SUM4Re

Creating materials banks
from digital urban mining

D8.1 REPORT OF SCENTIFIC CHALLENGES:

Guideline for dealing effectively with current challenges and barriers in sustainable material supply and CDW upcycling

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EXECUTIVE SUMMARY

This report focuses on current challenges and barriers in sustainable material supply and construction and demolition waste (CDW) upcycling. In this regard, this report also takes into consideration relevant topics such as circular business models (CBMs).

This report adopts a comprehensive, holistic, mixed-method approach with diverse methods to achieve comprehensive scientific and practical insights about the barriers, challenges, and circular business models that emerge from material reuse and CDW upcycling practices in SUM4Re.

To achieve a comprehensive understanding of state-of-the-art, we conducted the following tasks:

- A systematic review of scientific literature: When it comes to the review of scientific articles, we use the following analyses:
  - Bibliometric analysis to comprehensively and holistically examine the landscape of CBMs, material reuse and CDW upcycling in the state-of-the-art literature.
  - Text mining and text analysis of scientific papers to identify barriers, challenges and CBMs.
- A review of relevant research projects: When it comes to other relevant research projects, we conducted a review on recently completed and on-going research projects to understand the applications of material reuse and CDW in other project contexts.
- Interviews with some key stakeholders: Interviews were conducted with the partners from the three SUM4Re demonstration sites in the Netherlands, Norway and Spain.

The results of the study are structured, for example making clusters of several CBMs, barriers and suggestions to deal with the barriers. The suggestions point out addressing the barriers at three different levels:

- Strategic level that focuses on devising policies and regulations
- Tactical level that focuses on sharing and transferring knowledge (about reusing materials and sustainable construction and materials management) between projects and organisations
- Operational level that focuses on using modern digital solutions (artificial intelligence, robotics, etc.) improving collaboration

GLOSSARY

Terms, Abbreviations, and Acronyms

EC	European Commission
CDW	Construction and Demolition Waste
CBMs	Circular Business Models
CEAP	Circular Economy Action Plan
EDA	European Demolition Association
ETA	European Technical Assessment
EAD	European Assessment Document

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1. Introduction

The built environment is essential across various economic sectors, impacting local employment and the overall quality of life. According to a report from European Commission (2020-a), the built environment utilizes significant resources and constitutes around 50% of all materials extracted. The construction sector is responsible for over 35% of the total waste generated in the EU (Eurostat, 2016). Greenhouse gas emissions from material extraction, the production of construction materials, and the construction and renovation of buildings are estimated to represent 5-12% of total national GHG emissions (Boverket, 2025). Enhancing material efficiency could potentially lead to an 80% reduction in these emissions (Hertwich et al., 2020).

Gobbo et al. (2024) states that in North-West European nations, the adoption of reusing construction materials after their initial application in a building remains limited. Despite many elements being technically suitable for reuse, they are often recycled through crushing or melting or simply disposed. This leads to significant environmental consequences and a reduction in economic value.

Citing other researchers, Gobbo et al. (2024) further emphasize that minimizing the environmental impact of material consumption is crucial for mitigating climate change. The use of materials has a significant effect on global emissions and contributes to the creation of considerable waste, highlighting the necessity for sustainable resource consumption. The linear economic model requires large material inputs, resulting in notable emissions and waste production. Consequently, it is essential to lessen the environmental impact of our existing linear production and consumption systems. The built environment is a key factor in raw material extraction (40%) and accounts for the majority of all in-use material stocks. The construction sector faces a considerable challenge in reducing its use of natural resources. One approach to achieving a circular economy in construction and decreasing the need for new materials is through the reuse of materials and treating the current building stock as a resource that would otherwise be discarded as waste.

The above description points out the importance of addressing issues related to sustainable material supply and reuse of building materials. This report focuses on current challenges and barriers in sustainable material supply and construction and demolition waste (CDW) upcycling. In this regard, this report also takes into consideration relevant topics such as circular business models (CBMs).

This report is organised in the following manner:

- Chapter 1: Introduction
- Chapter 2: Relevant concepts
- Chapter 3: Methodology
- Chapter 4: Circular business models
- Chapter 5: Barriers and challenges
- Chapter 6: Suggested solutions to address the barriers
- Chapter 7: Conclusion
- Bibliography

2. Relevant concepts

This chapter presents the concepts that are relevant to this report. In this regard, the following concepts are presented:

- Circular economy in construction: The topics such as construction and demolition waste (CDW) and material reuse are also described here.
- Circular business models

2.1 Circular economy in construction

The construction industry has long been a significant driver of environmental impact, bringing about issues like extensive waste from construction and demolition, high levels of CO2 emissions, depletion of natural resources, excessive energy usage, and overwhelming reliance on landfills. Globally, construction accounts for almost half of all raw material extraction, with 40% of steel and over half of concrete and brick production directed toward this sector (European Commission, 2020). The European Commission states that buildings within the EU account for 40% of energy consumption and 36% of greenhouse gas emissions (European Parliament, 2024). Additionally, large volumes of end-of-life materials, including concrete, bricks, wood, metals, plastics, and glass—materials that could otherwise be reused or recycled—are instead sent to landfills. In Europe, construction is responsible for approximately 35% of all waste produced (European Commission, 2020).

The CE Action Plan (2020) has emphasized the construction sector as one of the key sectors in an urgent need for circular transitions. Circular economy (CE) has emerged as a significant strategy to reduce waste and GHG emissions, reduce resource and energy consumption by increasing energy and resource efficiency, prolonging product lifetime in the production-consumption loop, recycling, and regenerating end-of-life materials and products. The CE Action plan (2020, p.11) underscored that “ensure coherence across the relevant policy areas, such as climate, energy and resource efficiency, management of construction and demolition waste, accessibility, digitalization and skills for the building sector”.

CE in construction is defined as “the design and construction as well as the use phase, the smart operation, and maintenance of the built environment. A circular economy in construction is also a solution towards the environmental impacts of building” (Walter, 2024, p. xvii)

The concept of CE can be integrated with all stages of a construction process (Benachio, Freitas and Tavares, 2020), including:

- Design: design for disassembly, design for adaptability, design in modularity, design with reused materials.
- Manufacturing: use sustainable and biomaterials, optimize material use, digital material and product passports, prefabrication/ modular production.
- Construction: minimise construction waste, construct or renovate with reused materials, and construct or renovate with engineering techniques that make it easy easily for future deconstruction.
- Operation/ use: prolong building lifecycle by maintenance and repair by 3D printing, renovate, optimize resource and energy consumption in building operation, adaptability and flexibility.
- End-of-life management: building repurposing, deconstruction, recycling, upcycling, material reuse, CDW management.

Bocken et al. (2016) defines the three main principles in the CE, including ‘narrowing the loop’, ‘slowing the loop’ and ‘closing the loop’. Narrowing the loop entails using less materials and improving resource and energy efficiency. Slowing the loop involves prolonging the product

lifecycle. Closing the loop entails reusing materials or products and recycling and regenerating waste at the end of the product and material lifecycle.

The three CE principles are closely incorporated with circular construction. Evertsen and Knotten (2024) explained the three principles: 'narrowing the loop', 'slowing the loop' and 'closing the loop in circular construction. First, 'narrowing the loop involves improving building operations and opting for materials with higher decarbonisation benefits" (Evertsen and Knotten, 2024, p. 96). This strategy can be achieved, for example, by reducing material use in the design of buildings or optimising energy and resource consumption during the construction and operation phases.

Second, "slowing the loop focuses on extending the building's lifetime by repair, maintenance, or repurposing to keep buildings longer in the loop" (Evertsen and Knotten, 2024, p. 96). For example, old buildings can be renovated or repurposed instead of being demolished or newly rebuilt. Repurposing would reduce the impact of GHG up to 20-41% compared to new construction (Assefa and Ambler, 2017).

Finally, 'closing the loop' involves recycling and reusing materials at the end of a building's life (Evertsen and Knotten, 2024). This principle is also a main focus of SUM4Re. Material reuse has been considered as a key strategy to close the material loop in the construction sector (Nußholz *et al.*, 2020). Some materials and building components may be reused directly without the need for further processing and recycling process, whereas some other materials need to be retreated in a recycling process before they can be used again for new buildings.

CE is also strongly connected to widely known "R" strategies. In circular construction, ten 'R' strategies are identified along the construction process.

Ciano et al (2025) summarise the ten 'R' strategies in circular construction in the following table.

Table 1. 10 "R" strategies in circular construction (Ciano et al, 2025, page 3)

Circular economy strategies (10R)	Description
Refuse (R0)	Rendering a product redundant by either abandoning its function or replacing it with a radically different product offering the same function. Additionally, refuse can be extended to encompass the rejection of certain materials or production processes, aiming to foster a more circular economy.
Rethink (R1)	Re-elaboration and reconceptualization of ideas, dynamics, processes, concepts, uses, and post-uses related to a product to make it use-intensive.
Reduce (R2)	Using fewer natural resources results in reduced energy, raw materials, and waste inputs. This concept can also be extended to reducing the overall number of products, such as decreasing car ownership, thereby promoting reuse.
Reuse (R3)	Utilizing a product still in good condition for a second or subsequent time, either by another user or owner. In this process, the product continues to serve its original function effectively. A reused product retains both its function and identity intact.
Repair (R4)	Repair involves restoring the original function of a defective product and making a broken product operational again by fixing or replacing failed parts. Corrective maintenance is often considered synonymous with repair.
Refurbish (R5)	Refurbishing involves restoring an old product and updating it to meet modern standards. It aims to upgrade or modernize the product's functionality. Unlike remanufacturing, refurbishing usually does not entail disassembly; instead, it focuses on replacing parts. Refurbished products are generally improved and restored to meet specific quality standards.

Remanufacture (R6)	Incorporating parts of discarded products into a new product with the same function. The process ensures that the remanufactured product attains the quality equivalent to a brand new one, even when utilizing components retrieved or reclaimed from other products.
Repurpose (R7)	Utilizing discarded products or their components to create a new product with a different function. It also refers to reusing a product for an alternative purpose, termed open-loop reuse.
Recycle (R8)	Extracting secondary materials from discarded products. Secondary materials may undergo upcycling, a transformation that converts them into materials of higher quality, or in the opposite direction, i.e., downcycling, which occurs in most cases. While upcycling is intuitively the preferable solution due to its higher value, it is not always a feasible solution.
Recover (R9)	Incineration of materials with energy recovery. In a broader context, it refers to waste that is not recycled but used as a source of energy or valuable biochemical compounds. Recovery encompasses various conversion processes, primarily focused on organic waste.

The strategies from R9 to R0 are associated with increasing circularity, ranging from linear economy (R9) to circular economy (R0) (Kirchherr et al., 2027). The authors categorise R0-R2 as “Smarter product use and manufacture”, R3-R7 as “Extend lifespan of product and its parts” and R8 and R9 as “Useful application of materials”.

Interreg Europe – which is an interregional cooperation programme, co-funded by the European Union – says that approximately 40% of construction waste is recycled or reused during the demolition of buildings. Typically, recycled construction materials are utilized in second-grade construction projects rather than in new construction of buildings. Embracing a circular approach within the construction industry holds significant potential for providing environmental, social, and economic advantages (Interreg Europe, 2025).

Interreg Europe (2025) also points out that circular construction necessitates a re-evaluation of building design by minimizing embedded carbon, utilizing recycled or bio-based materials, designing for the reuse of materials and components, and prolonging the lifespan of buildings through maintenance. It also mentions that the EU Circular Economy Action Plan identifies the construction sector as one of the eight sectors with significant potential for circularity and specifies a series of actions that are to be implemented. EU’s Waste Framework Directive, which lays down some basic waste management principles, considers construction and demolition waste as a priority waste stream.

We will look more into EU’s Circular Economy Action Plan and address construction and demolition waste and material reuse in the following sections.

2.1.1 Circular Economy Action Plan

In its Circular Economy Action Plan, European Commission mention the following regarding construction and buildings (European Commission, 2020):

In order to harness the opportunities for enhancing material efficiency and minimizing climate effects, the Commission will introduce a new all-encompassing Strategy for a Sustainable Built Environment. This Strategy will promote consistency across pertinent policy domains, including climate, energy and resource efficiency, management of construction and demolition waste, accessibility, digitalization, and skills development. It will advocate for circularity principles throughout the entire lifecycle of buildings by:

- tackling the sustainability performance of construction products within the framework of the revision of the Construction Product Regulation (Regulation (EU), 2011), including the potential implementation of recycled content requirements for specific construction products, while ensuring their safety and functionality;

- encouraging measures to enhance the durability and adaptability of built assets in accordance with the circular economy principles for building design (European Commission, 2025-a) and creating digital logbooks for buildings;
- utilizing Level(s) (European Commission, 2025-b) to incorporate life cycle assessment into public procurement and the EU sustainable finance framework, and examining the feasibility of establishing carbon reduction targets and the possibilities for carbon storage;
- evaluating a revision of material recovery targets outlined in EU legislation for construction and demolition waste and its material-specific fractions;
- advancing initiatives to minimize soil sealing, restore neglected or contaminated brownfields, and promote the safe, sustainable, and circular use of excavated soils.

Additionally, the 'Renovation Wave' initiative, introduced in the European Green Deal, aims to achieve substantial enhancements in energy efficiency within the EU, and will be executed in accordance with the principles of a circular economy, particularly focusing on optimized lifecycle performance and extended longevity of building assets. In the process of revising the recovery targets for construction and demolition waste, the Commission will give particular emphasis to insulation materials, which are contributing to an increasing waste stream.

2.1.2 Construction and demolition waste

The Waste Framework Directive (WFD) (EU – Waste Framework Directive, 2025) aims to achieve the following objectives:

- By 2020, the preparation for re-use and recycling of waste materials (including paper, metal, plastic, and glass) from households shall be raised to at least 50% by weight.
- By 2020, the preparation for re-use, recycling, and other material recovery, including backfilling operations that utilize waste to replace other materials, of non-hazardous construction and demolition waste shall be increased to a minimum of 70% by weight.
- By 2025, the preparation for re-use and recycling of municipal waste shall be elevated to a minimum of 55%, 60%, and 65% by weight by 2025, 2030, and 2035, respectively.

Disposal is placed as the lowest priority in the waste hierarchy, whereas recovery, recycling and reuse are higher (respectively, in order). The prevention of non-waste products is the top priority. This hierarchical priority of WFD is also relevant to the SUM4Re project, which aims to enable and accelerate material reuse and recycling in circular construction. In addition, circular business models, together with digitalization and data enhancement, increase automated decision-making in deconstruction and material management. This shows a high relevance and alignment of SUM4Re with the European strategy toward a CE transition of the construction sector by focusing on material reuse and upcycling in the SUM4Re project.

As Interreg Europe (2022) mentions, construction and demolition waste (CDW) represents over a third (35%) of the total waste produced in the EU. This waste comprises a diverse range of materials, including concrete, bricks, wood, glass, metals, and plastics, along with hazardous substances like asbestos. Each year, approximately 450 to 500 million tonnes of CDW are generated within the EU. It encompasses all waste resulting from the construction and demolition of buildings and infrastructure, in addition to road maintenance activities. The technology for the separation and recovery of construction and demolition waste is well-developed, widely available, and generally cost-effective. However, the rates of recycling and material recovery for construction and demolition waste differ significantly across the EU, with figures ranging from less than 10% to more than 90% (reference)

According to European Demolition Association (EDA, 2025), the European Union has introduced new policies aimed at reforming the construction and demolition industry, with an emphasis on waste management and recycling. This indicates that the entire sector needs to be informed about the regulations regarding demolition practices.

Additionally, by the end of 2025, EU member states are required to enhance the recycling and recovery of non-hazardous construction and demolition waste to at least 70% by weight, as outlined in The Waste Framework Directive. To support the achievement of sustainable waste management goals, the EU Construction and Demolition Waste Management Protocol recommends the implementation of pre-demolition audits. These audits consist of comprehensive evaluations, performed prior to the demolition of a building or infrastructure, with the purpose of systematically identifying, cataloguing, quantifying and assessing all constituent materials, structural components, and any hazardous substances present within the site. These audits contribute to promote the sustainable management of construction and demolition waste by enabling the recovery, reuse, and recycling of valuable resources.

In conclusion, the essential policy initiatives and new requirements can be summarized in three main points (EDA, 2025):

1. Advocating for selective demolition to ensure the safe extraction of hazardous materials and promote high-quality recycling.
2. Introducing waste reduction strategies within construction processes, while encouraging the use of sustainable materials.
3. Promoting green public procurement practices for construction projects at both local and regional levels.

These initiatives highlight the EU's dedication to spearheading global efforts in sustainable construction practices and circular economy principles. Additionally, they aim to diminish the environmental impact of the construction sector, which presently accounts for nearly one-third of all waste generated in the EU.

The EDA is presently engaged with the European Commission's initiative to establish the End-of-waste criteria for mineral construction and demolition waste. Considering that waste management regulations vary across EU member states, the EDA has been conducting meetings with national associations to discuss these criteria and gather their viewpoints.

2.1.3 Material reuse

Referring to previous studies, Lin et al. (2025) say that the extensive construction activities around the world have led to substantial amounts of construction and demolition waste, presenting one of the most intricate challenges in the construction industry due to factors such as limited landfill space, energy consumption, water contamination, and detrimental emissions (Aslam et al., 2020; Ding et al., 2016). Currently, recycling is considered the most environmentally sustainable method among waste management strategies known as the 3Rs, which include reuse, reduction, and recycling (Nawaz et al., 2023). However, despite global initiatives, it is clear that CDW recycling rates are still low in both developing and developed countries (Menegaki and Damigos, 2018). Even in nations with comparatively higher recycling rates, the predominant practices often emphasize unsustainable downcycling (that is, recycling materials in a way that yields lower value than their original condition), rather than primary recycling. For example, in Germany, 75% of the recovered C&DW is categorized as downcycled (Bayram and Greiff, 2023). Therefore, improving both the recycling rate and the quality of C&DW has become an urgent necessity.

Referring to other researchers, Gobbo et al. (2024) describe current methods / strategies adopted in building design and construction. Current methods in building design and construction seldom consider closed-loop material systems, and integrating reuse into building projects encounters various challenges from both technical and economic viewpoints. In the last decade, some companies have begun to transition from the linear model of extraction, production, and disposal to a more circular approach, as illustrated by the 9R Framework of Circular Approaches and the commonly known "10R ladder" of circularity strategies. These strategies, ranked from most to least impactful, encompass R3 for reuse, R4 for repair, and R5 for refurbishing. Within the circular model, the focus is primarily on reduction and reuse even before recycling, which requires a deeper commitment to these principles. Reuse entails

taking apart existing materials without damaging them, with the goal of repurposing these materials. This process of reuse substitutes materials that would otherwise need to be newly acquired. In contrast to recycling, which involves chemical or physical processes to transform materials back into raw forms, reuse maintains the materials in their original condition. Legally, reuse is also defined as: "any operation where products or components that are not waste are used again for the same purpose for which they were originally intended" (Ordinance of 14 June 2012 of the Brussels-Capital Region on waste, B.S., 27 June 2012, art. 3, 18).

By taking other research work into consideration, Gabbo et al. (2024) further say that the reuse strategy emphasizes the practicality of repeatedly using disposable items, which helps to lessen environmental impact by prolonging product life cycles. This approach not only minimizes waste generation and accumulation but also significantly reduces the necessity for producing new items. The production stage has the most considerable influence on the overall product life cycle (Gabbo et al., 2021; Douguet & Wagner, 2021). Research from Norway indicates that enhancing communication and collaboration among various stakeholders in the supply chain could greatly benefit reuse initiatives. Manufacturers should take on a more proactive role in reuse processes. A well-established research framework can improve effective planning and practical implementation of reuse (Knoth et al., 2022). Furthermore, public authorities, as essential participants, play a crucial role in promoting reuse practices.

Furthermore, for a reuse strategy to be successful, it is crucial to take into account several key factors: a comprehensive understanding of the quantities of materials available, their accessibility, and their potential for recovery in both environmentally and economically viable ways (Lismont & Allacker, 2019). Nevertheless, this potential is frequently hindered by informational deficiencies throughout the material life cycle (Byers et al., 2023). Additionally, there exists a knowledge gap regarding the potential reuse rate that can be applied within the construction industry. The Ellen MacArthur Foundation indicates that only 20–30% of construction and demolition waste CDW) is suitable for recycling or reuse (Ellen Mc Arthur Foundation, 2019; Ellen Mc Arthur Foundation, 2013), while there is insufficient knowledge and a lack of standardized methodology to accurately report the reuse rate specifically within the construction sector (EU Decisions, 2021; European Commission, 2020).

2.2 Circular business models

Circular business models (CBMs) are a significant, emergent concept adopted in practice to implement CE strategies. Circular business models “represents a holistic system of co-evolving managerial practices for collective value creation, delivery and capture, which provide solutions for sustainable development” (Ünal *et al.*, 2019, p. 291)

Circular business models “aim to apply the CE principles […] preserving and enhancing natural capital, optimising yields from resources in use, and fostering system effectiveness (minimising negative externalities) […] to their business models and shift from a linear business to more circular one” (Manninen *et al.*, 2018, p. 414).

Circular business models are embedded on the three CE principles of ‘narrowing the loop’, ‘slowing the loop’, and ‘closing the loop’ (Bocken *et al.*, 2016; Geissdoerfer *et al.*, 2017)

A business model, in general, includes three important elements (Richardson, 2005; Guldmann and Huulgaard, 2020):

(1) *Value proposition* defines the product and service offering.

(2) *Value creation and delivery* defines how the organisation generate product and service offerings and how to deliver them to the customers through the organisation’s resources such as value chain, activities, channels and partners.

(3) *Value capture* defines how the organisation generates profits and turnovers through revenue sources.

New business models have emerged in recent years to facilitate material reuse and CDW recycling practices in circular construction. However, the diffusion is slow because many companies struggle to deal with different barriers related to regulations, markets, technologies or culture (Hart *et al.*, 2019; Nußholz *et al.*, 2020).

For material reuse and CDW upcycling to be economically viable, it must be incorporated with appropriate circular business models with market affordability and compliant products yielding strong sustainability benefits. Examining business models provides a useful perspective on innovation processes, exploring how companies generate value by adopting circular economy principles. This includes new products and technologies, value propositions, value chain networks, and stakeholders suitable for the new circular business models (Nußholz et al., 2020).

Stakeholders such as the value chain actors and customers are a vital part of a circular business model because circular business models may involve new value propositions, value delivery, and value capture compared to conventional models (Manninen *et al.*, 2018). Therefore, the collaboration and acceptance of the stakeholders would determine the success of a circular business model.

When describing circular business models, Geissdoerfer et al. (2020) present the following figure (Figure 1) and relevant description:

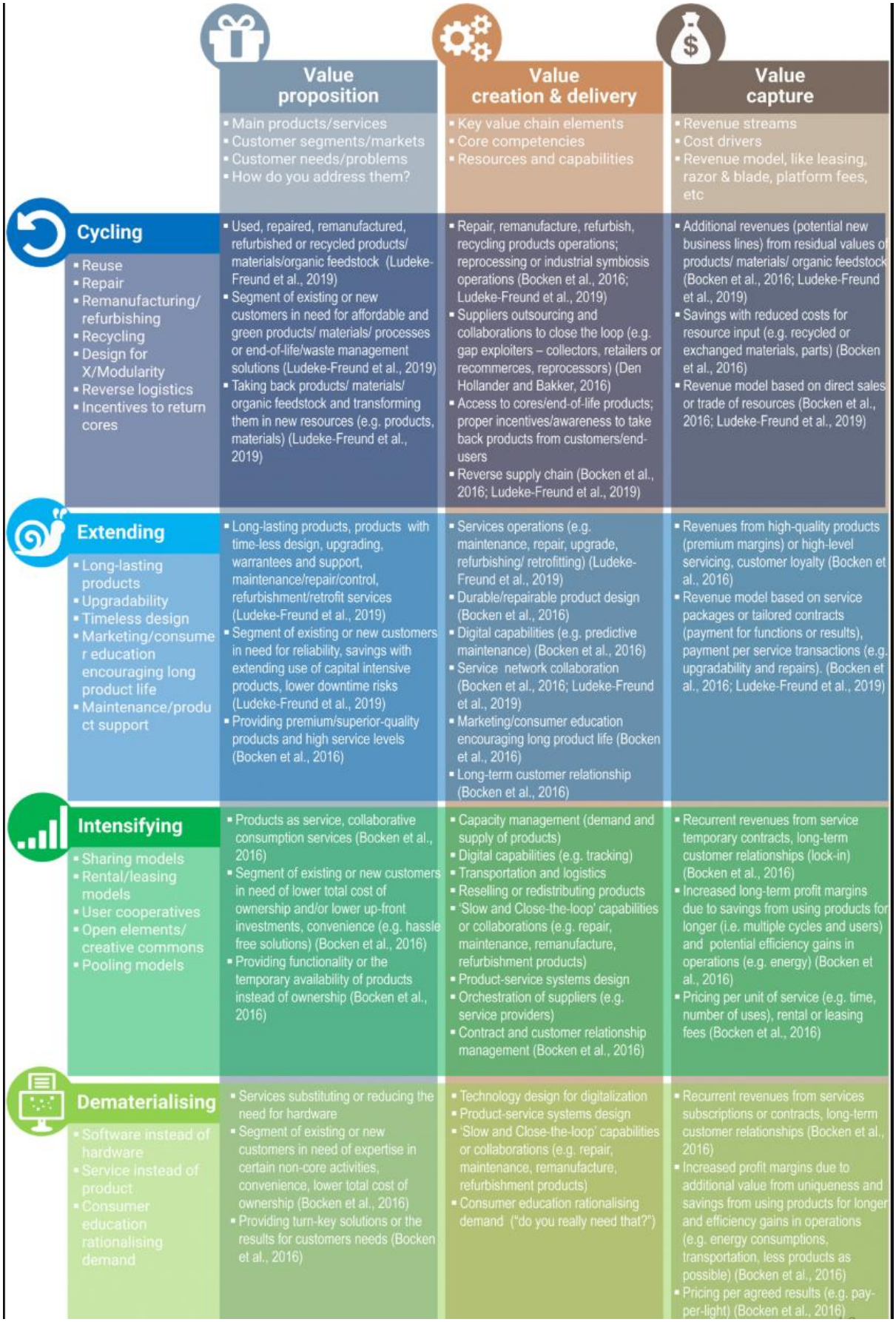

Figure 1. Strategies for operationalising circularity within businesses (Geissdoerfer et al., 2020, page 11)

The key terms cycling, extending, intensifying and dematerialisation are briefly described here (Geissdoerfer et al., 2020):

- Cycling encompasses the implementation of various end-of-use strategies, such as reuse, repair, and remanufacturing. From a value proposition perspective, take-back is a vital element, supported by collaborations within the value chain and effective reverse manufacturing processes (including repair, remanufacture, refurbishing, and recycling). In this framework, value capture mainly relates to lower costs for acquiring materials and increased revenues from end-of-use products or materials. This strategy prolongs the lifespan of cores or materials, providing the environmental advantage of reducing energy consumption and the demand for new materials, while also minimizing waste generation.
- Extending aims to maximize product usage, primarily achieved through design and operational practices. Products crafted for durability (value proposition) that undergo maintenance during their lifespan can nurture long-lasting customer relationships (value creation & delivery) and create new revenue opportunities during the product's usage phase via service offerings or tailored contracts. The implementation of this strategy leads to a diminished need for manufacturing new products.
- Intensifying results in the embrace of new value propositions focused on sharing models, bolstered by capacity management, digital capabilities, and customer relationship management. This intensification encourages new business models featuring enhanced servitisation elements, such as Product-Service Systems (PSS), which yield recurring revenue streams. The main environmental benefits of this approach include reduced idle time and structural waste (disposing of products before their intended lifespan), which results in a lower need for producing new products and a decrease in waste generation.
- Dematerialisation minimizes the use of physical resources by enhancing the value derived from intangible solutions like services and software. The creation and delivery of value are facilitated by gradual and closed-loop capabilities alongside collaborative efforts. Essential factors for capturing value include recurring revenues, improved profit margins, and innovative pricing strategies.

3. Methodology

This chapter presents the methodology that we adopted for the analysis of this report. This report adopts a comprehensive, holistic, mixed-method approach with diverse methods to achieve comprehensive scientific and practical insights about the barriers, challenges, and circular business models that emerge from material reuse and CDW upcycling practices in SUM4Re.

To achieve a comprehensive understanding of state-of-the-art, we conducted the following tasks:

- A systematic review of scientific literature: When it comes to the review of scientific articles, we use the following analyses:
  - bibliometric analysis to comprehensively and holistically examine the landscape of material reuse and CDW upcycling in the state-of-the-art literature.
  - text mining and text analysis of scientific papers to identify barriers, challenges and CBMs.
- A review of relevant research projects: When it comes to other relevant research projects, we conducted a review on on-going research projects to understand the applications of material reuse and CDW in other project contexts.
- Interviews with some key stakeholders: It is interesting to understand the actual and practical insights of local stakeholders in SUM4Re when they implement the activities of SUM4Re. We conducted the interviews with the partners from the three SUM4Re demonstration sites in the Netherlands, Norway and Spain.

3.1 Systematic scientific literature review

3.1.1 Bibliometric analysis

Bibliometric methods are quantitative techniques used to analyse patterns in scientific publications and citations, providing insights into the structure, trends, and dynamics of research fields. By leveraging data from scientific databases, these methods enable the systematic exploration of large volumes of literature to uncover relationships among authors, institutions, topics, and publications. Common bibliometric techniques include citation analysis, co-citation analysis, bibliographic coupling, and co-word analysis, each offering a unique perspective on the intellectual landscape of a domain (Aria et al., 2017; Donthu et al., 2021).

These methods help in understanding the development of knowledge, identifying influential works and key contributors, and revealing emerging themes within a field. They also facilitate the mapping of collaborative networks and the identification of gaps in existing research, making them essential tools for guiding future studies. Bibliometric analyses often rely on specialized databases and software, such as Scopus (Baas et al., 2020) and VOSviewer (Van Eck et al., 2010), to visualize complex relationships and generate meaningful insights from extensive bibliometric datasets (Donthu et al., 2021).

Co-occurrence analysis—often referred to as co-word analysis—focuses on how frequently specific terms or keywords appear together within a given collection of documents. It assumes that terms that co-occur frequently are thematically related, providing a lens into the conceptual or topical structure of a research field. By extracting keywords or key phrases from titles, abstracts, or keyword lists, researchers can track patterns of co-occurrence to identify dominant themes, emerging topics, and the conceptual links connecting different areas of (Aria et al., 2017).

In a typical co-occurrence analysis, data are first obtained from sources such as Scopus, and relevant terms are extracted based on defined search criteria. Specialized software tools like VOSviewer or Gephi (Bastian et al., 2009) then visualize these data as a network, where each node represents a unique term and each edge reflects the frequency with which two terms appear together. Thicker, denser connections indicate stronger thematic associations or shared topic areas, often forming clusters around major research themes or theoretical frameworks. Larger, more interconnected nodes suggest terms that are particularly influential or central to the discourse.

This method is especially effective for mapping the conceptual or topical evolution of a field. By examining clusters of frequently co-occurring keywords, researchers can highlight prevailing discussions, detect novel interdisciplinary linkages, and even anticipate emerging trends. As such, co-occurrence analysis complements other bibliometric approaches by illuminating the content focus of the literature, thereby offering actionable insights into how knowledge is structured and where future investigations might be most fruitful.

3.1.2 Text mining & analysis

In order to identify the reported barriers and circular business models from the scientific papers identified in our systematic literature review, we employed an AI-based text-mining approach (Naveed et al., 2023). First, the primary AI model extracted potential mentions of barriers and CBMs from the full texts of the articles retrieved in our systematic literature review. Next, in a two-step quality-control procedure, we used a second AI model to verify each item flagged by the primary model. To further ensure credibility, we randomly sampled a subset of these AI-extracted items for manual inspection by human reviewers. During this process, potential errors were identified and categorized based on clear criteria. Specifically, instances where the model introduced content not explicitly supported by the underlying scientific literature were classified as errors. For example, an error was recorded if the model independently introduced concepts or statements that, although plausible and supported by the scientific literature, were not explicitly presented as a barrier in the original source. Finally, we applied a Bayesian hypergeometric model (Amati, 2006) to combine the manual verification data with the AI-generated results, treating the AI verification as an initial prior. This modelling approach quantified the uncertainty around the Ais findings, and allowed us to refine our estimates, providing both scalability and reliability in the final analysis.

3.2 Review of relevant research projects

Here, we look at on-going and recently completed research projects that are relevant to SUM4Re. The construction sector assumes that sustainable architecture is the future of their sector, for that reason, some real projects have been made to put into practice all the knowledge gathered about the circular economy.

The following research project were taken into consideration:

- ICEBERG: This European project focuses on innovating and improving recycling and recovery technologies, with the aim of significantly increasing the reuse rate of these materials. The objective is to design, develop and validate innovative reuse systems and technologies, which allow the production of recovered materials with high value (low level of impurities, less than 8%). The project introduced circular design solutions to improve the circularity of end-of-life building materials and develop innovative building products with high recycled content. It's funded under the EU's Horizon 2020 Research and Innovation Framework Programme, and it ran from May 2020 to April 2024.
- INNO-CIRCLE: It aims to support the necessary transformation towards a circular economy and to empower SMEs to redesign their products and business models according to circular economy (CE) principles. The methodology is trough coaching, training and developing toolkits to integrate the principles of CE. It's funded by the European Union through the Interreg Italy–Austria programme, which is co-financed by

the European Regional Development Fund (ERDF). The project started January 2024, and it will finish December 2025.

- CIRC-BOOST: This Project focuses on testing and upscaling circular solutions in buildings and the construction sector through five diverse pilots, it aims to facilitate the development of urban material data banks and digital twins, thereby promoting improved practices in demolition, construction waste processing and valorisation in new products. CIRC-BOOST is co-funded by the European Union through the Horizon Europe research and innovation programme. The project runs from June 2023 to May 2027.
- CIRCULess: This Project is about minimizing CDW as well as Manufacturing waste (MW), with a focus on mineral and timber-based material streams, by developing new processes for circularity of secondary materials from wastes/residues for all industrial processes, without compromising quality and performance as well as sustainable-by-design circular products. These actions will be supported by a tailored digital platform for waste management, orienting decision-making & operation, while recommendations for standards updates and relevant training material for both upskilling and training will be created. This project is funded by the European Union through the Horizon Europe research and innovation programme. The project commenced in July 2024 and is scheduled to run for 42 months, concluding in January 2028.
- MOBICCON-PRO: It focusses on developing, introducing and demonstrating innovative circular solutions to recover resources from construction and demolition waste (CDW) and decreasing consumption of raw materials by applying in-situ selective separation / demolition. It's funded by the European Union under the Horizon Europe research and innovation programme. The project commenced in December 2022 and is scheduled to run until November 2027.
- VALREC: it was born with the aim of developing innovative solutions to increase the circularity, traceability and purity of mineral resources present in Construction and Demolition Waste (CDW) and thus carry out an eco-efficient manufacturing of new construction products. It tries to ensure the closing of cycles in construction materials and products through efficient recovery and the use of new digital traceability technologies that consider circular economy criteria and resource and energy efficiency. The project was co-funded by the European Union through the European Regional Development Fund, as part of the ERDF Operational Programme of the Community of Madrid for the 2014–2020 period.

3.3 Stakeholder interviews

The intention of conducting interviews was to obtain information from SUM4Re partners, who represent demonstration-projects in SUM4Re, especially regarding barriers, challenges that are related to circular / sustainable construction, and utilise this information to supplement / enrich the literature study and the study on relevant research projects. Semi-structured interviews were conducted online with four key stakeholders who are associated with the demonstration-projects in SUM4Re. The interviews lasted approximately one hour. An interview-guide was developed and used in the interviews. The interviewees had received the interview-guide beforehand, so that they could prepare themselves for the interviews. The semi-structured interviews enabled a spontaneous and free flow of communication and a relaxed atmosphere while guiding the interviewers to focus always on gathering the needed information.

4. Circular business models

In this chapter, we will present key findings (summary) from our study that focuses on circular business models. This chapter explores the term business models and its evolution, usage and frequency among literature. At the same time, we propose a classification of the variety of business models currently applied within the construction industry, based on the type of strategy that they follow.

4.1 Key findings from the systematic scientific literature review

First, we will present the key findings from the bibliometric analysis and the findings from the text mining analysis. One of the main purposes of bibliometric analysis is to know how relevant concepts / topics are connected to each other.

4.1.1 Key findings from bibliometric analysis

- A total of 56 publications (published during the period of 2020-2025) were retrieved via Scopus, providing literature at the intersection of the construction sector and circular economy business models.
- The captured literature groups into 4 main clusters: circular economy, construction industry, recycling/waste management, and sustainability/life cycle, indicating a broad thematic spread.
- All papers connect to the construction industry, underlining the sector's central role in adopting and operationalizing circular strategies.
- "Circular business models" (plural) relates to broader, strategic discussions—including policy and decision-making—while "circular business model" (singular) emphasizes practical, case-specific implementations.
- The generic term "business models" forms a hub linking both plural and singular circular business model concepts, spanning strategic to operational topics.
- Slightly newer papers tend to use the singular form ("circular business model"), suggesting a move toward more detailed analyses of specific frameworks, though the overall timeframe is still relatively short.
- Frequent keywords—such as "construction industry," "circular economy," and "business models", reflect the consistently high emphasis on sustainability and circular practices in construction. Secondary topics, like "gas emissions" and "innovation," appear less often but remain integral to the broader research landscape.

Data collection and Analysis

This subsection presents a co-occurrence network analysis of 56 peer-reviewed articles retrieved from Scopus, all published in English and focused on circular economy business models within the construction sector. The aim is to visualize, identify and interpret central nodes within our sample of scientific literature. Moreover, we examine themes relative importance and if/how they connect with each other. For example, we explore how different forms of "circular business model(s)" relate to one another and to broader topics in the literature, thereby shedding light on evolving research directions and gaps.

A total of *56 peer-reviewed and English-language publications* were initially retrieved from Scopus using the following search strategy:

("construction industry" OR "construction sector" OR "building sector" OR "building industry" OR "built environment") AND ("circular economy business" OR "circular business" AND (model OR models))

This query aimed to capture literature at the intersection of the construction sector and circular economy business models.

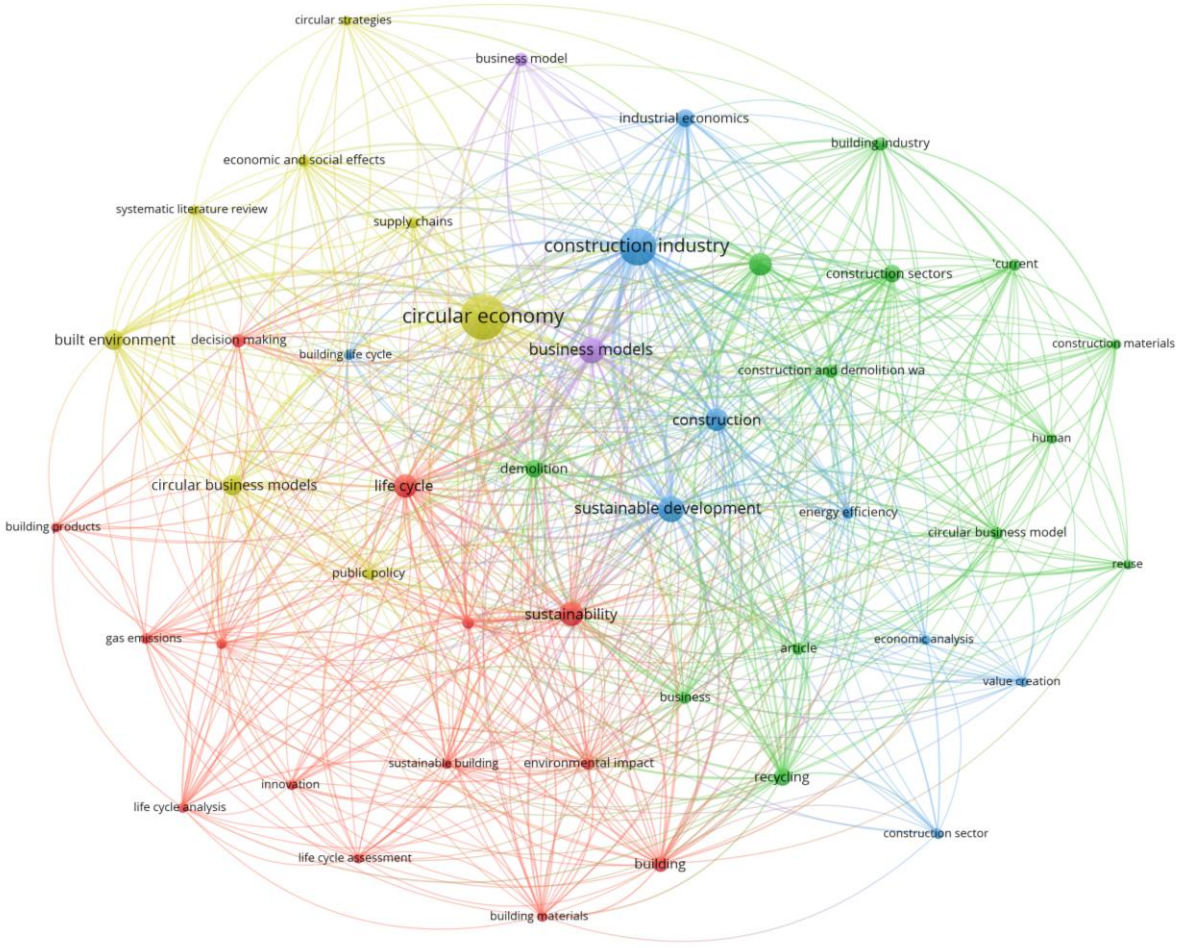

Figure 2. Overview of co-occurrence network for literature on circular business models

The initial co-occurrence network visualization shown in Figure 2 portrays four main clusters: circular economy (yellow), construction industry (blue), recycling/waste management (green), and sustainability/life cycle (red). The interconnected lines indicate that research on circularity and sustainability in the construction industry spans multiple topics, with particularly strong links between “circular economy,” “business models,” and “life cycle” approaches. We have several noteworthy connections:

- The circular economy node is strongly connected to business models, reuse, and waste management, signalling that much of the research is aimed at finding ways to minimize waste through the application of circular practices in the construction sector.
- The sustainability cluster is closely linked with public policy and innovation, reflecting government market interventions for correcting market failures related to sustainability within the construction industry.

- The emphasis on environmental impact, life cycle assessment, and gas emissions shows a thematic focus on quantifying and reducing the environmental footprint of construction activities, an essential part of sustainable development goals.

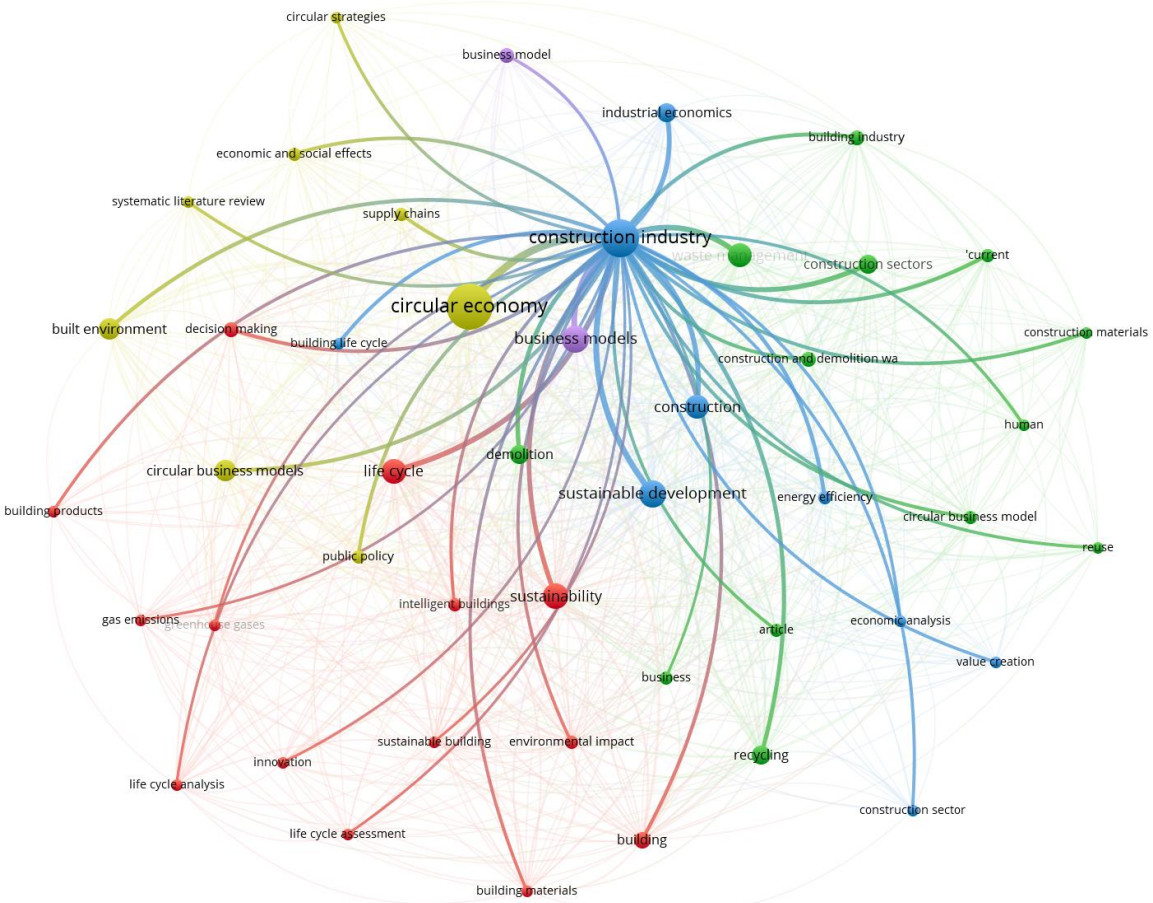

Figure 3. Co-occurrence network highlighting "construction industry" as a central node linking with all other nodes in the sampled scientific literature.

In Figure 3 we focus on the "construction industry" node, emphasizing that all the reviewed articles pertain to this sector. Radiating outward are key concepts such as "waste management," "building industry," and "construction and demolition," underscoring the centrality of industry-focused themes in the literature reviewed.

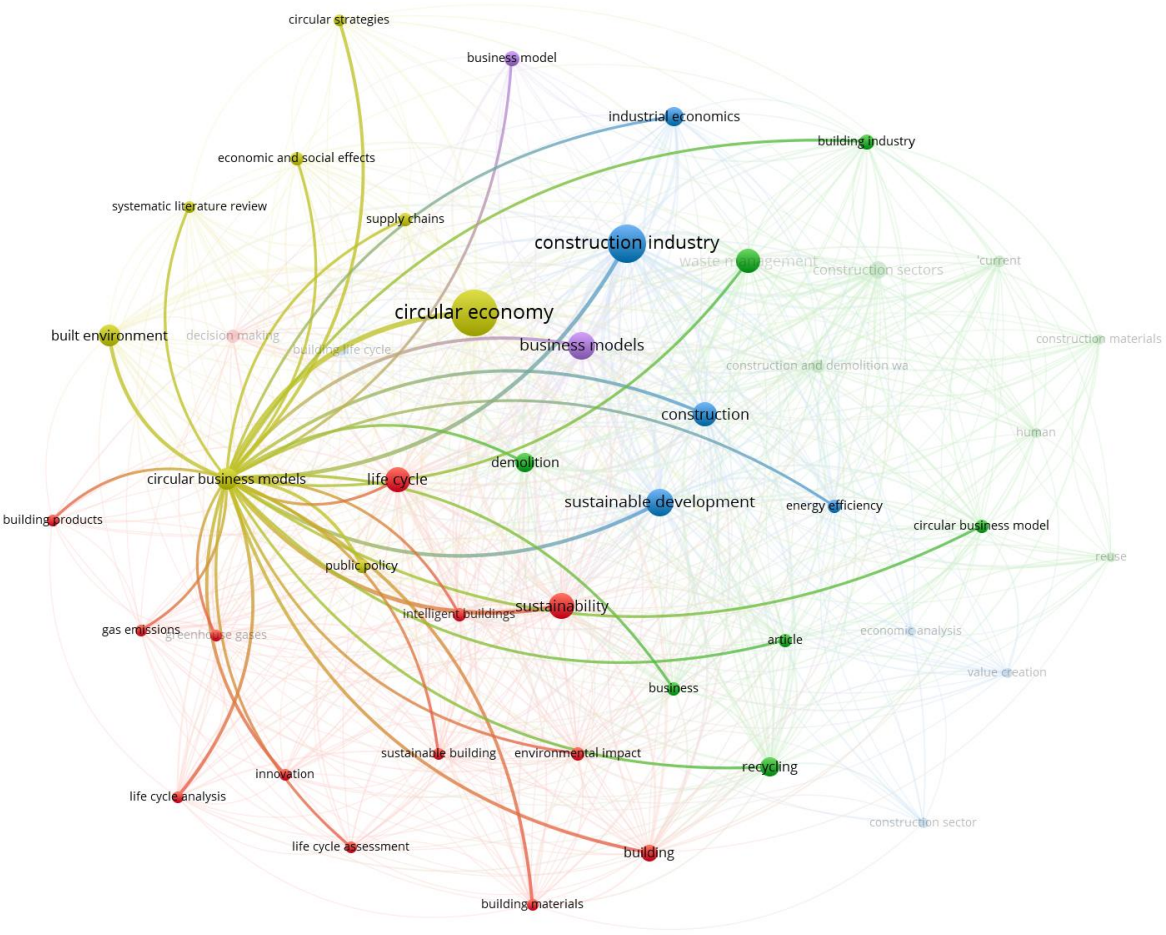

Figure 4. Co-occurrence network illustrating “circular business models” and its connection to overarching concepts

In the perspective presented in Figure 4, “circular business models” (plural) visibly anchor links to strategic terms such as public policy, decision making and environmental impact. The node draws connections to overarching frameworks and policy discussions around transitioning to circularity within the construction industry, with a focus on sustainability, reuse and life cycle considerations.

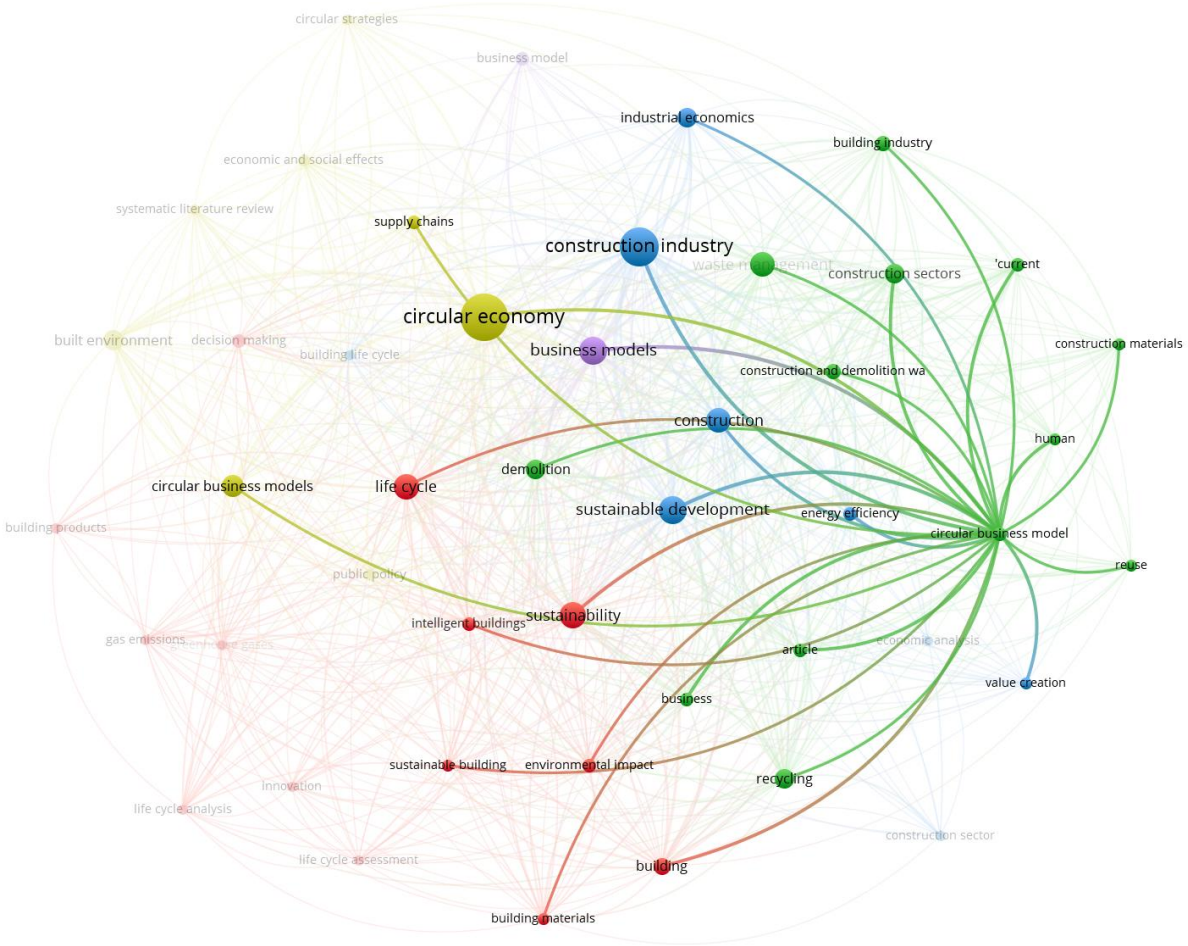

Figure 5. Co-occurrence network focused on "circular business model" (singular), highlighting practical and operational links to reuse, value creation, and construction materials within the construction sector

When focusing on circular business model (singular) in Figure 5, we see many the same connections as we saw in Figure 4; sustainability, reuse, innovation and life cycle. However, CBM (singular) links more strongly to practical or operational aspects like value creations, reuse and construction materials. Thus, the singular form focuses on the mechanics of implementing a specific business model within a construction context. This underscores, that whether addressed at a strategic or an operational level, the circular business model literature captured by our query fundamentally aims to close material loops and minimize environmental impact in the construction industry and built environment.

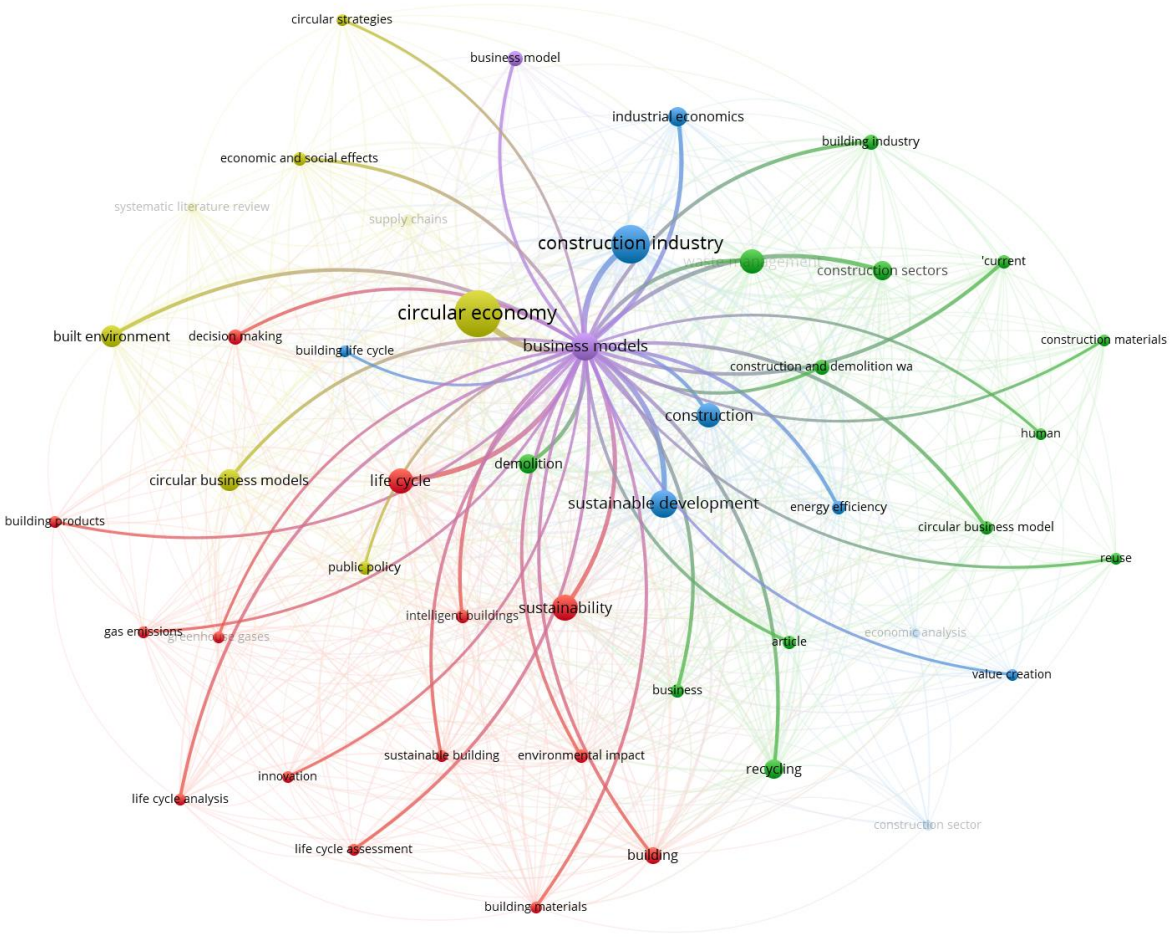

Figure 6. Co-occurrence network illustrating "business models" as a bridging node, linking both strategic (plural CBMs) and more operational (singular CBM) perspectives within the broader construction sector.

In Figure 6 we emphasize "business models", which emerges as a bridging node between both high-level strategy discussions, CBMs (the plural form), and more concrete single model analyses, CBM (the singular form). As a result, "business models" appears at the centre of the network, linking directly to most concepts within our sample of scientific literature.

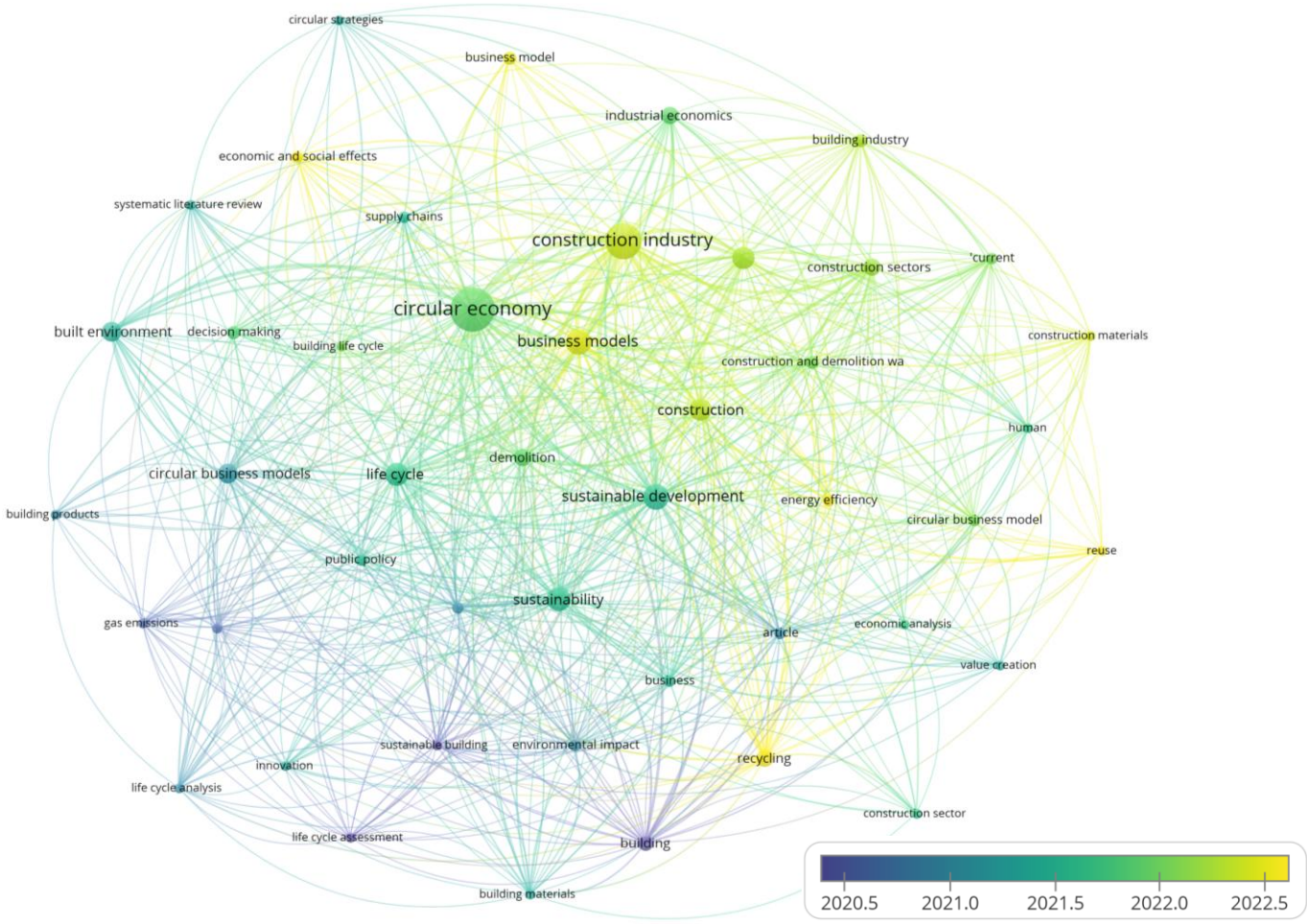

Figure 7. Color-coded co-occurrence network based on average publication year, with warmer (yellow) hues indicating newer literature and highlighting evolving research trends on circular business models in the construction sector.

A noticeable pattern in the average age of publications, as indicated by the colour coding in Figure 7, suggests that papers labelled with “circular business model” (singular) tend to be more recent compared to those labelled “circular business models” (plural). This may signal a progression from earlier conceptual and overarching discussions of multiple circular business frameworks to more narrowly focused explorations of specific business model implementations. Nevertheless, the entire dataset spans a relatively short timeframe, primarily within the last five years, underscoring both the rapid evolution of this research area and the continuing refinement of circular business concepts in the construction industry. Therefore, one should be careful to draw a conclusion at this point.

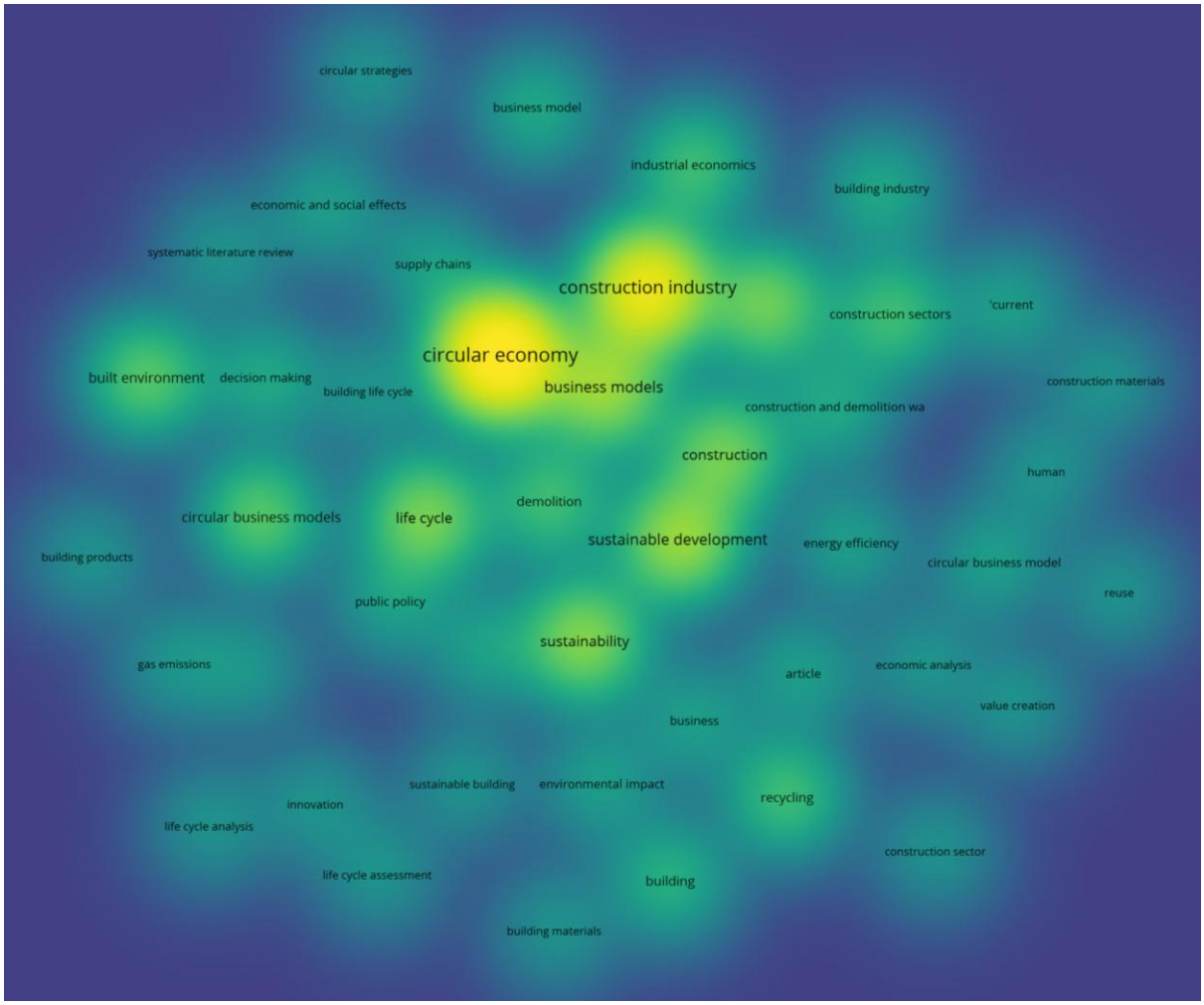

Figure 8. Heatmap of the co-occurrence network, with warmer (yellow) areas indicating higher keyword frequency and prominence—most notably "construction industry," "circular economy," and "business models."

This heatmap in Figure 8 illustrates the relative frequency or centrality of keywords, with warmer (yellow) areas signalling higher levels of emphasis in the dataset. Notably, "construction industry," "circular economy," and "business models" appear as the most prominent terms, reflecting their consistent co-occurrence and importance. By contrast, cooler (blue) regions indicate topics discussed less frequently—such as "gas emissions" or "innovation"—while still contributing to the broader research landscape. Overall, the heatmap underscores the literature's strong focus on the intersection of sustainability and circular economy within the construction sector, revealing that even when secondary concepts such as "life cycle assessment," "building materials," or "public policy" emerge, they tend to cluster around these core themes.

4.1.2 Key findings from text mining & analysis

- A total of 41 circular business models (CBMs) were identified and categorized into eight thematic clusters—spanning strategies that extend building lifespans, close material loops, and leverage digital platforms.
- Cluster 1 (Extending Building Life and Adaptive Reuse) highlights renovation, modularity, and durable design to prolong building usability.
- Cluster 2 (Industrial Symbiosis, Resource Recovery, and Closing Material Loops) emphasizes collaborative waste-to-input conversions and material loop closures.
- Cluster 3 (Product-as-a-Service and Product-Service Systems) shifts focus from ownership to service-based models, promoting lifecycle stewardship.
- Cluster 4 (Digital and Data-Enabled Circular Models) leverages technologies like BIM, blockchain, and digital marketplaces to enhance traceability and resource optimization.
- Cluster 5 (Sharing Economy and Collaborative Consumption) increases resource utilization through shared platforms for tools, equipment, and building components.
- Cluster 6 (Circular Supply Chains, Eco-Design, and Modular Approaches) integrates renewable or recycled materials, eco-friendly construction, and modular design to minimize upfront waste.
- Cluster 7 (Holistic and Framework-Based CBMs) applies structured methodologies (e.g., business model canvases, macro–meso–micro perspectives, lifecycle assessments) to guide circular transitions.
- Cluster 8 (Sector-Specific Innovations) tailors circular principles to particular industries—such as EV batteries and the pulp & paper sector—addressing niche challenges.
- Reliability checks using a Bayesian hypergeometric model suggest that approximately 39 of the 41 identified CBMs (94.2%) are explicitly discussed or proposed in the literature, with a 95% credible interval from 85.4% to 97.6%.

Thematic clustering of circular business models

This subsection outlines eight distinct thematic clusters capturing 41 CBMs identified in the reviewed literature. Each cluster reflects a specific strategic orientation, ranging from extending building lifespans to harnessing digital platforms for resource optimization. By grouping these models, we aim to highlight both the breadth of circular strategies and the underlying mechanisms, such as technological integration, stakeholder collaboration, and policy frameworks—that advance circularity in construction and related sectors.

Table 2. Overview of 41 circular business models identified in the literature, grouped into eight thematic clusters. Each cluster addresses distinct areas of resource efficiency, from extending building lifespans to sector-specific innovations.

Thematic Cluster	Circular Business Models	Description
1. Extending Building Life and Adaptive Reuse	*Extending the Life of Buildings* *Adaptable Building* *Never-Ending Building* Adaptive Reuse Models Product Life-Cycle Extension Building-Level CBMs	Prolonging the usability of buildings through renovation, adaptive reuse, modularity, and durability.
2. Industrial Symbiosis, Resource Recovery, and Closing Material Loops	Industrial Symbiosis Circular Input Materials CBMs for Construction and Demolition Waste Generic CBMs for CDW Resource Recovery CBM Waste Valorization Models Resource Recovery Models Circular Business Model Design for Resource Recovery	Transforming waste streams into valuable inputs and fostering cross-sector collaboration to close material loops.
3. Product-as-a-Service (PaaS) and Product-Service Systems (PSS)	Product as a Service Product-Service System CBM Product Service Systems PaaS in Pulp and Paper Industry	Shifting from product ownership to selling functionality, ensuring lifecycle stewardship through leasing and service models.
4. Digital and Data-Enabled Circular Models	Material Passport Systems Digital Marketplaces for Circular Products Blockchain Technology in CBMs BIM-Enabled CBMs Circular Digital Built Environment Digital Data Systems CBM Circular Construction Intelligence	Leveraging digital tools (e.g., BIM, blockchain, digital marketplaces) for transparency, traceability, and optimization.
5. Sharing Economy and Collaborative Consumption	Sharing Platforms for Construction Tools Collaborative Consumption Models Sharing Economy for Building Components Sharing Economy Models	Maximizing resource utilization through shared access to tools, equipment, and building components via sharing platforms.
6. Circular Supply Chains, Eco-Design, and Modular Approaches	Circular Supply Chain Models Circular Supply Models Eco-Construction Models Modular Business Modelling	Integrating renewable or recycled inputs, modular design for easy deconstruction, and eco-friendly construction practices.

	Dematerialization CBM	
7. Holistic and Framework-Based CBMs	Macro-, Meso-, and Micro-Level CBMs Circular Economy Business Model Canvas Nine Categories of CBMs Lifecycle Assessment Models	Utilizing structured frameworks, methodologies, and hierarchical approaches (macro, meso, micro) to transition toward circularity.
8. Sector-Specific Innovations	Repair + Reuse + Recycle CBM Circular Models for Energy Storage Systems Pulp and Paper Industry Models	Applying circular principles to specific industries, such as EV batteries and the pulp & paper sector, for tailored solutions.

Table 2 provides an overview of the 41 identified CBMs within the reviewed literature, organized into eight thematic clusters based on their core strategic focus and enabling mechanisms. These clusters emerged from a careful examination of how different models address resource efficiency, waste reduction, stakeholder collaboration, and technological integration. By categorizing the CBMs, this study highlights both the breadth and depth of circular strategies currently employed or proposed in the construction and related sectors.

The first cluster, Extending Building Life and Adaptive Reuse, groups CBMs prioritizing renovation, modularity, and durable design to lengthen asset lifespans. The second cluster, Industrial Symbiosis, Resource Recovery, and Closing Material Loops, captures collaborative initiatives that transform waste streams into inputs for new processes. In the third cluster, Product-as-a-Service (PaaS) and Product-Service Systems (PSS), CBMs embrace service-based models to shift emphasis from ownership to functionality, thus facilitating stronger lifecycle stewardship.

Clusters four and five, Digital and Data-Enabled Circular Models and Sharing Economy and Collaborative Consumption, underscore the role of technology and collaborative platforms in achieving resource optimization. Digital tools such as Building Information Modelling (BIM), blockchain, and digital marketplaces are crucial for ensuring traceability, whereas sharing platforms increase utilization rates of tools, equipment, and building components. The sixth cluster, Circular Supply Chains, Eco-Design, and Modular Approaches, emphasizes integrating renewable or recycled inputs, eco-friendly design, and modular construction methods to reduce waste from the outset.

In Holistic and Framework-Based CBMs (cluster seven), the focus shifts to structured approaches (e.g., business model canvases, macro-meso-micro perspectives, and lifecycle assessments) that guide organizations in applying circular principles across multiple levels. Finally, Sector-Specific Innovations (cluster eight) highlights CBMs tailored to particular industries such as electric vehicle (EV) batteries and pulp and paper production, indicating that circular solutions can be customized to address the nuanced needs and challenges of different sectors.

Statistical assessment of reliability

The AI-based text-mining approach identified 41 potential circular business models (CBMs) across our collection of scientific papers. A second AI system then checked these and confirmed all 41 (100%). However, we placed only partial trust in this second AI (using a “discount factor” of 0.5) to account for possible inaccuracies. In addition, we also manually reviewed 15 randomly selected CBMs from the AI’s results and confirmed 14 (about 93.3%). Combining both sources of information with a Bayesian hypergeometric model gave us a final estimate that around 39 CBMs (94.2%) have been explicitly discussed or proposed in the sampled scientific literature, with a 95% credible interval of 85.4% to 97.6%. This range shows

our level of confidence in the AI results, adjusted by manual inspection. The results are summarised in Table 3.

Table 3. Fact-check results and Bayesian hypergeometric estimate for circular business models.

Step	Proportion	Notes
AI Verification	1.000	Discount factor = 0.5
Manual Sample	0.933	Randomly sampled subset
Final estimate	0.942 (CI: 0.854–0.976)	Bayesian hypergeometric model result

4.2 Key findings from the review of relevant research projects

To collect data about what other research projects are doing about material reuse and CDW we consulted CORDIS with the search ("construction sector" OR "construction industry" OR "building industry") AND ("circularity" OR "material reuse" OR "secondary materials" OR "reusing materials" OR "waste management") with the filters “projects” and “start date from 2024-06-12". In addition, the database Eurac Research was also consulted with the same filters to discover more on-going projects working towards circularity.

Table 4. Summary of on-going projects working towards circularity in the construction industry, its barriers and suggested solutions

Project	Objective	Circular Business Models
ICEBERG	Develop innovative technologies to improve recycling and recovery.	- Industrial Symbiosis, Resource Recovery, and Closing Material Loops - Resource Recovery Models. - Design for Resource Recovery. - Digital and Data-Enabled Circular Models. - Circular Digital Built Environment - Blockchain technology
INNO-CIRCLE	Training SMEs to adopt CE principles such as redesign their products and business models.	- Holistic and Framework-Based CBMs - Circular Economy Business Model Canvas . Industrial Symbiosis, Resource Recovery, and Closing Material Loops - Resource Recovery Models - Extending Building Life and Adaptive Reuse - Adaptive reuse models
CIRC-BOOST	Testing and upscaling circular solutions in buildings trough 5 pilot projects.	- Industrial Symbiosis, Resource Recovery, and Closing Material Loops. - Resource Recovery Models

		- CBMs for Construction and Demolition Waste - Holistic and Framework-Based CBMs - Macro-, Meso-, and Micro-Level CBMs
CIRCULess	Minimizing CDW as well as Manufacturing waste (MW) focusing on timber and mineral based materials.	-Extending Building Life and Adaptive Reuse - Product Life-Cycle Extension -Industrial Symbiosis, Resource Recovery, and Closing Material Loops - Waste Valorization Models - Resource Recovery Models - Digital and Data-Enabled Circular Models - Digital Marketplaces for Circular Products - Material Passport Systems - Digital Data Systems
MOBICCON-PRO	Demonstrate innovative circular solutions to recover resources from construction and demolition waste in order to reduce raw material consumption and promote the use of recycled construction materials and products.	- Industrial Symbiosis, Resource Recovery, and Closing Material Loops - Waste Valorization Models - Resource Recovery Models - Holistic and Framework-Based CBMs - Lifecycle Assessment Models
VALREC	Develop innovative solutions to increase circularity traceability and purity of mineral resources present in Construction and Demolition Waste.	- Circular Supply Chains, Eco-Design, and Modular Approaches. - Eco-Construction Models. - Circular Supply Models. - Digital and Data-Enabled Circular Models. - Digital Data Systems. - Industrial Symbiosis, Resource Recovery, and Closing Material Loops - Circular Business Model Design for Resource Recovery.

A brief description / summary of the circular business models mentioned in the projects (in Table 4) is presented below:

- ICEBERG: The Circular Business Model used in the ICEBERG project is centred on the high-purity recovery, recycling, and reintegration of construction and demolition waste into new building materials. It integrates smart demolition tools, digital traceability systems, and advanced separation technologies to efficiently identify, collect, and process end-of-life building materials such as concrete, wood, plasterboard, and insulation. These materials are then transformed into high-quality, eco-designed products—like eco-cement and recycled insulation panels—that are suitable for reuse in construction. The model fosters a closed-loop system that minimizes waste and reduces reliance on virgin resources.
- INNO-CIRCLE: The INNO.CIRCLE project adopts a Circular Business Model that empowers small and medium-sized enterprises (SMEs) to redesign their products and

business strategies in alignment with circular economy principles. Central to this model is the INNO.CIRCLE Coaching Programme, co-developed with SMEs and implemented in 25 pilot companies across South Tyrol, Tyrol, and Salzburg. This program combines digital tools, individualized coaching, and peer learning to help businesses identify innovation areas and prepare for implementation. By fostering cross-regional collaboration and integrating stakeholders such as universities and startups, INNO.CIRCLE aims to create a holistic approach to circular innovation, facilitating the transition towards sustainable business practices.

- CIRC-BOOST: The CIRC-BOOST project implements a Circular Business Model designed to transform the construction sector by integrating circular economy principles across the entire value chain. This model emphasizes the development and deployment of Integrated Circular Solutions (ICS) through five pilot projects located in Barcelona, Paris, Belgrade, Vesterålen, and Prague. These pilots focus on demonstrating large-scale applications of circular practices in demolition, construction waste processing, management, and the creation of new products from recycled materials. Central to the project's approach is the utilization of digital technologies, such as a 3D circular economy web map, to enhance material tracking and waste management efficiency. Additionally, CIRC-BOOST explores innovative business models that support the economic viability of circular construction practices, assessing the cost-effectiveness of recycling technologies and developing financial models that incentivize the adoption of circular practices.
- CIRCULess: The CIRCULess project employs a Circular Business Model focused on transforming mineral and timber-based waste from the construction and manufacturing sectors into high-quality, sustainable secondary materials. This model integrates eco-design, advanced logistics, precise quality control, and digital solutions to minimize construction and demolition waste (CDW) and manufacturing waste (MW), particularly from concrete and wood-based materials. The project also emphasizes the creation of a digital waste management platform to guide decision-making and operational activities.
- MOBICCON-PRO: The MOBICCON-PRO project implements a comprehensive Circular Business Model aimed at revolutionizing construction and demolition waste (CDW) management in Southeast Europe. Central to this model is the deployment of a mobile pilot plant (MPP) capable of on-site processing of CDW, thereby reducing transportation emissions and facilitating the production of high-quality recycled construction materials. This approach is complemented by the establishment of a Territorial Circular Center (TCC) in Sofia, Bulgaria, which serves as a hub for collaboration among stakeholders—including businesses, academia, public authorities, and citizens—to promote circular practices in the construction sector. The project also emphasizes the integration of digital technologies for smart demolition and material tracking, as well as the development of innovative construction products derived from recycled materials.
- VALREC: The VALREC project adopts a Circular Business Model focused on transforming construction and demolition waste into high-value secondary materials through selective demolition, digital traceability, and advanced recycling technologies. It leverages tools like BIM for accurate waste estimation, blockchain for traceability, and machine learning for volume assessment, enabling up to 95% recycled content in new construction products such as eco-mortars and eco-concretes.

5. Barriers and challenges

In this chapter, we will present barriers, challenges and obstacles that are related to circular construction that includes, among other things, sustainable material usage and managing CDW.

5.1 Key findings from the systematic scientific literature review

Here, we will first present key findings from the bibliometric analysis and then the findings from the text mining analysis. One of the main purposes of bibliometric analysis is to know how relevant concepts / topics are connected to each other.

5.1.1 Key findings from bibliometric analysis

- Data collection and analysis: 109 peer-reviewed publications (published during the period of 2020-2025) were retrieved through Scopus and analysed using VoS-viewer.
- Major Themes: Five main research themes, focusing on the construction industry, sustainable development, circular economy, recycling, and sustainability.
- Dominant theme: Construction industry is both the most central and interconnected theme.
- Overlap and Integration: Clear interconnections exist among the themes.
- Temporal differences: Resource recovery keywords tend to be associated with older publications, whereas more recent studies focus on circular-economy approaches and advanced construction methods.
- Heatmaps: High-frequency keywords include “construction industry,” “sustainable development,” “circular economy,” and “recycling,” reflecting dominant interests in the literature.
- Lack of Barrier Nodes: Despite targeting barriers in the search query, no distinct barrier- or challenge-themed nodes appear, suggesting such topics may be embedded within other concepts.

Data collection and analysis

This section presents the results of a bibliometric analysis conducted on peer-reviewed papers retrieved from the Scopus database. The aim was to map major themes, identify prominent barriers, and examine keyword relationships and temporal patterns within research literature focused on challenges related to material reuse in the construction sector.

A total of 109 peer-reviewed and English-language scientific publications were retrieved from Scopus using the following search query:

("construction industry" OR "construction sector" OR "building sector" OR "building industry" OR "built environment")

AND

(barrier OR constraints OR challenges OR "missing gap" OR impeding OR bottlenecks OR deterrents)

AND

("material reuse" OR upcycling OR "reusing material" OR "reusing materials" OR repurposing OR "resource recovery" OR remanufacturing OR "waste valorization")

This query specifically targets research at the intersection of the construction sector, the barriers and challenges affecting sustainability, and strategies for reusing or repurposing materials in a circular economy context.

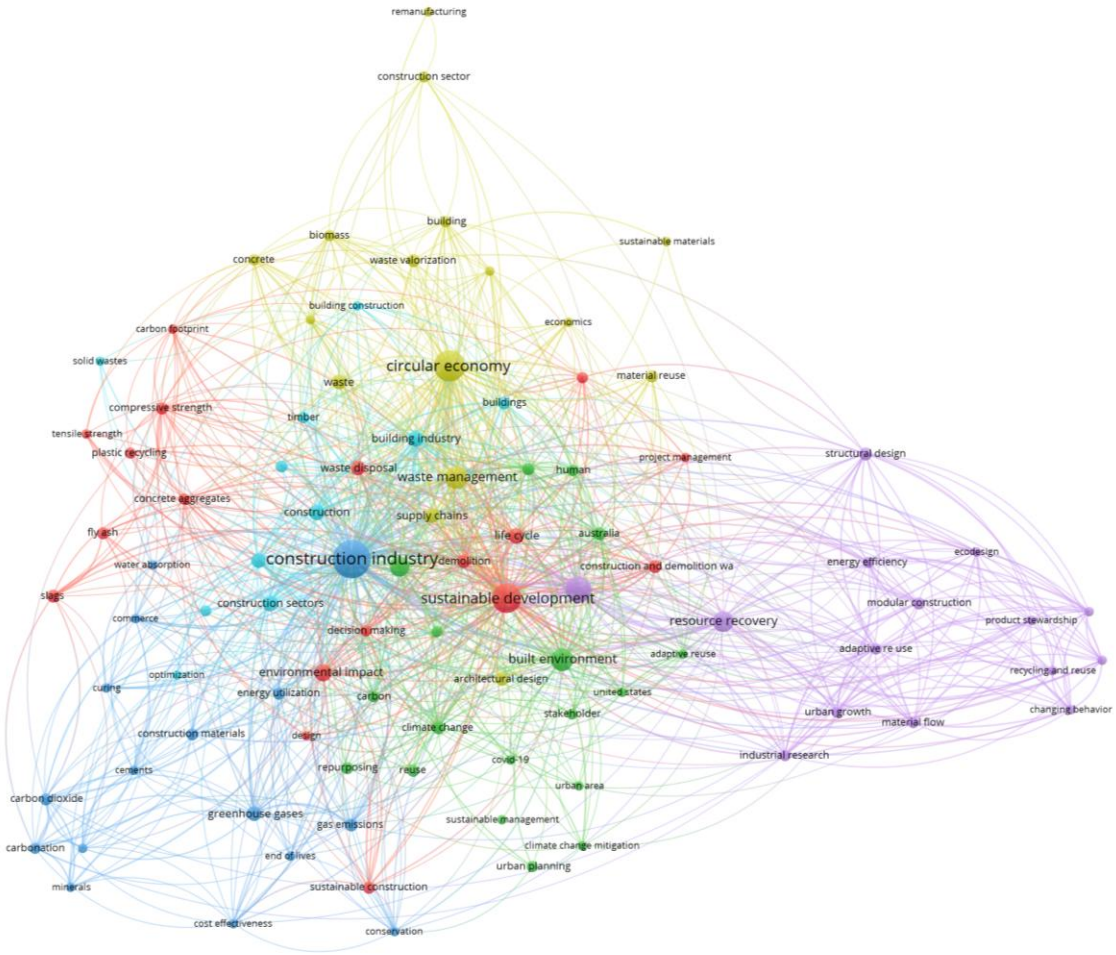

Figure 9. Overview of co-occurrence network for literature on barriers, gaps and challenges. A broad snapshot of the 109 selected papers' keywords, highlighting major themes.

Figure 9 provides a broad visualization of how the most prevalent keywords co-occur across the 109 sampled papers. Large, colour coded central nodes, particularly construction industry (blue cluster), circular economy (yellow cluster), resource recovery (purple cluster), sustainability (green cluster) and sustainable development (red cluster) dominate the network, suggesting these are key pillars of the literature. The clustering underlines how closely interconnected the topics are. For example, publications that discuss waste management or resource recovery often also engage with broader notions of sustainability and circular economy. Dense linkages between them reflect the interconnectedness of efforts to enhance sustainability in construction, from policy and design considerations to practical interventions like waste reduction.

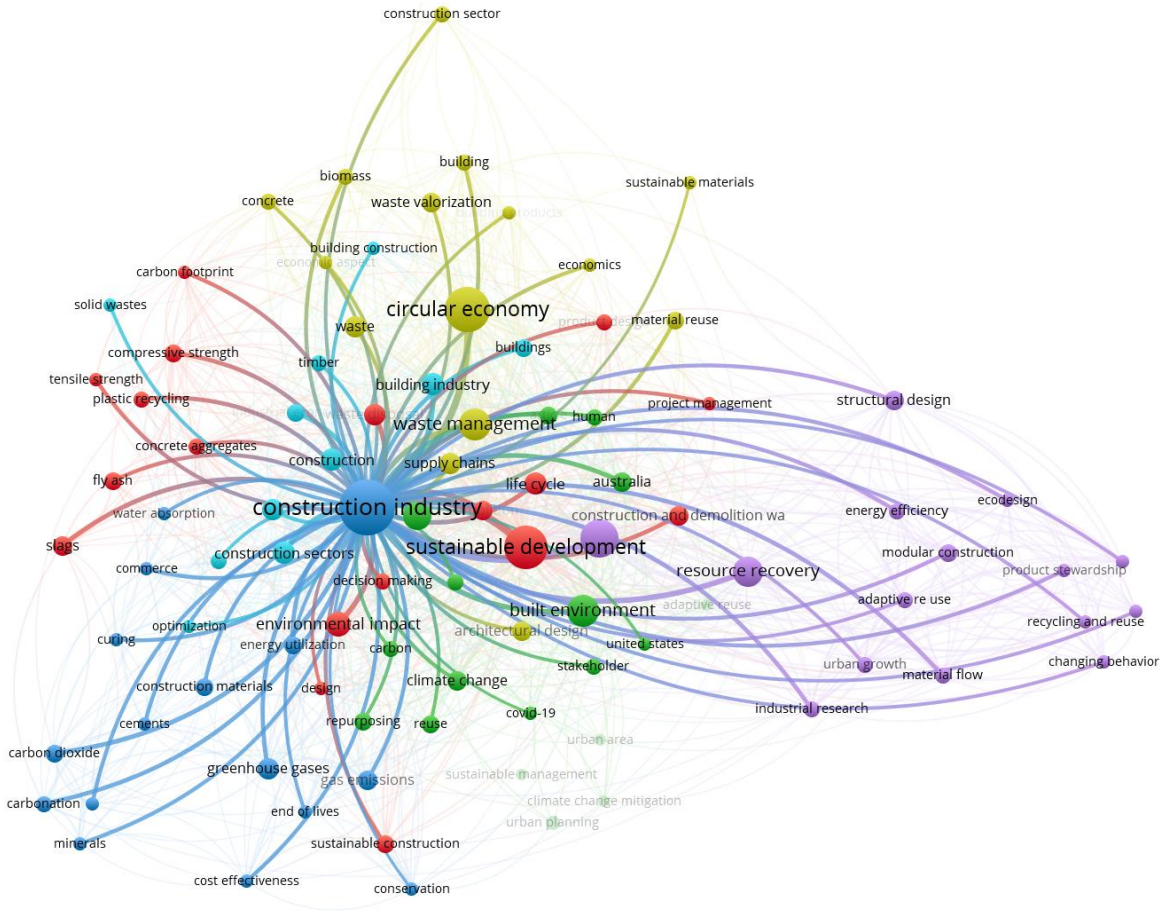

Figure 10. Co-occurrence network with a focus on the "construction industry" node. The construction industry emerges as a central theme and frequently used keyword in our sampled papers pertaining barriers to material reuse.

In Figure 10 the connectivity of the construction industry cluster in highlighted, emphasizing its strong interconnections with various sustainability themes. The figure portrays a tight bond between construction industry, sustainable development, recycling and circular economy. Each cluster radiates secondary concepts, such as waste management, buildings, environmental impact, and resource recovery. Nodes such as concrete aggregates, plastic recycling, and tensile strength highlight the technical aspects of material reuse and repurposing in construction processes. Meanwhile, links to environmental impact and decision-making signal that research extends beyond engineering concerns, encompassing policy, regulatory, and managerial dimensions. The network structure indicates that construction industry is central to our sample of literature and the research field is not siloed. Rather, it builds bridges among multiple threads of sustainability research, from high-level frameworks (e.g. circular economy) to tangible processes like material reuse.

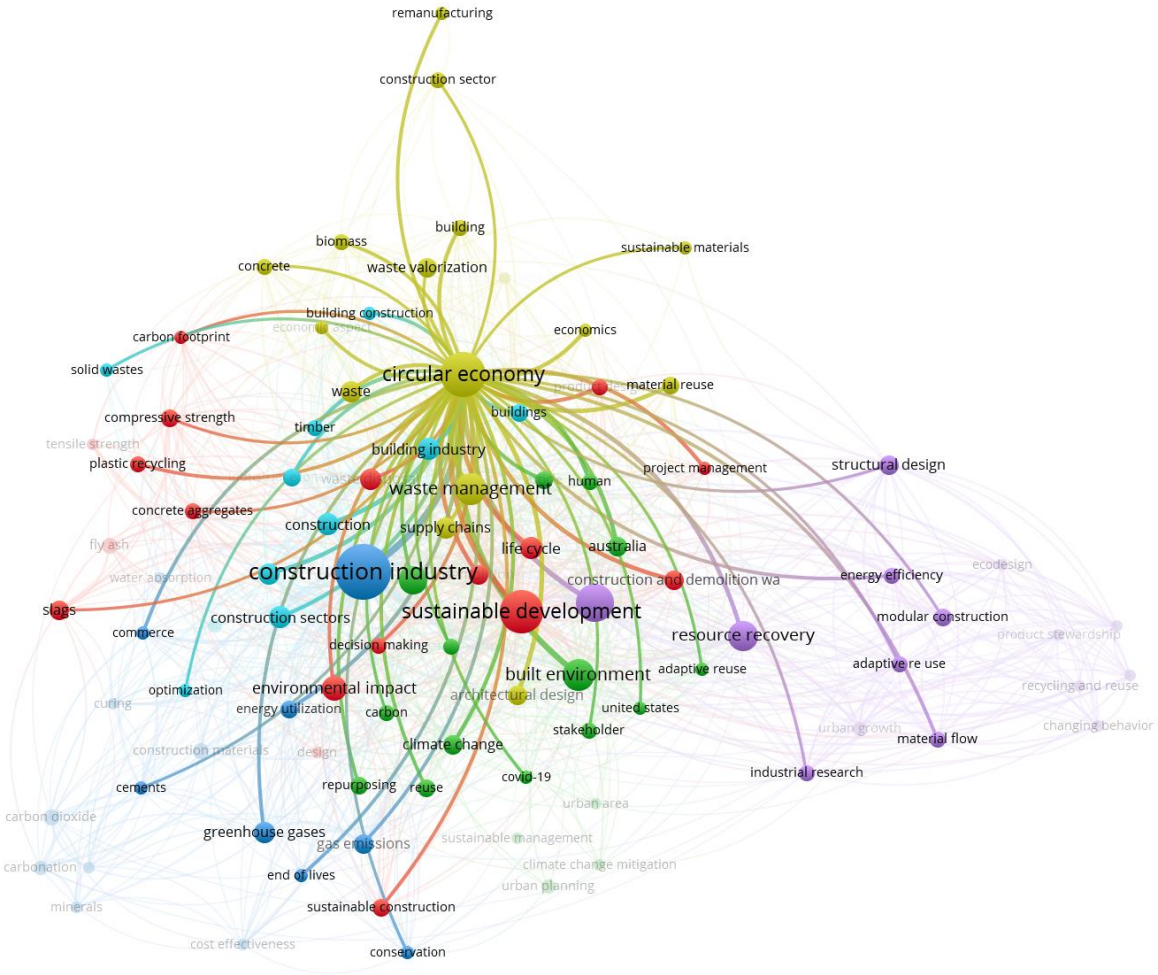

Figure 11. Co-occurrence network with an emphasis on the "circular economy" node. The figure illustrates links to material reuse and waste management, largely overlapping with the construction industry node.

Figure 11 puts focus on the circular economy cluster, illustrating how intertwined it is with the same concepts as the construction industry theme. Terms like biomass, material reuse, and remanufacturing appear alongside building industry and waste management, underlining the growing interest in applying circular principles to the built environment. The connections to economics and project management indicate a broader systems-level perspective, reflecting how circularity is now encompassing both purely technological solutions and less tangible concepts such as financial models, stakeholder involvement, and strategic planning.

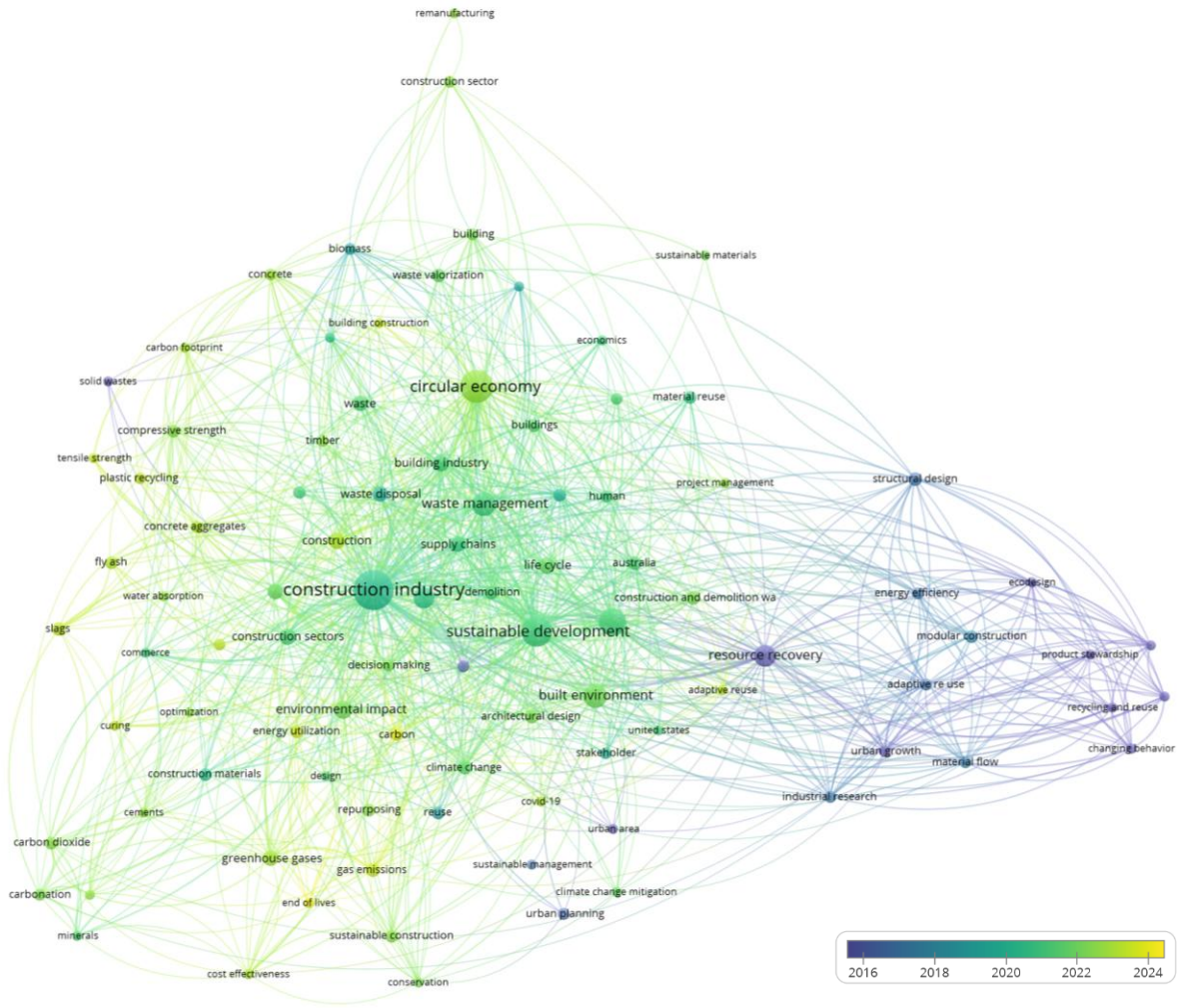

Figure 12. Temporal distribution of keyword usage, indicating average publication years across different nodes

The keyword age analysis is presented in Figure 12, where nodes are visually coded by the average publication year of the papers in which they appear. Earlier terms, such as resource recovery, have darker colour and cluster on one side, reflecting their relative prominence in older publications. Conversely, more recent topics, particularly those closer to the circular economy node, have an average age of and around 2021–2024. This temporal mapping suggests an emergence of nuanced research themes and/or a shift in focus: while resource-oriented strategies remain important, newer research increasingly explores cutting-edge frameworks and methodologies tied to circular economy principles in construction.

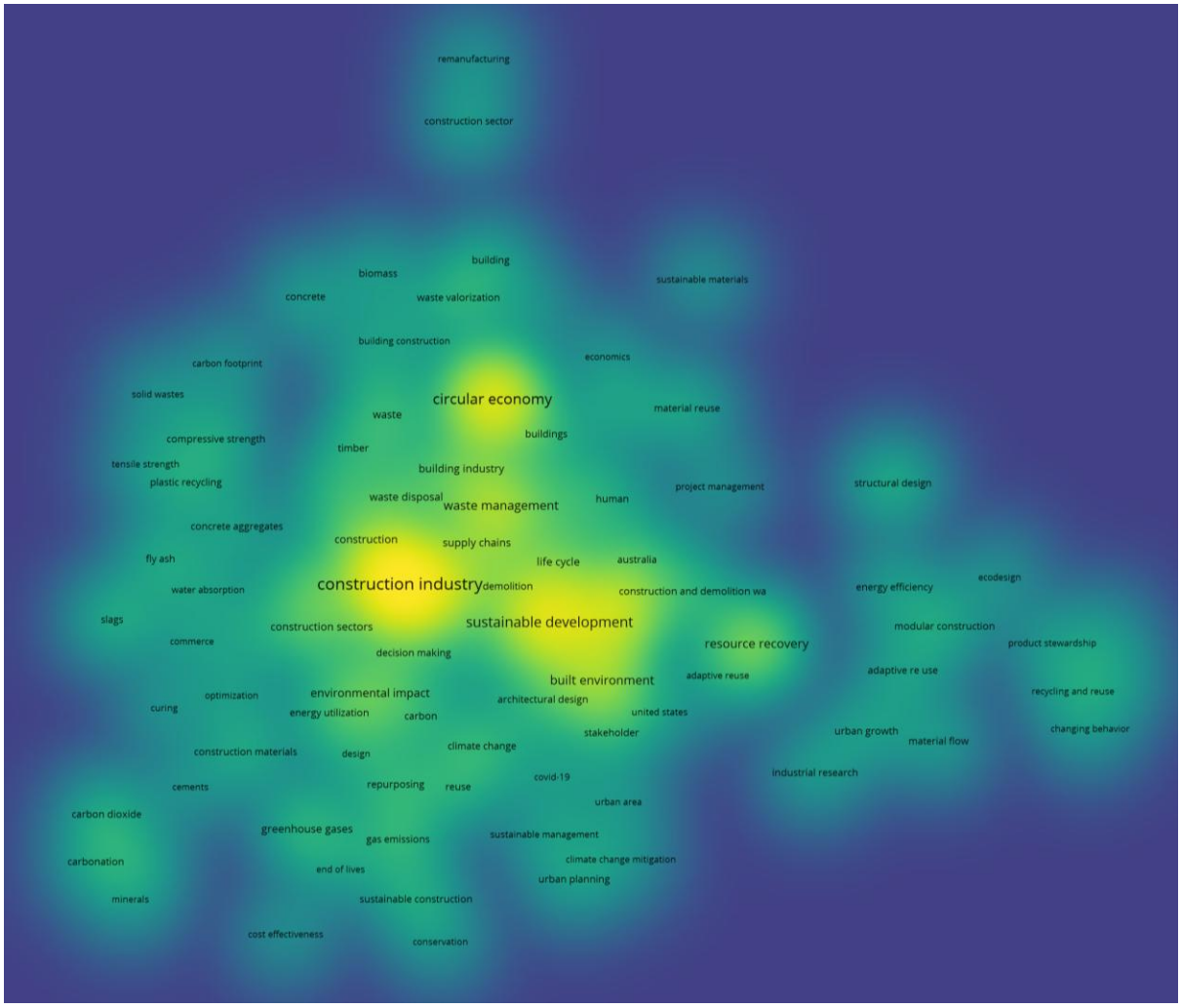

Figure 13. Heatmap visualization, indicating the frequency of key concepts across the dataset

The heatmap of the co-occurrence network highlighting presented in Figure 13. Heatmap visualization, indicating the frequency of key concepts across the dataset shows the density and frequency of keyword appearances. The brightest “hotspots” correspond to the most central and commonly used terms: construction industry, circular economy, sustainable development and recycling (which is not visible due to its proximity to the larger sustainable development node). Surrounding zones of moderate intensity, such as waste valorisation and material reuse, reflect core subthemes that connect strongly with the primary nodes. By contrast, peripheral areas, such as stakeholder or cost effectiveness, may represent emerging or less frequently addressed topics within the dataset.

5.1.2 Key findings from text mining & analysis

- An AI-based text-mining approach extracted 148 barriers from 40 of the 109 papers examined
- These barriers were organized into eight major themes—economic, technical, logistical, cultural, regulatory, environmental, organizational, and market-level—reflecting the multifaceted nature of reuse challenges.
- A second AI system validated 94.6% of the barriers, while a random manual check of 20 barriers confirmed 95% as correct.
- A Bayesian hypergeometric model combined both validation sources, discounting the AI result by 50% to account for its own uncertainties.

- The final estimate indicated that 93.9% of the barriers are valid, with a 95% credible interval of 87.2% to 98.0%.

Thematic clustering of barriers

This subsection presents a structured analysis of the key thematic clusters emerging from the identified barriers and challenges related to the reuse of construction materials. The aim is to extract and categorise barriers from the reviewed literature into distinct thematic clusters, thereby clarifying and synthesizing the landscape of obstacles to material reuse. This categorisation facilitates a deeper understanding of each barrier's context, interconnections, and implications, enabling targeted interventions and future research directions. The analysis was conducted by systematically consolidating barriers based on shared characteristics, resulting in clearly defined thematic groupings, as presented in Table 4.

Building on the bibliometric analysis, we gained access to 40 of 109 scientific works identified through Scopus. An AI-based text mining approach revealed a wide array of barriers that impede the efficient reuse of construction materials. To organize these findings systematically, we categorized the barriers into eight major themes, each encompassing specific, interrelated challenges. Table 4 presents these themes and their corresponding sub-barriers, underscoring how various economic, technical, logistical, cultural, and regulatory factors collectively constrain material reuse efforts in the construction sector.

The themes and underlying groups of barriers listed in Table 4 clarify the multifaceted nature of the problem: from short-term economic pressures discouraging investment in sustainable alternatives, to technological complexities in salvaging and repurposing materials, and to logistical hurdles arising from inadequate supply-chain coordination or infrastructure. Moreover, policy-related and societal barriers, such as inconsistent regulations or cultural resistance, reveal that achieving a circular economy in construction requires transformative approaches that address more than mere technical feasibility. By synthesizing this information into clearly defined categories, the table provides a structured foundation for targeted interventions, future research, and policy development aimed at improving the uptake of reuse strategies across the built environment.

Table 5. A thematic overview of the main categories and key issues affecting the reuse of construction materials, synthesizing and consolidating 148 barriers extracted from peer-reviewed scientific literature.

Thematic cluster	Consolidated barriers
1. Economic and Financial Barriers	- High initial and operational costs; low profitability and uncertain viability - Limited or inconsistent market demand; weak market development - Lack of incentives and clear business models - Prioritization of short-term cost savings over long-term sustainability - Difficulty recognizing long-term value and savings; cost uncertainties and risk aversion
2. Technical and Material-Related Barriers	- Complex design and construction methods for reused materials - Ensuring consistent quality, structural integrity, and compatibility - Material obsolescence, variability, and contamination issues - Downcycling tendencies leading to reduced material value - Limited technologies and methods for assessing, processing, and certifying reclaimed materials
3. Logistical, Supply Chain, and	- Inadequate reverse logistics systems, lacking collection, sorting, storage, and distribution infrastructure - High transport and handling costs; difficulty tracking material provenance

Infrastructure Barriers	- Inefficient material segregation and limited integration with BIM or digital tools - Fragmented supply chains; insufficient coordination and dedicated reuse marketplaces
4. Knowledge, Awareness, and Cultural Barriers	- Lack of awareness, training, and expertise among professionals on reuse methods - Cultural resistance and stigma against reused materials (seen as inferior or unclean) - Limited communication and knowledge exchange across project stakeholders
5. Regulatory, Policy, and Governance Barriers	- Inconsistent, restrictive regulations, codes, and standards not suited for reuse - Complex liability, warranty, and legal issues discouraging adoption - Weak or misaligned policy support; unclear responsibilities in Extended Producer Responsibility - Regional and national regulatory variations complicating standardization
6. Environmental, Health, and Safety Barriers	- Hazardous contaminants and toxic substances requiring extensive treatment - Environmental risks (e.g., leaching of toxins) and uncertain long-term ecological benefits - High energy and water consumption in certain recycling processes
7. Organizational and Collaborative Barriers	- Industry fragmentation and siloed decision-making - Lack of stakeholder coordination (demolition, design, construction, end-users) - Complex, time-intensive decision-making involving multiple parties
8. Structural and Market-Level Barriers	- Prevalence of linear economic models; reluctance to adopt circular approaches - Limited scaling beyond pilot projects and difficulty replicating at larger scales - Uncertainty in establishing stable secondary material flows and supply-demand balance

Our first thematic clustering presented in Table 5, Economic and Financial Barriers, encompasses barriers related to economic feasibility and the financial implications of reusing construction materials. It reflects factors that directly affect the cost-effectiveness and market competitiveness of reuse strategies. Central to this theme are high initial investments in technology and infrastructure, elevated transport and logistics expenses, and uncertainties in return on investment. The presence of established, cost-effective linear practices further reduce incentives for stakeholders to transition to more resource-efficient circular methods.

Cluster number two comprises challenges arising from the technical intricacies inherent in recycling and reusing construction materials. Technological and Technical Complexity include the variability in quality and reliability of reclaimed materials, technical inflexibilities in existing recycling technologies, and difficulties in dismantling hybrid or composite materials due to permanent structural connections. Such challenges significantly impact the structural performance, durability, and overall viability of recycled and reused materials within construction projects.

The third thematic cluster, Logistics and Supply Chain Challenges, reflects barriers related to the collection, transportation, storage, and tracking of reclaimed materials across supply chains. Key issues include inadequate reverse logistics networks, fragmented and uncoordinated supply chains, and insufficient facilities for processing and storing reclaimed materials. Together, these logistical inefficiencies impede effective material recovery, increasing time, cost, and complexity, thereby discouraging broader adoption and scalability of reuse practices in the industry.

Knowledge, Awareness, and Skills Deficiencies thematic cluster highlights barriers related to insufficient knowledge, awareness, and skill availability among industry stakeholders regarding sustainable reuse practices. It reflects limitations due to inadequate training, fragmented knowledge sharing, and limited awareness about reuse methods and benefits. These issues contribute to slow adoption rates and a general reluctance toward implementing circular solutions within the construction industry.

Regulatory and Policy Barriers addresses barriers arising from regulations, building codes, and policy frameworks that hinder the reuse of materials. Notably, it captures challenges posed by inconsistent standards, stringent building codes, inadequate policy incentives, liability concerns, and misalignment of international and local regulatory guidelines. Such regulatory uncertainties and gaps limit stakeholder willingness to engage in reuse activities, thus constraining widespread adoption and scalability of circular practices.

The next grouping, Environmental, Health, and Safety Barriers, emphasizes difficulties related to material performance, quality control, and technical implementation of reused construction materials. Central aspects include variability in the condition and quality of reclaimed materials, structural integrity concerns, lack of standardized assessment methods, contamination risks, and difficulties predicting long-term performance. The inherent variability and uncertainty of reclaimed materials often lead to perceptions of increased risks, affecting stakeholder confidence and acceptance in using recycled materials in mainstream construction projects.

Organizational and Collaborative Barriers encapsulate socio-economic and cultural obstacles, focusing on stakeholder attitudes and public perception. Negative perceptions concerning aesthetics, perceived inferiority, and safety concerns significantly limit market acceptance of reclaimed materials. The resistance toward shifting away from traditional, linear construction practices to more sustainable, circular alternatives further exacerbate barriers within this category.

The final category, Structural and Market-Level Barriers, highlights structural and systemic barriers stemming from industry fragmentation, sectoral silos, and limited integration across the value chain. It underlines challenges resulting from the absence of effective collaboration mechanisms, cross-sectoral coordination, and unified approaches to material reuse. Industry fragmentation inhibits innovation and impedes the scaling of successful circular solutions beyond pilot phases, underscoring the need for integrated strategies and improved stakeholder alignment.

Statistical assessment of reliability

Underlying the themes in 4 is 148 barriers extracted using our AI-based text-mining approach. Given that these barriers might have been misidentified by the AI, we used a second AI system to determine that 140 of these (94.6%) were valid. We then manually verified a random subset of 20 barriers, confirming 19 as valid (95%). Combining both sources of evidence in a Bayesian hypergeometric model yielded the posterior estimate that 93.9% of the barriers are valid, with a 95% credible interval of 87.2% to 98.0%. In other words, one should expect roughly 9 of 148 barriers to be not explicitly mentioned or outlined in the sampled scientific literature. This approach allowed us to quantify uncertainty and refine our overall estimate beyond either AI output or manual checks alone. The results are presented in Table 6.

Table 6. Fact-check results and Bayesian hypergeometric estimate for barrier identification

Step	Share	Notes
AI Verification	94.6%	Discount factor = 0.5
Manual Sample	95%	Randomly sampled subset
Final Estimate	93.9% CI 0.872–0.980	Bayesian hypergeometric model result

5.2 Key findings from the review of relevant research projects

Here are the barriers that were identified in the review of the following projects:

ICEBERG:

- Limited technologies and methods for assessing, processing, and certifying reclaimed materials.
- Inefficient material segregation and limited integration with BIM or digital tools.
- Inconsistent, restrictive regulations, codes, and standards not suited for reuse
- Cultural resistance and stigma against reused materials (seen as inferior or unclean)
- High initial and operational costs; low profitability and uncertain viability

INNO-CIRCLE:

- Lack of awareness, training, and expertise among professionals on reuse methods
- Limited communication and knowledge exchange across project stakeholders
- Industry fragmentation and siloed decision-making
- Lack of stakeholder coordination (demolition, design, construction, end-users)

CIRC-BOOST:

- Limited technologies and methods for assessing, processing, and certifying reclaimed materials
- Limited or inconsistent market demand; weak market development
- Prevalence of linear economic models; reluctance to adopt circular approaches
- Lack of incentives and clear business models
- Regional and national regulatory variations complicating standardization
- Lack of awareness, training, and expertise among professionals on reuse methods
- Cultural resistance and stigma against reused materials (seen as inferior or unclean)

CIRCULess:

- Inefficient material segregation and limited integration with BIM or digital tools
- Limited technologies and methods for assessing, processing, and certifying reclaimed materials
- High initial and operational costs; low profitability and uncertain viability
- Cultural resistance and stigma against reused materials (seen as inferior or unclean)
- Ensuring consistent quality, structural integrity, and compatibility

MOBICCON-PRO:

- Lack of stakeholder coordination (demolition, design, construction, end-users).
- Ensuring consistent quality, structural integrity, and compatibility
- High transport and handling costs; difficulty tracking material provenance

VALREC:

- Limited technologies and methods for assessing, processing, and certifying reclaimed materials

- Downcycling tendencies leading to reduced material value
- Ensuring consistent quality, structural integrity, and compatibility
- Uncertainty in establishing stable secondary material flows and supply-demand balance.

5.3 Key findings from the stakeholder interviews

Here are major barriers and challenges that were identified based on the responses obtained from the respondents (interviewees) in the interviews:

Building methods:

Building methods in certain countries have not been developed for reuse purposes. This makes it difficult for reusing materials. Therefore, the existing approaches and methods should be modified / changed to accommodate the focus on circular construction.

Legislations, regulatory aspects and policies:

Technical capabilities are / can be far greater than the ones that the legislation allow the companies to apply and practice. For example, the reuse of recycled asphalt in new asphalt layers, legislation only allows asphalt companies to use 15% in the last layer, the one that is in contact with the tire. However, technically, the company can incorporate up to 30%, and all the relevant mechanical requirements will be met. Hence, there is a gap between the legislation and technical capabilities.

Another challenge related to legislation is that there is no restriction or enforcement, at least in some countries, to adhere to certain percentage of circularity when constructing or renovating buildings. It is free choice. This can impede promoting circularity in construction.

Time, resources and cost:

It is not always possible in an easy way to reuse the materials. There is a need for manpower (and time) to effectively deal with reusing materials. Manual labour is needed. If labour costs are higher, then it will be expensive to work on reusing materials. High cost associated with reusing materials is a challenge at least in certain countries, even tax regulations in a way support reusing materials. In this regard, it is also to be noted that packaging of reusable materials is expensive. When it comes to building demolition, it is costly to identify reusable / recycle-able materials before demolition.

Economic and environmentally not feasible:

If there is a need for many people to involve in the work on reusing materials (as stated above), then the workers are going to use cars to get to the building site. So, the whole issue is not environmentally viable (in addition to the cost related challenges stated above).

The role of developers:

Everything about circular construction has probably to be coordinated with the developers or with the public administration. As one respondent said,

> “it is normal that there is a perception from our construction company that we have to make a change towards using sustainable materials. It is true that the construction companies have to be a main agent in that transformation. But the main point is in the development of the projects”.

If the developers do not point out or prioritize the need for sustainable construction in their requirement, then there will probably no use secondary materials. If the construction company chooses to include aspects of sustainable construction in the project, then that will be an additional cost for the construction company. This will affect the construction company to win the contract, if the contract considers the cost issue more than sustainability. Furthermore, using materials that are not included in the project requirement can pose risk, and it can also

complicate the interconnection between different components and optimal function of the whole system. In this regard, a respondent said:

> "So normally, I have seen that being meticulous with social aspects such as sustainability in a construction project, makes it have more work, which generally leads to higher expenses. That is why I think it is really important for the developers to include sustainability in the project. However, it is our responsibility to demonstrate that it is technically possible".

Possible risks and taking responsibility:

It is not always easy or possible to make sure the quality of the materials that are deconstructed / obtained from an old building. How to make sure that the obtained materials are environment friendly and do not harm people is a challenge. There may not be (old) documents that say about the nature and characteristics of the constituting components of the materials from the old building. This will create difficulties for reusing materials or recycled materials. Respondent mentioned:

> "If this goes wrong and there are injuries or environmental issues, who will take responsibility? Who will be accountable? Yes, here they want to use recycled material. Okay, and if that goes wrong, will you take responsibility for that? They say no, no, no, I am not signing for that. So, it is really difficult to make a step forward".

Difficult climate conditions / geographical distance:

Logistic / transport can be challenging especially in certain places, for example in Svalbard, Norway (that is situated in a challenging geographical distance). It is not that easy to transport materials between Svalbard and the mainland Norway quickly. It is also to be noted that the climate conditions in Svalbard – the dry weather – leads to dry wood. Thia It will be a challenge to reuse the materials.

Collaboration:

There should be a good collaboration among different actors in the process of sustainable construction (that includes, among other things, reuse and recycling). Lack of communication and collaboration can lead to negative impact for the projects.

Health issues:

Demolition of buildings is a process that provides opportunities for reusing and recycling materials. This process – especially, demolishing a building in the middle of a city – can create health related problems due to producing asbestos and dust. It can also create other inconvenience such as noise and traffic congestions.

Size of the company:

If a small construction company wants to embark on sustainable construction, it may be a challenge for that company. This company has to follow what big companies in the business do when it comes to sustainable construction.

Lack of indicators:

According to a respondent, there is a dashboard of indicators for circular economy, but not for circular buildings. This can hinder measuring performance (of processes, materials, etc.) and hence can become a barrier for taking initiatives to make appropriate improvement.

Decentralised digital marketplaces:

One of the respondents pointed out that several, decentralised digital marketplaces for second-hand materials in the country create difficulties for the (potential) buyers, because it is cumbersome to do the search in every site. A centralised site (like Trivago website for finding hotel accommodation) that provides information about the availability of the needed materials and corresponding details will help the buyers.

6. Suggested solutions to address the barriers

In this chapter, we will first suggest three circular business models as possible solutions. We suggest the models as a kind of general and overall solutions for organisations (including SUM4Re) that are involved or interested in applying circular / sustainable construction. And then, we will present solutions for addressing the barriers that are identified (presented in Chapter 5) in this study.

6.1 Circular business model

Based on the analysis of the literature review, project review and stakeholder interviews, we identify the following circular business models that appears to be relevant for consideration for the stakeholders and technologies of the SUM4Re project and organisations that are interested in applying circular business models.

Take back CDW and secondary materials into the primary material production line:

The concept here is to establish systems to collect and reintroduce construction and demolition waste (CDW) and secondary materials (e.g., recycled aggregates, metals) into primary material production processes, such as concrete manufacturing or metal smelting, minimizing virgin material use.

The model builds on the idea that materials discarded during construction and demolition activities still possess inherent value if properly processed. For instance, crushed concrete can be reused as aggregate in new concrete production, while steel from demolished structures can be melted, processed, and reformed. The model establishes a structured system where CDW is collected, sorted, and treated before being supplied to manufacturers for reintegration into production lines.

Key enablers for this model include technological advancements in material separation and processing, as well as strong partnerships among demolition contractors, waste processors, and first-line material manufacturers.

This model aligns well with an economically and environmentally viable pathway to circularity in construction materials. By establishing robust partnerships, leveraging technology, and ensuring regulatory compliance, it can transform CDW into a valuable resource and generate revenue for building owners, demolition suppliers and primary material manufacturers. Table 7 presents core aspects of the business model.

Table 7. Take back CDW and secondary materials into the primary material production line

Value Proposition	Value Creation & Delivery	Value Capture
Environmental Benefits: • Reduces the extraction of virgin materials and the associated ecological degradation. • Lowers greenhouse gas emissions by minimising resource-intensive raw material production. ***Economic Advantages:*** • Substitutes costlier virgin materials with processed waste, reducing production costs.	***Material Processing:*** • Develop facilities to sort and process CDW into standardized, high-quality secondary materials suitable for reintroduction into production. ***Stakeholder Collaboration*** • Partner with demolition contractors to ensure consistent material supply. • Work with manufacturers to tailor secondary materials to their production needs. ***Logistics and Distribution:***	***Revenue Streams:*** • Sale of processed secondary materials to manufacturers. • Fees for material processing and preparation services. ***Cost Savings:*** • Reduced reliance on expensive virgin materials. • Decreased waste disposal costs for suppliers.

• Generates savings on landfill disposal fees for construction and demolition companies. ***Regulatory Compliance:*** • Supports adherence to circular economy policies and waste management regulations.	• Establish efficient collection and delivery systems to minimize transportation costs and carbon footprint. ***Quality Assurance:*** • Implement rigorous testing and certification processes to ensure that secondary materials meet industry standards.	

This circular business model is associated with several challenges that must be addressed to succeed. One of the most significant issues is to ensure that processed construction and demolition waste (CDW) consistently meets the performance and safety standards required for material production. Variability in the quality of input materials, as well as contamination or degradation, can undermine the reliability of secondary materials, posing a barrier to their recyclability and redeposit in the first-line manufacturing processes.

Another challenge lies in coordinating the supply chain. Establishing reliable and consistent streams of CDW from multiple sources requires strong collaboration between demolition contractors, waste processors, and material manufacturers. Without such coordination, disruptions in the flow of materials can limit the scalability and effectiveness of the system.

Economic viability is also a critical consideration. The costs associated with collecting, sorting, processing, and transporting CDW must be carefully balanced against the potential savings achieved by reducing reliance on virgin materials. High logistical or operational expenses could render the model financially unsustainable without supportive policies or incentives. It would not be energy efficient and environmentally friendly if the CWD or secondary materials must be transported to a long-distance for recycling or reuse.

Finally, market acceptance is also a challenge. Despite the growing emphasis on sustainability and circular economy, scepticism about the quality and performance of products made from recycled inputs can deter adoption among stakeholders. Overcoming this resistance will require robust certification systems, transparency in material properties, and concerted efforts to educate stakeholders about the environmental and economic benefits of using secondary materials. Addressing these challenges will be crucial to realizing the full potential of this circular business model.

The following two business models can be considered as two different versions of this business model. The first one (“Retailing at the waste company”) is more suitable for municipalities or other public administration / organisational units. The second one (“Reuse through commercial retailers”) is suitable for the private / commercial sector.

Retailing at the waste company:

This business model (Buchard and Christensen, 2024) has been developed in association with certain recycling stations, but its main focus is on creating a store for the commercial sale of construction materials.

The economic expenses associated with operating the shops for the reuse of construction and demolition materials are funded by the revenue generated from sales, meaning that no waste fee is charged for store operations. Typically, additional personnel are hired specifically for the management of these stores, which can lead to the creation of social jobs. The number of extra staff can vary, ranging from 2 to 3 up to 14 employees, and some level of staff training can be required. The primary goal of the stores is not to generate profit; any potential earnings are used to offset existing waste fees or reinvested into the program. To encourage private businesses to provide construction and demolition waste for reuse in the shops, some systems

offer 24/7 operating hours and free disposal services for private companies, incentivizing them to supply reusable materials. This creates both an economic and practical motivation for private businesses to participate in the program, as they would otherwise need to resort to a fee-based conventional recycling method, which is limited to regular office hours.

For the waste management companies that run the recycling stations, there are further indirect economic advantages linked to the reuse shops, as the reduced recycling costs diminish. In certain instances, the creation of reuse shops is also indirectly backed by municipalities that fund the construction of the buildings accommodating these shops. Given that the sale of reusable construction materials through these stores necessitates a certain level of logistics, some of these initiatives feature an integrated IT system, with private companies even providing a collection service for reusable materials.

The main clientele in the stores consists of individual consumers, with small-scale construction companies being a secondary group. The variable inventory levels and supply uncertainties, along with concerns about material quality, continue to pose challenges for the development of a more extensive business-to-business model.

Reuse through commercial retailers:

This business model (Buchard and Christensen, 2024) is about a system is established to loop targeted materials from construction and demolition projects back into the construction sector via privately owned retailers.

There can be two main approaches to establishing reuse through a commercial retailer:

1. A comprehensive strategy aimed at items obtained during the soft-stripping phase of demolition projects (for instance, items removed from buildings before demolition, such as doors, windows, electrical equipment, or plumbing) and
2. A strategy that concentrates on a particular fraction. The first method generally encompasses items that are deemed easily marketable to private consumers. This category of building materials is often relatively challenging to incorporate into standardized quality control systems due to the significant variation in design, quality, and functionality (for example, doors and windows frequently vary in design, shape, and material composition, among other factors). Consequently, businesses within the construction industry tend to favour new construction products, which are subject to standardized quality control systems, over these types of reused materials. Value capture throughout the value chain is indirectly secured for the demolition contractor through a cost reduction linked to the soft stripping process, while simultaneously offering free access to materials for the retailer. The retailer profits from sales.

The second method is primarily applied to a particular category of materials, including bricks, construction timber, or temporary wood. Concentrating on a specific (and less complex) material streamlines the quality evaluation process and enables the implementation of standardized quality control systems and corresponding labelling systems (like CE). For instance, CE certification has been utilized in connection with the reuse of bricks. Establishing a quality control system (such as factory production control) for recycled bricks allows for the preparation of a European Technical Assessment (ETA) and a European Assessment Document (EAD). These documents outline the comprehensive technical specifications (including the documentation of the product's performance) necessary for obtaining CE certification. This facilitates the use of such bricks by private enterprises in the construction industry for new building projects where certification is required.

Companies that sell construction and demolition materials via a commercial retailer do not personally conduct screenings for environmentally hazardous substances; instead, they rely on data from the legally mandated environmental assessments performed in pre-demolition.

6.2 Solutions to address the barriers

Based on the analysis of the literature, project review and analysis of stakeholder's insights, we identified the following solutions (see Table 8) that appear to be suitable for most of the common barriers that exist when it comes to applying circular solutions within the construction industry. These solutions can also be relevant for SUM4Re.

Table 8. Solutions to the identified barriers

Thematic cluster	Solutions provided
1. Circular Design and Planning	Design for Disassembly Building Information Modelling (BIM) Digital Material Passports Modular Units Off-site Fabrication Cradle-to-Cradle Design
2. Material and Waste Management	Classification and Certification Systems for Materials Selective Deconstruction and Material Harvesting Urban Mining On-site Waste Sorting and Recycling Stations Recycled Aggregate Concrete Material Banks and Exchange Platforms Waste-to-Resource Infrastructure
3.Technological Innovation and Digitalization	Digital Twins Building Information Modelling (BIM) Digital Material Passports Artificial Intelligence (AI) and Machine Learning Internet of Things (IoT) and Sensors Circular Construction Marketplaces and Platforms Circular Design Software and LCA Tools Blockchain for Material Traceability
4. Economic and Regulatory Instruments	Green Public Procurement Fiscal Incentives and Subsidies Updated Standards and Regulations Extended Producer Responsibility Circular Economy Certification and Labelling Schemes Regulatory Requirements for Material Recycling and Waste Minimization Deposit Return Schemes for Building Materials Financial Instruments and Low-Interest Loans for Circular Projects Carbon Pricing and Emission Trading Systems

5. Education, Training, and Cultural Change	Circular Economy Curriculum Integration in Education Professional Development and Certification Programs Training for Demolition and Deconstruction Industry-Specific Circular Economy Workshops and training programs Public Awareness Campaigns and Cultural Shift Programs Sharing Success Cases Collaboration and Networking Opportunities Supporting Startups and Innovation in Circular Construction
6. Collaboration and Circular Economy Networks	Online or physical marketplaces Regional and Global Circular Economy Networks Industry-Specific Circular Economy Networks Collaborative efforts between government entities and private companies Cross-Sector Collaborations Collaborative R&D Networks for Circular Construction Circular Supply Chain Collaborations Collaborative Financing Models for Circular Construction Projects Industry Collaborations to Develop New Business Models Multi-Stakeholder Collaboration Platforms for Circular Construction

In addition to the solutions presented in Table 8, we will present and highlight the following solutions that are applicable for or relevant to SUM4Re:

Marketplaces:

Marketplaces to facilitate resource exchange and material reuse, enabling businesses to buy/sell surplus, secondary, or circular construction materials. SUM4Re aims to develop material banks with extensive data for clarity and assurance.

Collaborative efforts:

Collaborative efforts between government entities and private companies. Already taken into consideration within SUM4Re with policy recommendations and relevant policy stakeholders' engagement.

Cross-sector collaborations:

Cross-sector collaboration has already stated in SUM4Re with the consortium partners from different areas of expertise within the construction industry, public institutions, research institutions, SMEs, non-profit association that represents construction SMEs and technology providers. This enables knowledge transfer and learning and will lead to produce better results.

Industry-specific circular economy workshops and training programs:

There is already a focus on this aspect in SUM4Re by developing tailored training programs for different stakeholders and their expertise.

Sharing Success Cases:

Pilot sites are necessary to showcase the feasibility of the project's objectives and the solutions provided.

Building Information Modelling (BIM) and Digital Material Passports:

There is already consideration within SUM4Re on developing the C-BIM and Digital material passports with the intention to connect them to national construction material databases.

Urban mining:

SUM4Re's pilot demos are relevant to support the material banks.

On-site waste sorting and recycling stations:

Some technologies within SUM4Re can be used on-site and extract relevant databases.

Developing / identifying performance indicators for circular economy practices:

It is important to identify / develop performance indicators that can enable measuring performance (of processes, products, etc.). Performance measurement is vital for taking efforts to make improvement in the performance. Here are some examples of indicators that we obtained from the respondents whom we interviewed:

- CO2 emission
- Economy / cost related indicators
- The amount of virgin material
- The amount of cement production
- Landfill disposal amount
- Percentage or amount of materials that has been reused / recycled

Different approach to the building construction process:

The way of thinking and approaching the building construction process can lead to innovation and circular business models. One can start considering material reuse at the architectural level: In this regard, several questions can be asked and reflected upon. Some of them are:

- How do you develop the building?
- What materials do you use?

Taking material reuse into consideration at the architectural level can have several effects:

- Identifying reusable materials can help to plan and acquire those materials in an effective manner
- Identifying reusable materials can also influence the architectural process and designing the building that is to be constructed
- Individuals can identify and select materials that are going to use in constructing the building, which (the materials) they can reuse when the building will be demolished in for example 50 years.

Developing new business models:

Exploring the possibilities and potential in artificial intelligence and robotics can lead to develop circular business models.

Pre-demolition study:

Identifying reusable materials while the building is still operational and being used and starting to plan the process of obtaining the reusable materials from the building when it is demolished. There is no need to wait to do this until when the building is demolished.

This can be helpful in several ways. One such way is to solve the problem of space for a hub where materials from demolished buildings are collected for the purpose of possible reuse. In a dense city, this will be a problem. If the place where the building stands can become the hub and thus reduce or eliminate the problem of space for the hub.

7. Conclusion

This report focuses on current challenges and barriers in sustainable material supply and construction and demolition waste (CDW) upcycling. In this regard, this report also takes into consideration relevant topics such as circular business models (CBMs).

The following concepts are presented to provide a background thematic understanding:

- Circular economy in construction: The topics such as construction and demolition waste (CDW) upcycling and material reuse are also described here.
- Circular business models

This report adopts a comprehensive, holistic, mixed-method approach with diverse methods to achieve comprehensive scientific and practical insights about the barriers, challenges, and circular business models that emerge from material reuse and CDW upcycling practices in SUM4Re.

To achieve a comprehensive understanding of state-of-the-art, we conducted the following tasks:

- A systematic review of scientific literature: When it comes to the review of scientific articles, we use the following analyses:
  - Bibliometric analysis to comprehensively and holistically examine the landscape of CBMs, material reuse and CDW upcycling in the state-of-the-art literature.
  - Text mining and text analysis of scientific papers to identify barriers, challenges and CBMs.
- A review of relevant research projects: When it comes to other relevant research projects, we conducted a review on on-going research projects to understand the applications of material reuse and CDW in other project contexts.
- Interviews with some key stakeholders: Interviews were conducted with the partners from the three SUM4Re demonstration sites in the Netherlands, Norway and Spain.

Chapter 4 and 5 present key findings of the study. The findings of the study are structured; for example, making clusters of several CBMs, barriers and suggestions / solutions to deal with the barriers. The solutions that are mentioned in the study (Chapter 6) can be applied individually or in combination, based on the situation.

We suggest CBMs as a kind of general and overall solutions for organisations that are involved or interested in applying circular / sustainable construction. And then, we will present solutions for addressing the barriers that are identified (Chapter 5) in this study. It is to be noted that the barriers, challenges as well as the solutions were also derived from best practices and lessons learned that we looked into in this study.

The solutions point out addressing the barriers at three different levels:

- Strategic level: It focuses on devising policies and regulations that gives an overall guidance or a framework for circular building construction and sustainable material usage. (For example, thematic cluster “Economic and regulatory instruments” in *Table 8: Solutions to the identified barriers*)
- Tactical level: This level deals with developing appropriate business models and sharing and transferring knowledge about reusing materials and sustainable construction and materials management) between projects and organisations. Knowledge sharing and learning can contribute to develop and strengthen a common (effective) practice in the industry that adopts (or expected to adopt) the overall framework provided at the strategic level. (For example, thematic clusters “Education, training and cultural change” and Collaboration and circular economy networks” in *Table 8: Solutions to the identified*

barriers). It is to be noted that business models that are developed would reflect on the policies and regulations devised at the strategic level, and the knowledge transferring and learning processes would guide and support activities at the operational level.

- Operational level: Here, we are talking about the activities on the ground. In this regard, this level focuses on using modern digital solutions (artificial intelligence, robotics, etc.) and improving communication and collaboration to make sure effective work in individual projects and tasks. (For example, thematic clusters “Circular design and planning” and Technological innovation and digitalisation” in *Table 8: Solutions to the identified barriers*)

The following simplified figure (Figure 14) illustrates the above description:

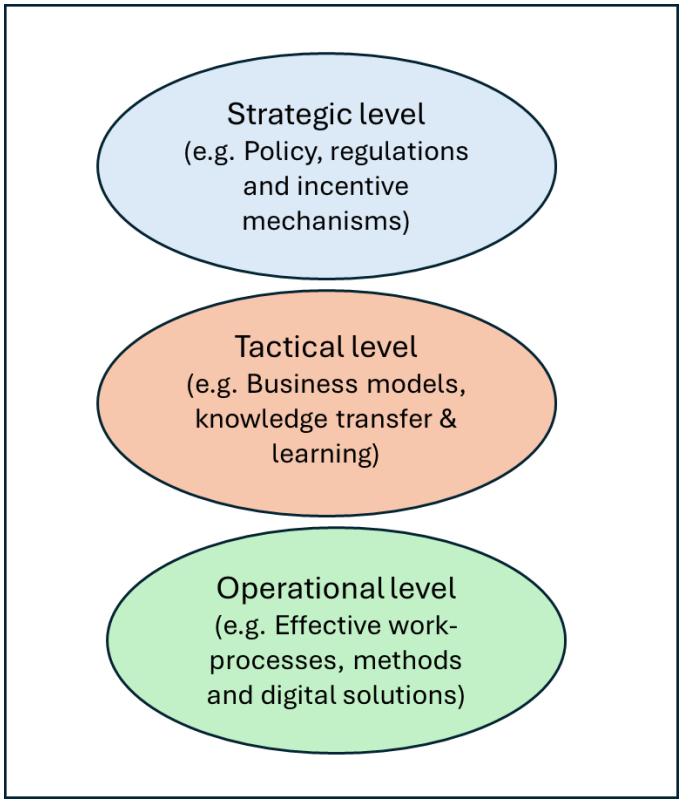

Figure 14. Solutions at different levels

This figure with the description can be considered as an overall framework. And the solutions presented in this study can then be considered and applied according to the nature and requirement of the given situation.

Both organisational structure (the formal side of organisations such as routines and reporting systems) and organisational culture (the informal side of organisations such as interpersonal relations and behavioural aspects) are to be taken into consideration in order to make sure effective implementation of the solutions in organisations.

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