may result in the exclusion of certain population groups and a lack of acceptance or support for circular economy initiatives, potentially leading to social unrest or resistance. It is therefore crucial that policymakers, businesses, and other stakeholders consider the financial and social effects of a CE alongside environmental objectives and technological implications.

Having established that the notion of CE relies on a closed-loop concept, then disassembly, cleaning, inspection and sorting, reconditioning, and reassembly are essential activities to enable the incorporation of remanufacturing as an industrial process [34]. Product return management, remanufacturing operations, and remarketing of remanufactured materials have all attracted industry attention and served as the foundation for decision support system models [35,64,65]. Decision-support models enable organisations to make data-driven decisions, optimise resource utilisation and identify opportunities for circular economy adoption. Despite being regarded as being essential for the adoption of the CE concept [66,67], decision support system models are not frequently utilised and do not usually consider the activities of policymakers, investor focus, consumer preferences, and demand. Hence, the notional basis of a CE lies in the concept of closed-loop systems and an associated life cycle approach, intending to expand the lifespan of materials, products, and buildings, a concept firmly rooted in a technical approach.

One commonly employed technique in the construction industry to extend the lifespan of materials and their components is disassembly. This enables the reuse of materials instead of discarding them in landfills. The critical element for achieving disassembly in the building sector is to consider reversibly building construction methods in line with the materials bank concept [68–70], in which buildings themselves act as a source of recoverable and reusable components and materials from the beginning of the design phase. The materials bank concept calls for the technical capability of managing individual materials to enable them to be re-mounted and reused numerous times. This requires the deployment of both Design for Assembly (DFA) methodologies to plan for the reuse and remounting of parts and Design for Disassembly (DFD) methodologies to facilitate separating building materials and components to reuse them.

A building materials passport (BMP) provides accurate data to assist with proper materials separation, reuse, and disposal. This BMP supports both DFA and DFD by offering methods for material separation and recording the quantity of recycled materials used. Consequently, including both DFA and DFD in the design process can contribute to more sustainable and efficient product design and support the development of appropriate manufacturing and consumption habits resulting in reduced waste and help to achieve a more sustainable and efficient product design and circular buildings.

DFD is also crucial for promoting the reuse of building materials as an alternative option to recycling. It has been established that the reuse process is generally the more ecologically friendly option compared to recycling because the process of reusing materials generally requires less energy and minimises quality degradation, which leads to downcycling,[3] [28]. But if the whole life cycle is not considered then, as previous studies have demonstrated [71–74], the reduction of Greenhouse Gas (GHG) emissions from building components with excellent reuse and recycling capabilities is not guaranteed. Reuse also needs very developed secondary markets with certified materials, products, and components to encourage reuse processes. It is to be noted that currently, most recycling is in the form of downcycling rather than upcycling.[4]

4. Discussion

The discussion of the results obtained from the literature review is based on the identification of the research gaps and barriers. Firstly, the analysis of the selected papers has determined that the reference dimensions required to embrace the CE concept are.

- The environmental dimension;
- The economic dimension;
- The social dimension;
- The technical dimension.

Fig. 9 then shows how these are distributed across the 55 papers returned by the literature review.

What emerges from this initial analysis is that the environmental dimension is the most frequently addressed in the reviewed papers, confirming what has already been identified. The technical dimension is the second most addressed and the economic and social dimensions are considered to a lesser extent and almost at the same level.

The findings established that these dimensions are not currently addressed equally and that some are frequently overlooked. It is crucial to consider these four dimensions as the foundation of the CE principle, and if one of them is overlooked or not carefully considered and, above all, if the relationships between these four dimensions are not properly evaluated, the application of the CE model risks being ineffective. This lack of a holistic and comprehensive approach to embracing CE does not maximize the impact required to provide an urgent response to climate change, the protection of the planet, and the protection of the most vulnerable populations. To obtain an effective adoption of the CE model in the building and construction sectors, these four dimensions are of necessity equally crucial to grounding a comprehensive definition on which a novel and looking-forward CE framework can be developed.

4.1. *Research gaps and barriers*

In the scientific literature and professional journals, there are over 100 distinct definitions of CE [75]. Since the concept has been adopted by diverse groups of researchers and professionals, the many and various interpretations that are in use create confusion and misunderstanding. Not to mention that comparisons between these varying views are often not possible, being based as they are on different definitions. According to the assessment of the literature review reported here, the adoption of the concept of CE and its underlying principles is still in its early stages [18], despite growing interest among politicians, business leaders, and researchers. This is due in the main to a lack of strategic guidelines including the standardising of processes for waste management, resource usage, product design, and supply chain practices and the weakness of not always including the economic, social and technical/technological dimensions. This has resulted in a significant delay in effectively implementing the CE concept.

From the majority of the papers in the review, the sustainability dimensions of environment, economy, and society are emerging [22,35,57], and are increasingly combined with a technical dimension. But rarely are these four dimensions considered together and, especially, their mutual relationships and interactions are not considered or assessed. What emerges from the analysis of the papers in the review is that, as presented in Fig. 10, 27 of them addressed two dimensions only and only 8 addressed all four dimensions.

Technology is the necessary fourth dimension required for the successful adoption and implementation of the CE concept in

[3] Downcycling refers to the process of recycling materials or products into ones of lower value or quality. It entails converting the original material into new forms that are frequently less resilient or have more restricted applications than the original. Because it lowers the overall value of the recycled material, downcycling is typically viewed as being less desirable.

[4] Upcycling describes the imaginative repurposing of materials or products in a way that raises their quality or value. Through upcycling, the original material is changed into a new and improved form without losing its original value. Repurposing an item to give it a new use or aesthetic appeal is a common upcycling. technique that produces a product of higher quality or greater value. Compared to downcycling, upcycling is thought to be a more environmentally beneficial and sustainable practise.

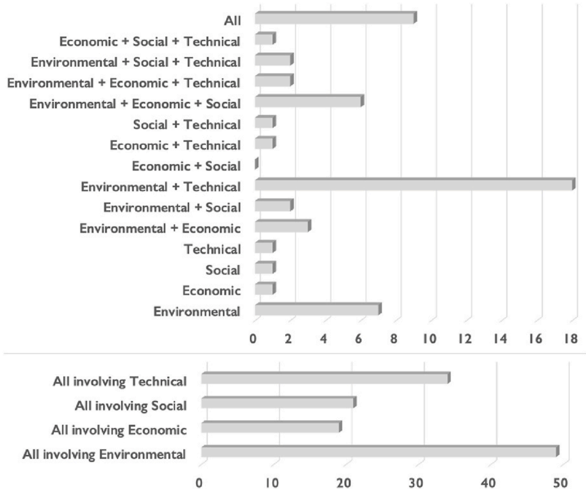

Fig. 9. Distribution of Environmental, Economic, Social and Technical dimensions across the papers sampled.

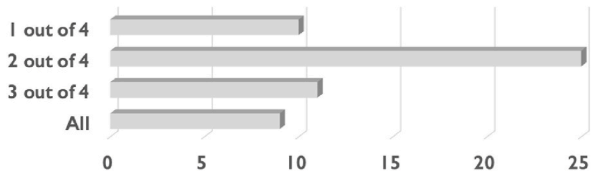

Fig. 10. Multiple dimensions addressed in the same reviewed papers.

building and construction to support the optimisation of resource use, reduce waste and emissions, and improve the durability and recyclability of building materials. This involves identifying and assessing existing technologies that align with CE strategies but also promoting innovation and the development of new technologies that facilitate circularity. Additionally, a comprehensive CE framework should address obstacles to technology adoption, such as cost, regulatory challenges, and lack of awareness and education. By integrating such technological considerations into CE frameworks, the building industry can effectively harness technology to support sustainable and circular building methods. Referring to Fig. 11, papers that focus on methodology tend to cover all four dimensions, with a strong emphasis on evaluating the environmental dimension and a lesser focus on the technical dimension.

This includes identifying ways in which the sustainability of the environment can enhance social and economic sustainability outcomes and vice versa. For example, incorporating renewable energy technologies into building design not only reduces environmental impact but also reduces long-term energy costs, leading to economic benefits for building owners and occupants. Additionally, designing buildings with spaces that promote community interaction and well-being can improve social outcomes, while also enhancing the building's overall functionality and marketability [34]. By considering the interplay between these four dimensions, the building sector can contribute more effectively to a sustainable future, meeting both the immediate needs of current stakeholders and the long-term needs of future generations.

The imbalance in considering all four dimensions in addressing climate change is a critical issue that requires more attention among all stakeholders. When technical dimension is the main focus, it is common to only consider the environmental impact of the technology without taking into account with the same weight the economic and social implications. This limited focus can lead to miss

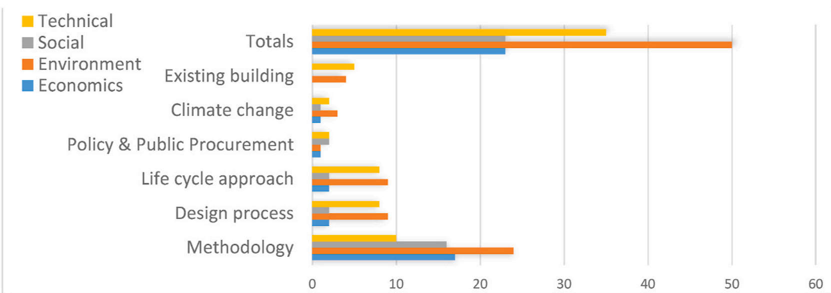

Fig. 11. Relationship between primary and secondary subject areas of reviewed papers.

opportunities for integrating sustainability measures that address the need of all stakeholders.

In papers that discuss the design process or take a Life Cycle approach, the tendency to prioritise the technical and environmental dimensions persists. While these aspects are vital in implementing the sustainability of technologies and building sustainability, neglecting the economic and social dimensions can limit the effectiveness of solutions in addressing climate change. On the other hand, the few papers that address issues related to existing buildings often neglect economic and social dimension.

Similarly, when policy is the main focus, both technical and environmental assessments are prioritised, while economic and social dimensions are not given sufficient consideration. This can result in policies that may be technically sound but fail to adequately consider the economic and social impacts on communities and individuals.

To address this imbalance, researchers and policymakers need to adopt a more holistic approach that integrates equally all dimensions – environmental, social, economic, and technical – in addressing climate change and considering the needs and perspectives of all stakeholders involved in the whole value chain of the building construction process can lead to more effective and sustainable solution to effective and massive results.

The literature review reveals that current research has primarily concentrated on limited dimensions, specifically the environment. As a result, the concept of a CE does not have well-defined criteria for activity selection or explicit guidance on practical implementation. The necessity for tailored or sectorial methods makes it difficult to provide broad guidance since the implementation of a CE differs greatly for different goods and marketplaces [24]. The analysis of the papers reviewed confirms that the primary factors contributing to financial and economic barriers are the absence of market mechanisms and unclear financial cases and business models [28,29,53].

While the concept of a CE has been present in the building and construction sectors for some time, the use of market mechanisms to accelerate the transition to a CE is a relatively recent development. Despite gaining considerable attention in the early 2000s, the concept remains an emerging business model without a fixed timeline for full implementation. The review shows that ongoing efforts are being made to develop and test financial cases and business models, and market mechanisms are being explored and applied in different ways across various contexts. However, the lack of economic incentives within the current regulatory framework means that pursuing the CE concept may not be attractive to everyone. The issues associated with establishing metrics as drivers of change in the building and construction sectors are also related to the development of new financial and business models supported by incentives introduced by policymakers. The introduction of new policies and regulations is closely linked to economic support in the form of changing tax structures or incentive schemes aimed at offsetting upfront investment costs [78,79]. Finally, the papers reviewed have identified a lack of interest and awareness along with cultural barriers as significant obstacles to implementing the necessary behavioural changes required to advance the CE concept.

Even though CE is increasingly envisioned as one of the most effective strategic alternatives to the linear model, and hence for achieving a more sustainable future [28–30,35,76], currently it is lacking in clarity as to the benefits or the social or economic advantages of its adoption at scale. By adopting a systematic and transformative approach, businesses and industries can innovate and find new ways to reuse, recycle, and regenerate materials, which in turn can lower costs, increase efficiency, and enhance brand reputation. Additionally, a CE approach can lead to new business opportunities, such as the development of new technologies and services, as well as the creation of new markets based on products made from recycled materials.

Because of this currently fragmented approach, CE research is often limited to specific areas such as building and demolition waste management with an environmental perspective. When it comes to the recycling of materials, the emphasis is mainly on structures or specific materials like aluminium, with a primary emphasis on the environmental impacts [43,76,77].

5. Conclusions

The paper offers an evaluation of the CE concept based on extensive literature review. The analysis begins by tracing the roots of the CE concept presented in section 3.1 to clarify which are the key dimensions to consider while implementing the CE.

The literature review has highlighted the presence of multiple definitions of CE that reflects the diversity of interpretation at the academic, policy and business levels. The review has also revealed that CE definitions are largely determined by a sectorial strategy in developing a CE transition with a narrow focus. The proliferation of definitions framed in specific sectors has resulted in the development of sectorial practices that have remained confined to those sectors. This has resulted in a spread of CE practices that are difficult to replicate and compare with each other. More importantly, this fragmented approach leads to an ineffective adoption of CE practices as an urgent response to climate change.

Firstly, a natural ecosystem operates with minimal waste and resources are recycled within the system. This contrasts with the linear economy model, which is based on the '*take-make-dispose*' consumption pattern. A CE aims to replicate the efficiency of natural ecosystems by closing the loop on material flows and lowering waste production.

However, the definitions of CE that were analysed in the review may not fully capture this near-closed-loop system concept. For example, some definitions focus more on resource efficiency and waste reduction, rather than the holistic view of a circular system that mimics the resilience and efficiency of natural ecosystems.

Additionally, the concept of a CE as a response to the protection of the planet and the promotion of a fairer society may not be adequately reflected in the definitions found in the review. A true CE should aim to address environmental and social challenges, such as resource scarcity, climate change, and social inequality, by designing systems that are regenerative, inclusive, and sustainable in the long term. To align with the concept of a near closed-loop system based on natural ecosystems, definitions of a CE should emphasize not just resource efficiency and waste reduction, but also the importance of regenerative practices, biodiversity conservation, and social equity. These elements are crucial in creating a truly sustainable and resilient circular economy model that benefits both the planet and society as a whole.

The second element found by the literature review is that several definitions of a CE rely on the concept of sustainability. This in turn is based on the development of three dimensions social, economic, and environmental. Despite the foundation of the CE concept on these three dimensions, the findings from the literature review reveal that the economic and, overall, the social dimension is generally neglected. While some studies focus on the employment potential of the circular economy, there is a lack of attention to other social and employment impacts such as gender, skills, occupational and welfare effects, poverty, and inequalities. More study is needed to address these issues and assist policymakers in anticipating the consequences for various social groups.

section 4.1 provided the analysis of the barriers and gaps that prevent the effective adoption of the CE. It was found that there was a predominance of environmental evaluations over social assessments, and that when economic assessments are addressed these are in general developed without considering the associated and related social effects. Even technical issues, which are regarded as critical in the implementation of CE practices, are limited to specific technical fields and applications, and when they are addressed, it is often only the environmental consequences that are considered. Another subject that has received insufficient attention in current literature is the need for more research into measuring the economic and social implications associated with CE initiatives to guarantee consistent messaging about the direct and indirect outcomes across diverse stakeholders.

Finally, the main findings suggest that technical elements are seen as a key driver of CE practices, thus the four fundamentals underlying the concept of CE to be effective are the environmental, social, economic, and technical dimensions. Based on the assessment of the papers selected, these dimensions are rarely evaluated together. When a paper did address all four dimensions, it tended to assign them varying weights without effectively assessing the relationships and reciprocal implications between them. This approach may fail in respect of CE adoption. However, while the potential of the adoption of a CE in respect of climate change mitigation has generally been accepted, the full relationships between these has yet to be fully explored and evaluated to determine areas of maximum impact.

Despite these challenges, there are numerous benefits associated with CE adoption, such as reduced environmental impact, increased resource efficiency, and the creation of healthier and more affordable buildings along with the potential for societal benefits. Consequently, the field of CE is dynamic and continuously evolving, necessitating ongoing innovation and collaboration to achieve its full potential.

While there is still work to be done, there is growing recognition of the importance of the CE and efforts are underway to address barriers to adoption. An appropriate CE definition for the building sector should encompass the four dimensions; environmental, economic, social, and technical, with equal weight, aiming to create a regenerative framework that allows the adoption of CE to make the building sector to be resilient, equitable, profitable, and sustainable for all stakeholders.

Appendix A and Appendix B together provide a summary of and the dimensions for the respective CE models reported for each article analysed to establish the full context of the research.

Ethical declaration

Review and/or approval by an ethics committee was not needed for this study because there is not any involvement of human subjects and/or animals.

Data availability statement

No original data was created for this review article.

CRediT authorship contribution statement

Margherita Finamore: Writing – original draft. **Crina Oltean-Dumbrava:** Writing – original draft.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Crina Oltean-Dumbrava reports was provided by University of Bradford. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank and acknowledge the valuable inputs received from anonymous reviewers.

Appendix A

N.	Title	Authors	Year	Circular Economy Dimensions of the examined 55 papers				Focus
				Environment	Economic	Social	Technical	
1	Circular economy in construction: current awareness, challenges and enablers	[80]	2017		X		X	Material recovery for second or further life
2	Design of A Sustainable Building: A Conceptual Framework for Implementing Sustainability in the Building Sector	[81]	2012	X	X	X	X Within the resources conservation	Life cycle perspective
3	Application of circular economy principles in buildings: A systematic review	[82]	2012	X Recycling material			X Design for disassembly, design for recycling, building materiality, building construction, building operation, building	Recycling material end of life approach
4	Translating the circular economy to bridge construction: Lessons learnt from a critical literature review	[83]	2020	X Environmental impacts		X Use behaviours & ownership	X Design process	Design process
5	Standardisation: An essential enabler for the circular reuse of construction components? A trajectory for a cleaner European construction industry	[84]	2021	X			X	End of life approach design for disassembly, design for recycling
6	New Methods for Sustainable Circular Buildings	[85]	2019	X Environmental impacts			X Architectural solutions	Building design process
7	A review of the circularity gap in the construction industry through scientometric analysis	[86]	2021	X Waste management Material			X	Building design & construction process
8	From principles to practices: first steps towards a circular built environment	[87]	2018	X	X	X	X	Methodology
9	Circular economy in the construction industry: A systematic literature review	[88]	2020	Material				Design process
10	Clarifying the new interpretations of the concept of sustainable building	[89]	2013	X		X		Definition of a sustainable building
11	Current state and barriers to the circular economy in	[90]	2020	X	X			Propose a framework

(continued on next page)

(*continued*)

N.	Title	Authors	Year	Circular Economy Dimensions of the examined 55 papers				Focus
				Environment	Economic	Social	Technical	
	the building sector: Towards a mitigation framework							
12	Saving resources and the climate? A systematic review of the circular economy and its mitigation potential	[91]	2020	X				Climate change mitigation
13	Circular Digital Built Environment: An Emerging Framework	[92]	2021				X	Digital Technologies end of life approach
14	Innovation in sustainable construction materials and the circular economy	[93]	2019	X			X	Material use End of life material
15	Construction and built environment in circular economy: A comprehensive literature review	[94]	2021	X			X	end of life approach stakeholders value chain
16	A circular construction evaluation framework to promote designing for disassembly and adaptability	[95]	2021	X			X	Design Process
17	Building design and construction strategies for a circular economy	[96]	2022	X Environmental performance and related benefits			X	Building design
18	Measuring circular economy strategies through index methods: A critical analysis	[97]	2017	X Resources' consumption, material losses and the use of renewable resources				Framework at micro level Life cycle approach
19	Green Public Procurement and the circularity of the built environment	[98]	2022	X	X	X	X	Sustainable Public Procurement
20	Links between circular economy and climate change mitigation in the built environment	[99]	2020	Improving resource efficiency through material reuse or recycling to reduce GHG emissions			Technologies for low carbon energy and energy efficiency	Climate change mitigation in the built environment
21	Simulation optimisation towards energy efficient green buildings: Current status and future trends	[100]	2020	Minimise the energy consumption and carbon emissions in buildings			X	Life cycle design optimisation
22	The Circular Economy – A new sustainability paradigm?	[101]	2017	X	X			Conceptual clarity

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(*continued*)

N.	Title	Authors	Year	Circular Economy Dimensions of the examined 55 papers				Focus
				Environment	Economic	Social	Technical	
23	Design for Change and Circularity - Accommodating Circular Material & Product Flows in Construction	[102]	2016	X Circular materials and products			X	Cradle-to-Cradle frameworks Design-for-Adaptability Long life spam Existing buildings
24	A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems	[103]	2016	X Waste management	X	X Consumers responsibility	X	Origins, basic principles, advantages and disadvantages, modelling and implementation of CE at the different levels
25	Methodology to assess the circularity in building construction and refurbishment activities	[104]	2021	X Materials, energy and water use,	X	X Healthy condition		Methodology of five indicators: energy, materials water social impact economic value indicator
26	Circular Economy in the Construction Industry: A Step towards Sustainable Development	[105]		X	X	X		Organisational Incentive Schemes-Policy Support-Sustainable Development
27	GlobalABC Roadmap for Buildings and Construction 2020–2050	[106]	2020	x	x	x	x	Methodology & Existing buildings
28	Barriers and drivers in a circular economy: the case of the built environment	[107]	2019	X Material recovery C&D	X	X Value chain collaboration		Categorisation of barriers and enablers
29	A Circular Economy: Where Will It Take Us?	[108]	2021	X	X	X	X	Contribution of CE to the achievement of environmental objectives
30	The circular economy umbrella: Trends and gaps on integrating pathways	[109]	2018	X	X			Lack of consensus on terminologies and definitions understanding of circular economy definition.
31	Critical consideration of buildings' environmental impact assessment towards adoption of circular economy: An analytical review	[110]	2018	X Environmental impact Waste generation			X Refurbishment exiting building	Use of LCA
32	Circular Economy in the Built Environment: Supporting Emerging Concepts	[111]	2019	X Waste management Material production			X Construction process	Life cycle stages of circular buildings
33	Circular economy practices in the built environment	[112]	2020	X Waste management			X Life extension through practices of adaptive reuse, design-for-disassembly, design-for-repair	Concept of urban-rural symbiosis as a potential approach for resource recovery in integrated urban waste, water and energy systems.

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N.	Title	Authors	Year	Circular Economy Dimensions of the examined 55 papers				Focus
				Environment	Economic	Social	Technical	
							and remanufacturing	
34	Conceptualising the circular economy: An analysis of 114 definitions	[113]	2017	X				Most common conceptualization of the 'how-to' of CE is a combination of reduce, reuse and recycling
35	Share, Preserve, Adapt, Rethink – a focused framework for circular economy	[114]	2020	X Reduce climate impact recycling of building materials			X Maintenance, repair, minor refurbishment	Circularity in the context of existing buildings 1) Share; 2) Preserve; 3) Adapt, 4) Rethink
36	Narrating expectations for the circular economy: Towards a common and contested European transition	[115]	2017			X Social and political space	X Technological innovation and sustainability transitions	The European Union (EU) actions to become a circular economy.
37	Transitioning from a Linear to a Circular Construction Supply Chain	[116]	2021	X	X	X Stakeholder value chain decision making Policy	X Design for deconstruction	Current business model in the construction sector and the current legislation concerning waste managemen
38	Sustainable development: Meaning, history, principles, pillars and implications for human action: Literature review	[117]	2019	X	X	X		Sustainable development centres around inter- and intragenerational equity anchored essentially on three-dimensional distinct but interconnected pillars, namely the environment, economy
39	A systematic literature review on the circular economy initiatives in the European Union	[118]	2021	X Reducing the ecological footprint waste reduction and efficient waste management	X Business model			Framework of circular strategies
40	Circular economy in built environment – Literature review and theory development	[119]	2020	X Environmental impacts -materials - demolition waste management				Present a review of the evolution of literature and the development of theory in the given field.
41	Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment	[120]	2020	X Flow and stock of materials Renewable energy production green gas emissions		XGovernment support Decision making	X Minimising and reusing construction and demolition waste	A comprehensive and holistic overview of how the built environment approaches the study and the actions of the circular economy
42	Materials passport's review: challenges and opportunities toward a circular economy building sector	[121]	2021	X he recovery and reuse of materials across a building's life cycle.				Materials passport (MP) tool

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N.	Title	Authors	Year	Circular Economy Dimensions of the examined 55 papers				Focus
				Environment	Economic	Social	Technical	
43	How close is the built environment to achieving circularity?	[122]	2019	X Environmental impacts of energy reduction		X People – the onsite academy trains and houses staff, providing social capital and new career opportunities	X Re-useable, reversible and modular construction<	ReSOLVE framework indicators.
44	Circular economy in the building and construction sector: A scientific evolution analysis	[123]	2021	X • Waste management • Recycling • Reuse • Renewable energies energy efficiency • Resource efficiency	X Life cycle cost		X Building information modeling	A comprehensive, quantitative analysis of the literature of the CE in buildings
45	The Circular Economy in Cities and Regions: Synthesis Report	[124]	2020	X		X		3Ps analytical framework (people, policies and places Methodology
46	Circular economy for the built environment: A research framework VERY CRUCIAL PAPER	[125]	2017	X Environmental impacts	X Resource efficiency	X Policy, people and society	X Developed a design framework based on two circular loops, the technical and biological cycles	Frame of reference
47	Sustainable design, construction, refurbishment and restoration of architecture: A review	[126]	2020	X Environmental impacts			X Construction and refurbishment processes -architectural solutions	Critical overview of all the Sustainability evaluation alternatives developed in research studies in the fields of architectural design, construction, refurbishment and restoration
48	Towards a new taxonomy of circular economy business models	[127]	2017		X Business model perspective			The customer value proposition & interface and the value network
49	Circular economy in the construction sector: advancing environmental performance through systemic and holistic thinking	[128]	2021	X Biodiversity Renewable energy Material life cycle		X Policy	X Design for reuse	Assessing environmental performance with a life cycle perspective
GREY LITERATURE DOCUMENTS								
50	Towards a more circular construction sector: Estimating and spatialising current and future non-structural material replacement flows to maintain urban building stocks	[129]	2018			X Decision making	X Existing buildings	A framework to quantify, spatialise and estimate future material replacement flows to maintain urban building stocks.
51	Towards a circular built environment	[130]	2019	X Energy materials	X		X	A design tool that can support industry in

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N.	Title	Authors	Year	Circular Economy Dimensions of the examined 55 papers				Focus
				Environment	Economic	Social	Technical	
								developing circular building components
52	Sustainability and sustainable development: A review of principles and definitions	[131]	2021	X		X		
53	The Circular Economy A review of definitions, processes and impacts	[132]	2017	X	X	X		Methodology
54	2021 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector	UNEP	2022	X	X	X	X	Methodology
55	Towards the circular economy: Accelerating the scale-up across global supply chains	World Economic Forum, Ellen MacArthur Foundation	2014	X Defining materials formulations is the key to unlocking change.	X Reorganising and streamlining flows of pure materials will create arbitrage opportunities that generate economic benefits and make investments in reverse cycle setups profitable.	X Supply chains are the key unit of action and will jointly drive change		The circular concept fosters wealth and employment generation against the backdrop of resource constraints. Methodology

Appendix B

Paper	Circular Economy Dimensions of the examined 55 papers			
	Environment	Economic	Social	Technical
1		X		X
2	X	X	X	X
3	X			X
4	X		X	X
5	X			X
6	X			X
7	X			X
8	X			
9	X		X	
10	X	X		
11	X			
12				X
13	X			X
14	X			X
15	X			X
16	X			X
17	X			
18	X	X	X	X
19	X			X
20	X			X
21	X	X		
22	X			X
23	X	X	X	X

(*continued on next page*)

(*continued*)

Paper	Circular Economy Dimensions of the examined 55 papers			
	Environment	Economic	Social	Technical
24	X	X	X	
25	X	X	X	
26	X	X	X	
27	X	X	X	X
28	X	X		
29	X			X
30	X			X
31	X			X
32	X			
33	X			X
34			X	X
35	X	X	X	X
36	X	X	X	
37	X	X		
38	X			
39	X		X	X
40	X			
41	X		X	X
42	X	X		X
43	X	X	X	X
44	X			X
45	X		X	X
46			X	X
47	X	X		X
48		X		
49	X		X	
50	X	X	X	
51	X		X	
52	X	X	X	
53	X	X	X	X
54	X	X	X	X
55	X	X	X	X
Totals	**50**	**23**	**24**	**35**

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