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OPPORTUNITIES FOR INVOLVING CIRCULAR ECONOMY IN CONSTRUCTION SECTOR

Summary: *The construction sector, a major contributor to global resource consumption and waste generation, offers significant opportunities for implementing circular economy principles to reduce resource consumption, minimize waste, and enhance sustainability. By adopting strategies such as material reuse, design for disassembly, modular construction, and recycling of building components, the sector can shift from a linear to a circular model. The 10R model encourages a shift from the traditional linear "take-make-dispose" economy to a regenerative system that designs out waste and pollution. The 10R strategies form the foundation of the circular economy framework, promoting sustainable resource management across various sectors. These strategies aim to minimize resource input, waste, emissions, and energy leakage by extending the lifecycle of products and materials. This paper provides an overview of the conceptual basis of the circular economy and 10R strategies and their interconnections, highlighting how they can be applied to construction sector. Successful case studies on circular buildings involving steel, concrete, and timber demonstrate the practical potential of circular approaches, highlighting the importance of innovation, collaboration, and supportive policies in driving this transition*

Key words: *circular economy, construction sector, 10R strategy,steel, concrete, timber*

MOGUĆNOSTI UKLJUČIVANJA CIRKULARNE EKONOMIJE U GRAĐEVINSKI SEKTOR

Rezime: *Građevinski sektor, koji ima veliki doprinos globalnoj potrošnji resursa i stvaranju otpada, nudi značajne mogućnosti za primenu principa cirkularne ekonomije kako bi se smanjila potrošnja resursa, smanjio otpad i povećala održivost. Usvajanjem strategija kao što su ponovna upotreba materijala, projektiranje za demontažu, modularna konstrukcija i reciklaža građevinskih komponenti, sektor može da pređe sa linearnog na kružni model. Model 10R podstiče prelazak sa tradicionalne linearne ekonomije „uzmi-napravi-odloži“ na regenerativni sistem koji proektira otpad i zagađenje. Strategija 10R čine osnovu okvira cirkularne ekonomije, promovišući održivo upravljanje resursima u različitim sektorima. Ova strategija imaju za cilj da minimizira unos resursa, otpad, emisije i curenje energije produžavanjem životnog ciklusa proizvoda i materijala. Ovaj rad daje pregled konceptualne osnove cirkularne ekonomije i 10R strategije i njihove međusobne povezanosti, naglašavajući kako se one mogu primeniti na građevinski sektor. Uspešne studije slučaja o kružnim zgradama koje uključuju čelik, beton i drvo pokazuju praktičan potencijal kružnih pristupa, naglašavajući važnost inovacija, saradnje i politike podrške u pokretanju ove tranzicije.*

Ključne reči: *cirkularna ekonomija, građevinski sektor, 10R strategija, čelik, beton, drvo*

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1. INTRODUCTION

Pollution, the overuse of natural resources, and the generation of waste are deeply interconnected issues that pose significant challenges to achieving sustainability. The extraction and exploitation of natural resources—such as fossil fuels, minerals, and water—often result in pollution through emissions, habitat destruction, and chemical contamination. This unsustainable use of resources depletes ecosystems and reduces the Earth's capacity to regenerate itself. At the same time, the waste generated by human activity, especially non-biodegradable and hazardous waste, contributes to land, air, and water pollution, further straining the environment.

Sustainability aims to break this destructive cycle by promoting the responsible use of natural resources and reducing pollution and waste. This involves shifting from a linear economic model—where resources are taken, used, and discarded—to a circular model that emphasizes reuse, recycling, and regeneration. Sustainable practices encourage the design of products that last longer, use fewer raw materials, and are easier to repair or recycle. By minimizing waste and managing pollution, societies can preserve natural resources for future generations and protect the ecosystems that support life. In essence, addressing pollution and waste through sustainable resource management is key to creating a healthier, more resilient planet.

Clean technologies, green infrastructure, and policy measures such as emissions regulation and waste management are vital tools in aligning economic activity with environmental protection. Underpinned by a transition to renewable energy and materials, the circular economy is a resilient system that is good for business, people, and the environment.

In our current economy, we take materials from the Earth, make products from them, and eventually throw them away as waste – the process is linear. In a circular economy, by contrast, we stop waste being produced in the first place. We must transform every element of our take-make-dispose system: how we manage resources, how we make and use products, and what we do with the materials afterwards (Fig. 1).

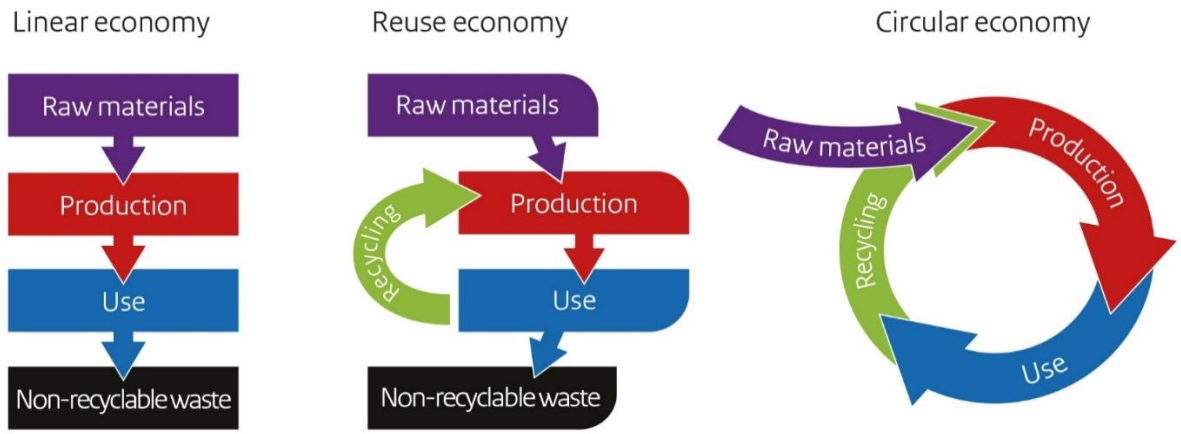


Figure 1. Transition from Linear to Circular economy [1]

The circular economy gives us the tools to tackle climate change and biodiversity loss together, while addressing important social needs. It gives us the power to grow prosperity, jobs, and resilience while cutting greenhouse gas emissions, waste, and pollution.

Unlike the traditional linear economy—which follows a "take-make-dispose" model—the circular economy seeks to create a closed-loop system where materials are constantly repurposed, minimizing environmental impact and promoting sustainability.

2. CIRCULAR ECONOMY AS SYSTEMS SOLUTION FRAMEWORK

A widely accepted and foundational definition of the circular economy is provided by the Ellen MacArthur Foundation. According to this foundation, “Circular economy is a systems solution framework that tackles global challenges like climate change, biodiversity loss, waste, and pollution” [2].

The circular economy is based on three principles, driven by design:

- Eliminate waste and pollution
- Circulate products and materials (at their highest value)
- Regenerate nature

The circular economy tackles climate change and other global challenges, like biodiversity loss, waste, and pollution, by decoupling economic activity from the consumption of finite resources [2]. It is a system where materials never become waste and nature is regenerated. In a circular economy, products and materials are kept in circulation through processes like maintenance, reuse, refurbishment, remanufacture, recycling, and composting.

The circular economy system diagram, known as the **butterfly diagram**, illustrates the continuous flow of materials in a circular economy. There are two main cycles – the technical cycle and the biological cycle. In the technical cycle, products and materials are kept in circulation through processes such as reuse, repair, remanufacture and recycling. In the biological cycle, the nutrients from biodegradable materials are returned to the Earth to regenerate nature (Fig. 2).

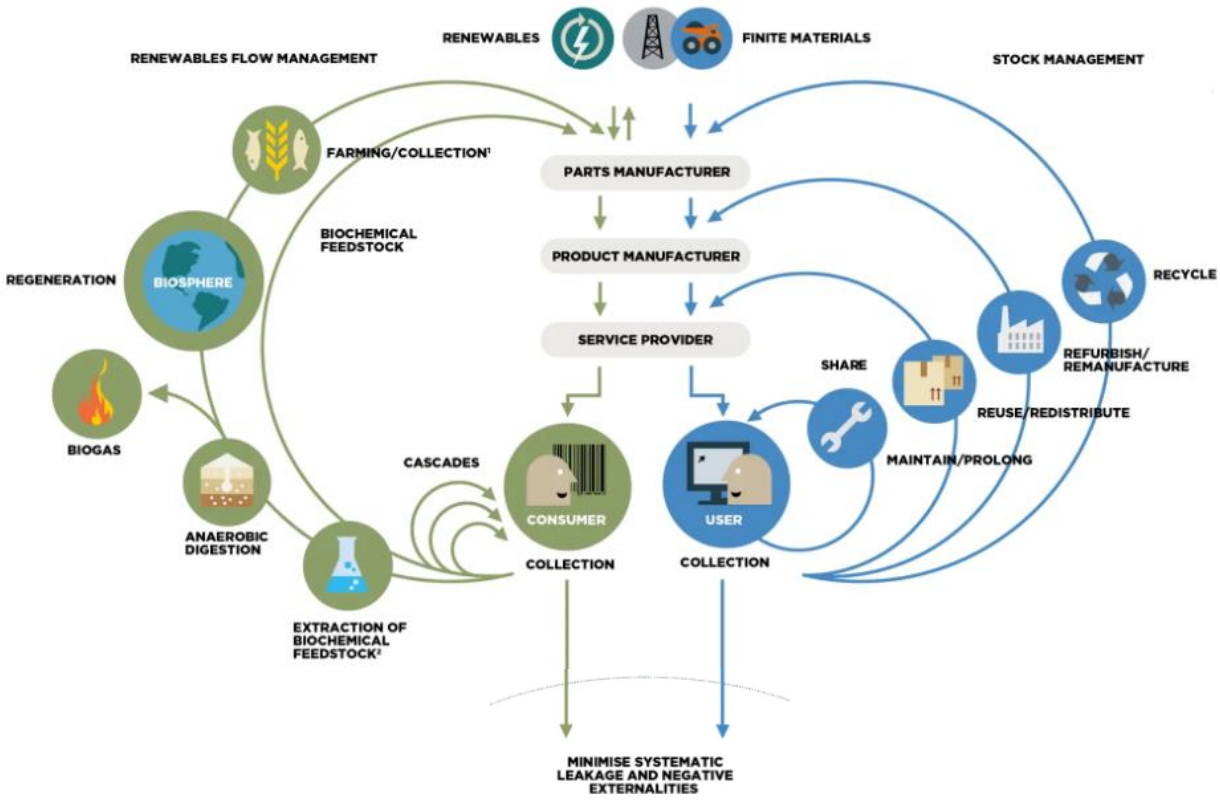


Figure 2. Butterfly diagram for Circular Economy system [2]

The **Butterfly Diagram by the Ellen MacArthur Foundation** is not just a graphic—it's a powerful conceptual tool for understanding the systemic changes needed to shift from a linear "take-make-dispose" economy to a circular, regenerative economy. It emphasizes designing out waste, keeping products and materials in use, and regenerating natural systems. By understanding and applying the principles represented in the Butterfly Diagram, businesses, governments, and individuals can contribute to a more sustainable and resilient economic model.

The Butterfly Diagram is a visual representation of the Circular Economy system. It illustrates the continuous flow of materials in two distinct but interconnected cycles: the biological cycle and the technical cycle. These cycles work together to maintain the value of products, materials, and resources in the economy for as long as possible, and to minimize waste.

The Butterfly Diagram is split into two “wings” resembling a butterfly—each representing one of the fundamental loops of the circular economy.

- **The Biological Cycle (Left Wing)**

The biological cycle includes materials that can safely re-enter the natural environment after use. These are biodegradable materials—typically derived from renewable resources such as food, wood, cotton, or other organic matter. This cycle supports regenerative systems, such as agriculture and forestry.

The flow of materials in this cycle involves several key stages:

- ✓ **Biological Feedstock**: Sourced from renewable resources (e.g., plants, animals).
- ✓ **Cascades**: Materials are used several times before becoming waste—such as using cotton rags for insulation after they can no longer be used as clothing.
- ✓ **Anaerobic Digestion/Composting**: Organic waste is processed to extract energy and nutrients.
- ✓ **Restoration of Nature**: Nutrients are returned to the soil to regenerate natural systems, completing the cycle.

The key principle in the biological cycle is "safe return"—designing products so that they decompose and enrich ecosystems without harming them.

- **The Technical Cycle (Right Wing)**

The technical cycle applies to non-biodegradable materials, such as metals, plastics, and synthetic chemicals, which should be kept in the economy through reuse and recycling rather than being discarded.

This cycle involves several circular strategies, including:

- ✓ **Maintenance and Prolongation:** Keeping products in use longer through repair and servicing.
- ✓ **Reuse and Redistribute:** Extending the life of products by giving them to new users (e.g., through resale or donation).
- ✓ **Refurbishment and Remanufacturing:** Reconditioning or rebuilding products to original or improved specifications.
- ✓ **Recycling:** Recovering materials from used products for manufacturing new items.

Unlike the biological cycle, which relies on decomposition, the technical cycle emphasizes "closed-loop systems"—retaining the maximum value of materials and minimizing the need for virgin resources.

- **The Inner vs. Outer Loops**

An essential concept in the Butterfly Diagram is the idea of inner vs. outer loops. Inner loops (like maintenance and reuse) retain more value and consume less energy compared to outer loops (like recycling). The closer the loop to the center of the butterfly, the better it is for efficiency and sustainability.

For example, reusing a whole product is more resource-efficient than recycling its components, or refurbishing a device is generally better than melting it down for raw materials.

The Butterfly Diagram also implicitly acknowledges the need for **enabling systems**, such as:

- ✓ Product design that supports longevity, modularity, and recyclability.
- ✓ Reverse logistics to retrieve used products.
- ✓ Business models such as leasing, sharing, and service-based models.
- ✓ Policy frameworks that support circular practices.
- ✓ Consumer behavior oriented toward sustainability.

Although the two cycles are distinct, they are not isolated. Designing for material separation ensures that each component ends up in the correct loop.

2.1. The 10R Framework of the Circular Economy

The 10R strategy is a pivotal element of the circular economy, providing several sustainability advantages (see Fig. 3). This approach involves designing out waste by implementing a waste-free system which concentrates on high-quality products and materials that are optimised for disassembly and utilization [3].

The goal is to optimise resource yields by obtaining the highest possible utility of products, components, and materials in both technical and biological cycles [4]. Products are designed to be of highest use for a long time before being disassembled and reused or recycled, minimizing waste, and decreasing the reliance on virgin materials. As a result, businesses can achieve triple bottom line sustainability benefits that include economic, social, and environmental advantages [3].

The **10R framework** is a structured hierarchy of strategies used to implement the principles of the circular economy. It guides businesses, governments, and individuals in shifting from the traditional linear model—take, make, dispose—toward a regenerative system where resources are kept in use for as long as possible.

By following the 10R strategy, businesses can reduce their environmental impact, create new opportunities for growth and cost savings, promote the circular economy, and drive innovation. By adopting a sustainable future, businesses can play their role in lessening reliance on virgin materials and resources, contributing positively towards a sustainable future.

The 10Rs represent ten strategies ranked by their potential to retain value and reduce environmental impact, with the first few being the most desirable and impactful (Fig. 3).

Refuse (R0) – Avoid using unnecessary products or materials in the first place. This could mean refusing single-use plastics or avoiding products with excessive packaging.

Rethink (R1) – Rethink how products are used or offered. This often involves business model innovation, such as product-as-a-service, shared use, or multifunctional design.

Reduce (R2) – Use fewer resources by increasing efficiency or reducing consumption. This includes designing products that require less material or encouraging minimalist consumption.

Reuse (R3) – Extend the life of products by reusing them for the same or different purposes. This could involve second-hand markets, donation, or repurposing items.

Repair (R4) – Fix faulty products instead of discarding them. Promoting repair helps extend product lifespan and reduces the need for new materials.

Refurbish (R5) – Restore old products to good working condition, often by replacing or upgrading components. This is common with electronics and furniture.

Remanufacture (R6) – Rebuild products using a mix of used and new parts to bring them back to like-new condition. This strategy is widely used in industries such as automotive and machinery.

Repurpose (R7) – Use a product or its parts for a new function without processing it extensively. An example might be turning old tires into playground surfaces.

Recycle (R8) – Process materials to obtain raw materials that can be used to make new products. While important, recycling typically consumes more energy and value than strategies earlier in the hierarchy.

Recover (R9) – Extract energy from waste that cannot be reused or recycled, such as through incineration with energy recovery. This is considered the last resort before disposal.

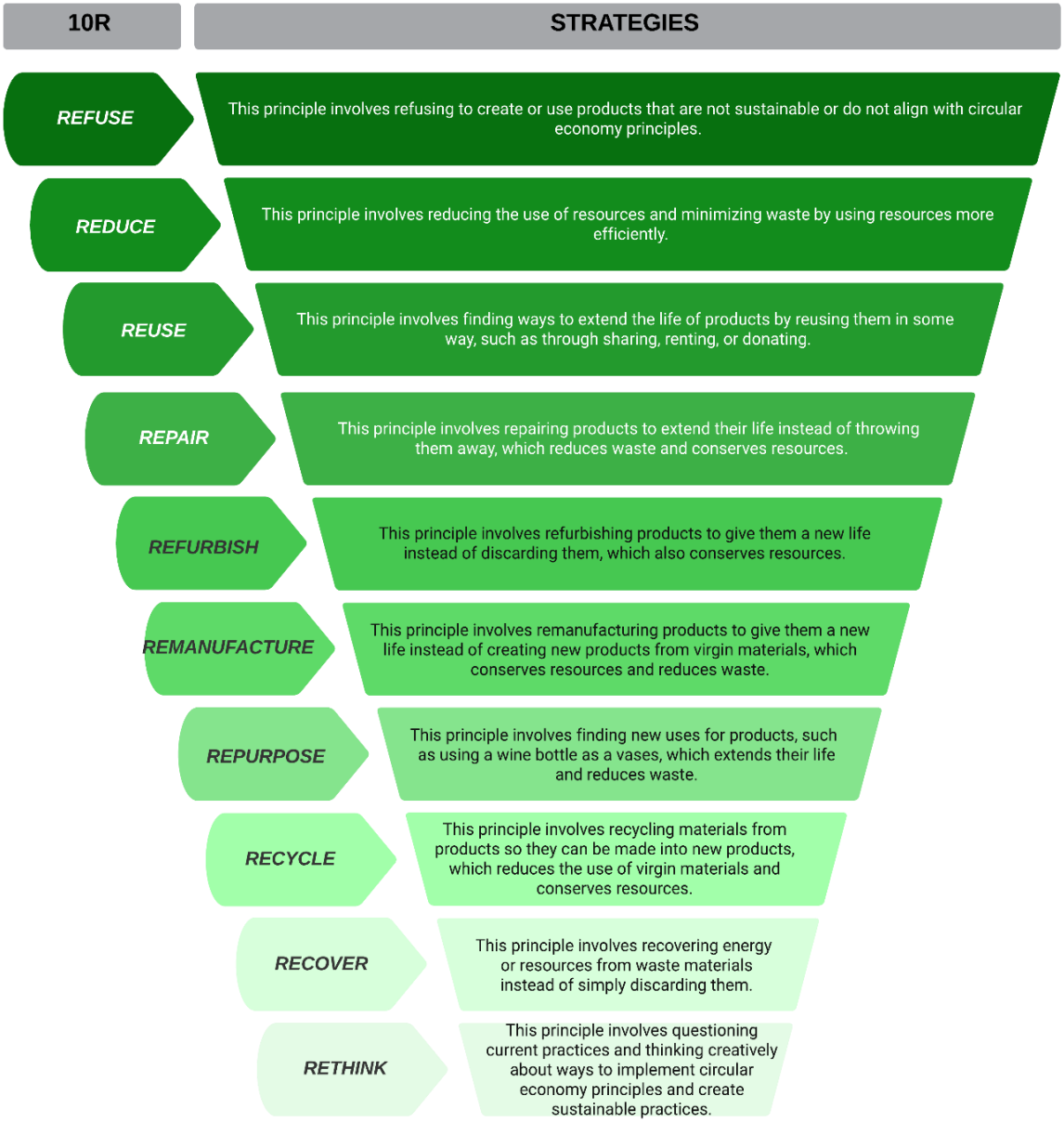


Figure 3. 10R Strategy [5]

3. ENVIRONMENTAL IMPACTS OF THE BUILT ENVIRONMENT

Buildings and infrastructure—encompassing everything from residential, commercial and industrial buildings to roads, bridges, and utility systems—are essential for modern life. However, their development and operation are major contributors to global environmental degradation. From their construction through operation to demolition, buildings and infrastructure contribute significant energy use, carbon emissions and material

depletion. Addressing these impacts from a sustainability perspective is essential to mitigating environmental degradation and fostering a healthier and more resilient planet.

The built environment, and the infrastructure have far-reaching impacts on natural ecosystems, resource consumption and climate change. Their environmental impacts span multiple phases: extraction of raw materials, construction, operation, maintenance, and eventual demolition or repurposing. The cumulative effects touch nearly all aspects of the natural environment (Fig.4).

The construction sector is one of the world's largest consumers of raw materials. It accounts for 50% of global raw material consumption, but in same time it accounts for 40% of total global energy consumption and 30% of global water usage. According to the International Energy Agency (IEA) and UN Environment Programme report for 2021 [6], buildings are responsible for approximately 39% of CO_2 emissions and they are responsible for over one-third of global greenhouse gas emissions. Much of this impact comes from operational energy consumption, such as heating, cooling, lighting, and appliance use. However, the embodied energy in building materials—the energy required to extract, manufacture, transport, and install them—is increasingly recognized as a critical environmental concern. Processes related to production, transport and the use of building materials, in particular, cement, concrete and steel, account for an ever-growing CO2 footprint of buildings.

Construction activities also generate huge amounts of waste. In many countries, construction and demolition (C&D) waste accounts for over one-third of total solid waste generated. Most of this waste ends up in landfills, where it contributes to land degradation and methane emissions. While some countries have made progress in recycling concrete, asphalt, and steel, a significant portion of material still goes unrecovered due to poor design for disassembly and lack of infrastructure for material reuse.

Urban sprawl and infrastructure expansion often lead to: deforestation and loss of biodiversity, fragmentation of ecosystems, soil erosion and degradation. The conversion of natural land into urban areas not only destroys wildlife habitats but also reduces the Earth's natural carbon sinks. Impervious surfaces like asphalt and concrete also increase surface runoff, contributing to flooding and water pollution.

Buildings and construction activities consume large amounts of freshwater, particularly in concrete mixing, dust suppression, and equipment cooling. Moreover, improper waste disposal and chemical runoff from construction sites can contaminate water bodies and storm water runoff from urban infrastructure can carry pollutants like oil, heavy metals, and microplastics into rivers and oceans.

Dense urban areas with abundant concrete and asphalt absorb and retain heat, leading to the urban heat island (UHI) effect, where cities are significantly warmer than surrounding rural areas. This contributes to: increased energy consumption for air conditioning, worsening air quality due to trapped pollutants and health issues such as heat stress and respiratory problems.

Environmental Impact Pathways of Buildings and Infrastructure are presented on the diagram in Figure 4.

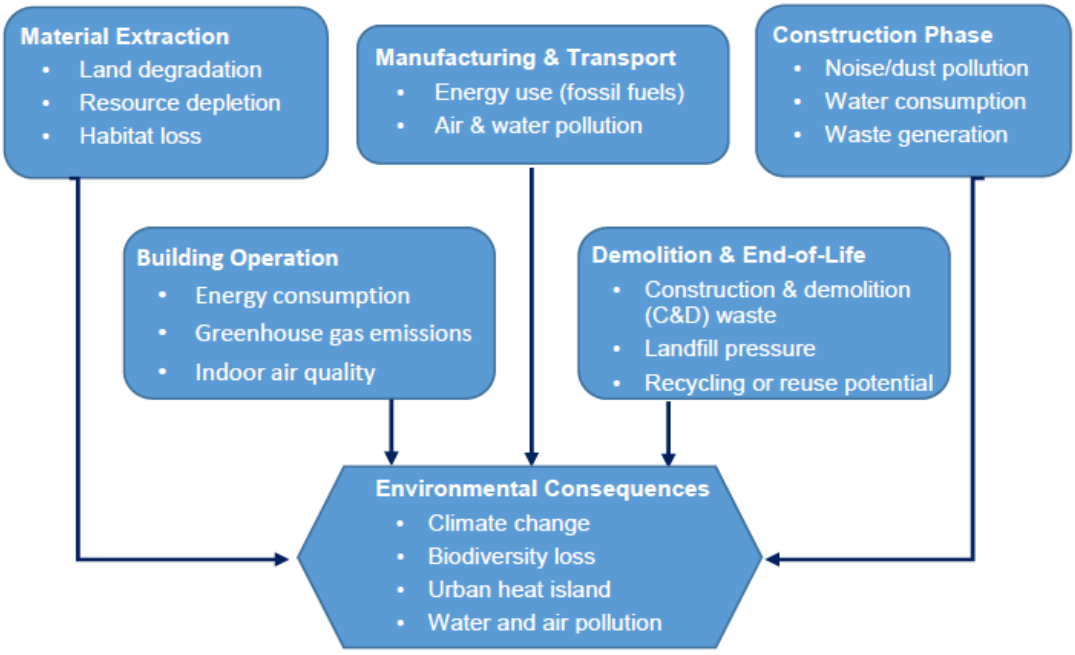


Figure 4. Environmental Impact Pathways of Buildings and Infrastructure

In response to these challenges, the construction industry is shifting towards sustainable building practices, which aim to reduce negative environmental impacts while enhancing efficiency and occupant well-being. Key strategies include:

- Energy-efficient design. By involving passive solar design, insulation, energy-efficient windows, and HVAC systems, the operational energy needs could be reduced.

- Sustainable materials. The use of recycled, low-carbon, or locally sourced materials reduces environmental footprints and supports circular economy goals.
- Green certifications. Programs like LEED (Leadership in Energy and Environmental Design) and BREEAM help measure and encourage sustainability in building projects.
- Renewable energy integration. Solar panels, wind turbines, and other renewable technologies can significantly reduce reliance on fossil fuels.
- Infrastructure planning is also shifting toward low-impact development, prioritizing public transport, green spaces, and compact city designs that reduce the need for sprawling land use and minimize resource consumption.

Adopting a lifecycle approach to buildings—from design and construction to use and eventual deconstruction—is central to sustainability. This approach evaluates a building's environmental impacts over its entire lifespan, encouraging strategies such as design for disassembly, modular construction, and reuse of building components. These principles are tied to the circular economy, which seeks to minimize waste and keep materials in use for as long as possible.

4. CIRCULAR ECONOMY IN CONSTRUCTION SECTOR: KEY PRINCIPLES, OPPORTUNITIES AND STRATEGIES

A circular economy in construction represents a transformative shift from traditional linear construction practices to more sustainable, resource-efficient approaches. Instead of the conventional "take-make-dispose" model, the circular economy emphasizes designing buildings and infrastructure with the entire life cycle in mind – especially the end-of-life phase. This approach aims to minimize waste, reduce environmental impact, and maximize the value of materials and components by enabling reuse, recycling, and adaptability.

The key principles of Circular Economy in construction are:

1. **Use of Recycled and Renewable Materials**

   Incorporating recycled concrete, reclaimed wood, recycled steel, or bio-based materials (like hempcrete) helps reduce the extraction of virgin resources.

2. **Design for Disassembly and Reuse**

   Buildings are designed so components (like steel beams, façade panels, flooring) can be easily taken apart and reused elsewhere, rather than demolished and discarded.

3. **Modular Construction**

   Prefabricated and modular designs enable easier upgrading, relocation, or reuse of building elements.

4. **Material Passports**

   These are digital records of materials used in a building, making it easier to reuse or recycle them at the end of the building's life.

5. **Adaptive Reuse of Existing Structures**

   Repurposing old buildings for new functions rather than tearing them down extends the lifecycle of both materials and structures.

6. **Waste Minimization On-Site**

   Efficient project planning and lean construction practices reduce material waste during the construction process.

Applying circular economy principles to construction can deliver long-term environmental, economic, and social benefits. It fosters innovation, reduces dependence on raw materials, and aligns the built environment with broader sustainability goals. As urbanization accelerates and resource pressures increase, embracing circular design is not just a responsible choice – it is an essential step toward a resilient and regenerative future.

Central to this vision are several strategic design principles. One key strategy is the use of modular and prefabricated components, which not only simplify construction processes but also facilitate future dismantling and relocation. Modular buildings can be expanded, reconfigured, or dismantled with minimal disruption, facilitating the reuse of entire units and individual parts. This flexibility significantly extends the life of materials and reduces the demand for raw resources.

Another important principle is design for disassembly (DfD). This concept involves planning buildings from the outset so that their parts can be easily separated and recovered at the end of their useful life. DfD considers how connections are made, the sequencing of materials, and labeling systems, enabling efficient deconstruction without damaging valuable elements. This process supports the recovery of components in high-quality condition, increasing the potential for reuse and reducing construction and demolition waste.

Material selection also plays a key role. The circular construction model prioritizes sustainable, recyclable and bio-based materials that have a lower environmental impact and can be reintegrated into production cycles. Examples include recycled steel, reclaimed wood, biodegradable insulation and natural fiber composites.

Salvaging bricks, steel, wood and other components from demolition sites not only reduces waste, but also preserves the embodied energy in these materials. Urban mining — the extraction of valuable resources from existing buildings — has become a promising area of growth. The materials obtained in this way not only help conserve limited resources, but also support a healthier indoor environment and reduce carbon emissions.

Better planning and tracking of resources throughout a building's life cycle is enabled by technologies such as Building Information Modelling (BIM). Policy frameworks, green procurement requirements and certification systems (e.g. LEED, BREEAM) further encourage the adoption of circular practices.

While challenges such as regulatory barriers, market demand and logistical complexity remain, the transition to a circular economy in construction is gaining momentum. With coordinated efforts from policymakers, industry stakeholders and designers, the construction sector can play a vital role in building a more sustainable, circular future.

Applying the key principles of the circular economy in construction sector brings significant benefits, such as:

- Reduces environmental footprint and landfill waste
- Lowers material and lifecycle costs
- Enhances resilience and long-term value of buildings
- Encourages innovation in building design and materials

The six principles of the circular economy in construction sector can provide the expected benefits only if they are incorporated into a well-developed circular business model based on the 10R strategy (Fig. 5).

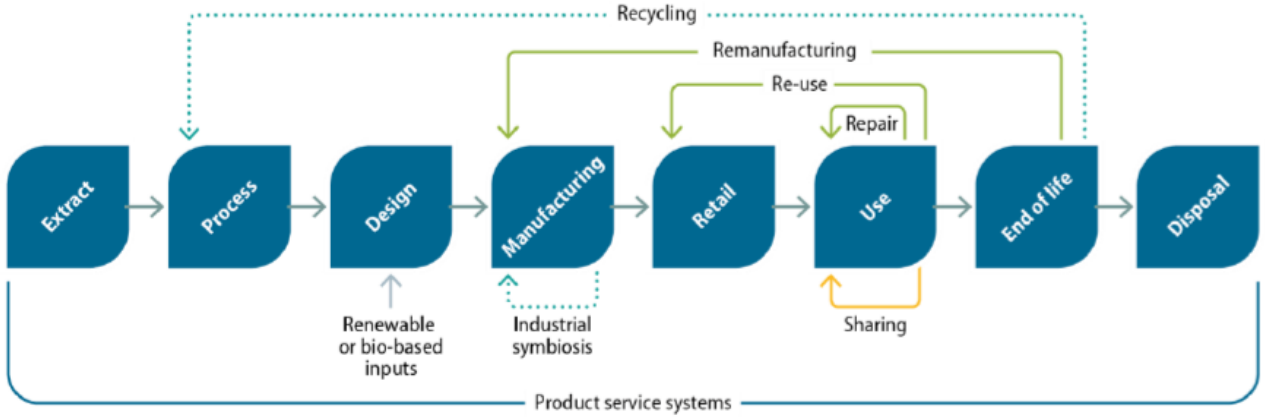


Figure 5. Typology of Circular Business Model in construction sector

5. IMPLEMENTING CIRCULAR ECONOMY IN THE CONSTRUCTION SECTOR: FOCUS ON STEEL, CONCRETE, AND TIMBER STRUCTURES

Common materials like concrete, steel, and glass are energy-intensive to produce and often sourced through mining or quarrying, which disrupt ecosystems and deplete non-renewable resources. The continued demand for these materials puts pressure on finite resources and accelerates environmental degradation.

To effectively integrate circular principles in the construction sector, it is essential to understand the specific opportunities and challenges associated with different structural materials, especially the most commonly used ones, such as steel, concrete and wood.

5.1. Steel Structures

Steel is one of the most recyclable construction materials. The opportunities that make it highly suitable for circular applications are:

- **Design for Disassembly (DfD):** Steel structures cen be designed with demontable connections. The components can be bolted rather than welded, allowing for easy disassembly and reuse in future projects.
- **Standardization and Modularity:** Standardized steel elements enable easy replacement, reuse, and integration into new structures.
- **Recycling:** Steel retains its properties after recycling, making it ideal for closed-loop recycling systems.
- **Urban Mining:** Decommissioned steel structures can be systematically dismantled, and components can be reused or recycled.

Parallel to opportunities there are few challenges, as:

- Ensuring structural integrity and meeting modern codes for reused elements.
- Tracking material history and quality, which can be addressed using digital tools like BIM and material passports.

5.1.1. Case Study: The Circular Building, London

The Circular Building, developed for the 2016 London Design Festival, exemplifies circular construction through its fully reusable components and modular steel frame (Fig.6). The project was a collaboration between Arup, The Built Environment Trust, Frener & Reifer, and BAM [7], aiming to demonstrate how buildings can be designed for complete disassembly and material reuse.



Figure 6: Circular building, London, erection of steel frame, and structural conection detail

The circular strategies are implemented in all phases of the building's life-cycle:

1. Design Phase

- Circular Economy Integration: The design prioritized the use of reclaimed materials, with the building's size and form adjusted to accommodate available steel off-cuts from other projects.
- Modular Construction: Standardized steel components were used to facilitate easy assembly and future disassembly.
- Digital Material Tracking: Each component was tagged with a QR code linked to a digital Building Information Modeling (BIM) system, detailing material specifications and assembly instructions to aid in future reuse.

2. Construction Phase

- Dry Assembly Techniques: The structure was assembled using bolts and screws instead of welding or adhesives, allowing for straightforward disassembly without damaging components.
- Efficient On-Site Assembly: The modular design enabled rapid construction with minimal waste, as components were prefabricated and fitted together on-site.

3. Operational Phase

- Temporary Installation: The building served as a temporary exhibition space during the London Design Festival, showcasing sustainable construction practices.
- Educational Demonstration: Visitors could scan QR codes on building components to learn about their origins, materials, and potential for reuse, promoting awareness of circular construction.

4. Deconstruction Phase

- Planned Disassembly: After the festival, the building was systematically dismantled in the reverse order of assembly, guided by the BIM system and component tagging.
- Material Reuse: All components were recovered without damage and stored for future use in other construction projects, demonstrating the feasibility of material circularity.

5. Reuse and Legacy

- Component Repurposing: The reclaimed steel components have been earmarked for use in future construction projects, reducing the demand for new materials and associated environmental impacts.
- Influence on Industry Practices: The project has served as a model for integrating circular economy principles into building design, influencing subsequent projects to adopt similar strategies.

Demonstration projects like The Circular Building play a crucial role in educating stakeholders and promoting the adoption of circular construction practices. Incorporating modular design and dry assembly techniques facilitates easy deconstruction and material reuse. Utilizing BIM and component tagging enhances transparency and efficiency in both construction and deconstruction phases. Prioritizing the use of reclaimed materials and planning for their future reuse contributes to sustainability and resource efficiency.

5.2. Concrete Structures

Concrete poses more challenges in circular applications due to its monolithic nature and lower recyclability compared to steel or timber. The opportunities for concrete are:

- **Concrete Recycling:** Crushed concrete can be used as aggregate for new concrete or road sub-base material.
- **Precast Modular Elements:** Prefabricated concrete components can be designed for disassembly and reuse.
- **Carbon Capture in Concrete:** Emerging technologies allow for CO_2 to be captured and stored in concrete during production.
- **Adaptive Reuse:** Instead of demolition, concrete buildings can be refurbished or repurposed, preserving embodied energy.

The challenges for the concrete reuse are:

- Dismantling reinforced concrete is labor- and energy-intensive.
- Quality control of recycled aggregate can be variable.
- Cement production remains highly carbon-intensive, requiring innovation in low-carbon binders (e.g., geopolymer concrete).

5.2.1. Case Study: Super Circular Estate (SCE) Project, Kerkrade, Netherlands

The Super Circular Estate (SCE) project in Kerkrade (Fig. 7) stands as a pioneering initiative in circular concrete construction [8]. It involved the deconstruction of a 10-story apartment building and the subsequent reuse of its concrete components to construct new housing units, aiming to minimize waste and promote material circularity. The aim of the construction of the three new houses was to construct them using at least 95% of reused materials that are re-sourced from the donor building. Foundation has been made out of circular concreate (aggregate for the concrete have been acquired by crushing the existing concreate structure and only 7% of new cement has been added during production of concrete for the foundation).

Main loadbearing structure of the two houses has been directly reused from the existing building by cutting 3D concrete modules from the existing structure, while the main loadbearing structure of third house has been made of circular concreate (aggregate and cement for the concrete, only 5% of new cement has been added during production of concrete for the structural walls).

Partitioning walls have been directly reused from the exiting building as well as wooden frames for doors and kitchen cabinets have been directly reused and finally, façade has been constructed out of parts using crushed concrete pieces from the existing building brick, cut off elements, and recycled concrete.

The circular strategies are implemented in all phases of the building's life-cycle:

1. Design Phase

- Design for Disassembly (DfD): The original building was not initially designed for disassembly. However, the SCE project retroactively applied DfD principles by carefully planning the deconstruction process to maximize material recovery.
- Stakeholder Collaboration: An interdisciplinary team, including architects, engineers, and contractors, collaborated to identify reusable components and plan their integration into new constructions.
- Material Assessment: A thorough audit was conducted to assess the quality and suitability of existing concrete elements for reuse, ensuring structural integrity and compliance with current building standards.

2. Construction Phase

- Selective Deconstruction: Instead of traditional demolition, the building underwent selective deconstruction. Concrete elements, such as slabs and panels, were carefully removed to preserve their usability.
- Component Processing: Recovered concrete elements were cleaned, tested, and, where necessary, modified to fit new design specifications. This process ensured that the materials met safety and performance requirements.
- Integration into New Structures: The processed concrete components were then incorporated into the construction of new housing units within the same area, demonstrating a closed-loop material cycle.

3. Operational Phase

- Monitoring and Evaluation: The newly constructed units were monitored to assess the performance of reused materials over time, providing valuable data on durability and occupant satisfaction.

- Community Engagement: Residents were informed about the sustainable aspects of their homes, fostering awareness and appreciation for circular construction practices.MDPI

4. Deconstruction Phase (Future Planning)

- Design for Future Disassembly: The new structures were designed with future disassembly in mind, incorporating features that would facilitate the easy removal and reuse of components at the end of their lifecycle.
- Material Documentation: Detailed records of the materials used, including their origin and properties, were maintained to aid future deconstruction and recycling efforts.



Figure 7: Hoisting of elements and two 3D units for the construction of two circular houses (Type A left and Type B middle). The structure for the third house (Type C) has been made of recycled concrete.

The SCE project successfully demonstrated that concrete components from deconstructed buildings could be effectively reused in new constructions, reducing the demand for virgin materials. By reusing existing materials, the project significantly reduced construction waste and associated carbon emissions, contributing to more sustainable building practices. While initial costs were higher due to the labor-intensive deconstruction process, the long-term benefits included material savings and reduced environmental remediation expenses.

The methodologies developed during the SCE project serve as a model for similar initiatives, highlighting the potential for broader application of circular construction principles in the industry.

The Super Circular Estate project exemplifies how thoughtful planning and collaboration can transform traditional construction practices, paving the way for a more sustainable and resource-efficient built environment.

5.3. Timber Structures

Timber is a renewable material with strong potential in circular construction, especially with the rise of engineered wood products like cross-laminated timber (CLT). The circular process throughout the entire life cycle of a timber building is shown in Figure 8.

The opportunities for implementing the circular economy in construction of timber buildings are:

- **Reusability and Bio-based Design:** Timber elements can be easily dismantled and reused with minimal processing.

- **Carbon Storage:** Wood stores carbon throughout its lifecycle, contributing to carbon neutrality.
- **Design for Flexibility:** Timber lends itself well to modular design, allowing for future modifications or reuse of components.
- **Biodegradability**: End-of-life timber products can be composted or used in bioenergy systems (with care to avoid treated wood).

The challenges for circular timber structures are:

- Durability and fire resistance must be managed carefully in reused timber.
- Preservatives and adhesives may affect recyclability or biodegradability.
- Market demand and regulations for reused wood may be limited in some regions.

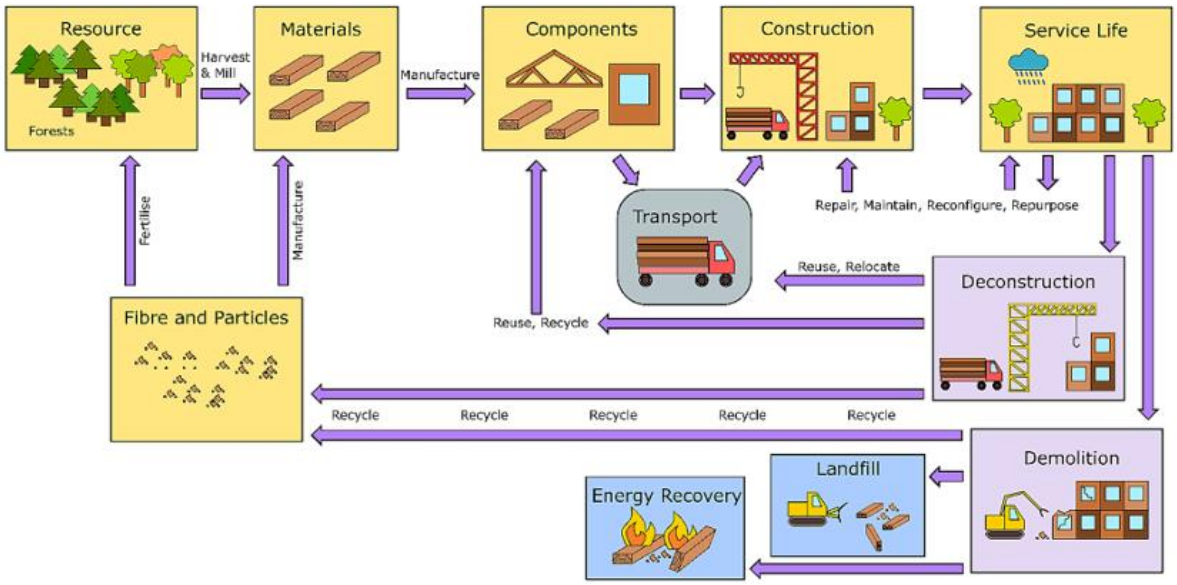


Figure 8. Circular process throughout the entire life cycle of a timber building

5.3.1. Case Study: Pikku-Finlandia (Little Finlandia), Helsinki, Finland

Pikku-Finlandia is a temporary timber building constructed as an events venue during the renovation of the iconic Finlandia Hall in Helsinki. Designed with circular economy principles, it exemplifies sustainable timber construction through its use of natural materials and a design that facilitates disassembly and relocation.

Pikku-Finlandia was designed as a temporary replacement events facility during the three-year renovation of the landmark Finlandia Hall [9]. The project was organised by Aalto University, the City of Helsinki, and Finlandia Hall in the autumn of 2019. The design used whole untrimmed tree trunks as load-bearing columns, thus minimising processing costs and impacts. The 2000 m^2 Pikku-Finlandia has four multifunctional halls, a gallery, and a cafe (Fig. 9). Three of the multifunctional halls can be combined into one large area together with the lobby. This flexibility allows the building to fulfil a variety of functions and meet a variety of needs. Following the renovation, the building will be disassembled and moved to a new location and continue its life serving another function, such as a school or day-care centre for example, for at least the next 50 years. In this way, this circular, low-impact building not only uses natural, non-hazardous recyclable materials, but can also be moved, reused, and adapted as needed.

The circular strategies are implemented in all phases of the building's life-cycle:

1. Design Phase

- Natural Material Utilization: The design incorporated whole, untrimmed tree trunks as load-bearing columns, minimizing processing and preserving the natural aesthetics of the timber.Nordic Publishing
- Modular Design: The building was conceived with modular components to allow for easy disassembly, relocation, and reassembly, aligning with circular construction principles.
- Multi-Functionality: Pikku-Finlandia was designed to accommodate various functions, including events, exhibitions, and gatherings, enhancing its utility and lifespan.

2. Construction Phase

- Efficient Assembly: The use of prefabricated timber elements facilitated a swift and efficient construction process, reducing on-site waste and labor.
- Minimal Environmental Impact: The construction process emphasized low-impact methods, utilizing sustainable materials and techniques to minimize the building's ecological footprint.

3. Operational Phase

- Temporary Venue: Pikku-Finlandia served as a temporary events venue during the Finlandia Hall's renovation, hosting various cultural and public events.
- Public Engagement: The building's unique design and sustainable construction attracted public interest, raising awareness about circular construction practices.

4. Deconstruction Phase

- Planned Disassembly: Upon completion of its temporary function, Pikku-Finlandia was designed to be disassembled efficiently, with components preserved for reuse.
- Relocation and Reuse: The building is intended to be relocated and repurposed, potentially serving as a school or daycare center, thereby extending its lifecycle and utility.

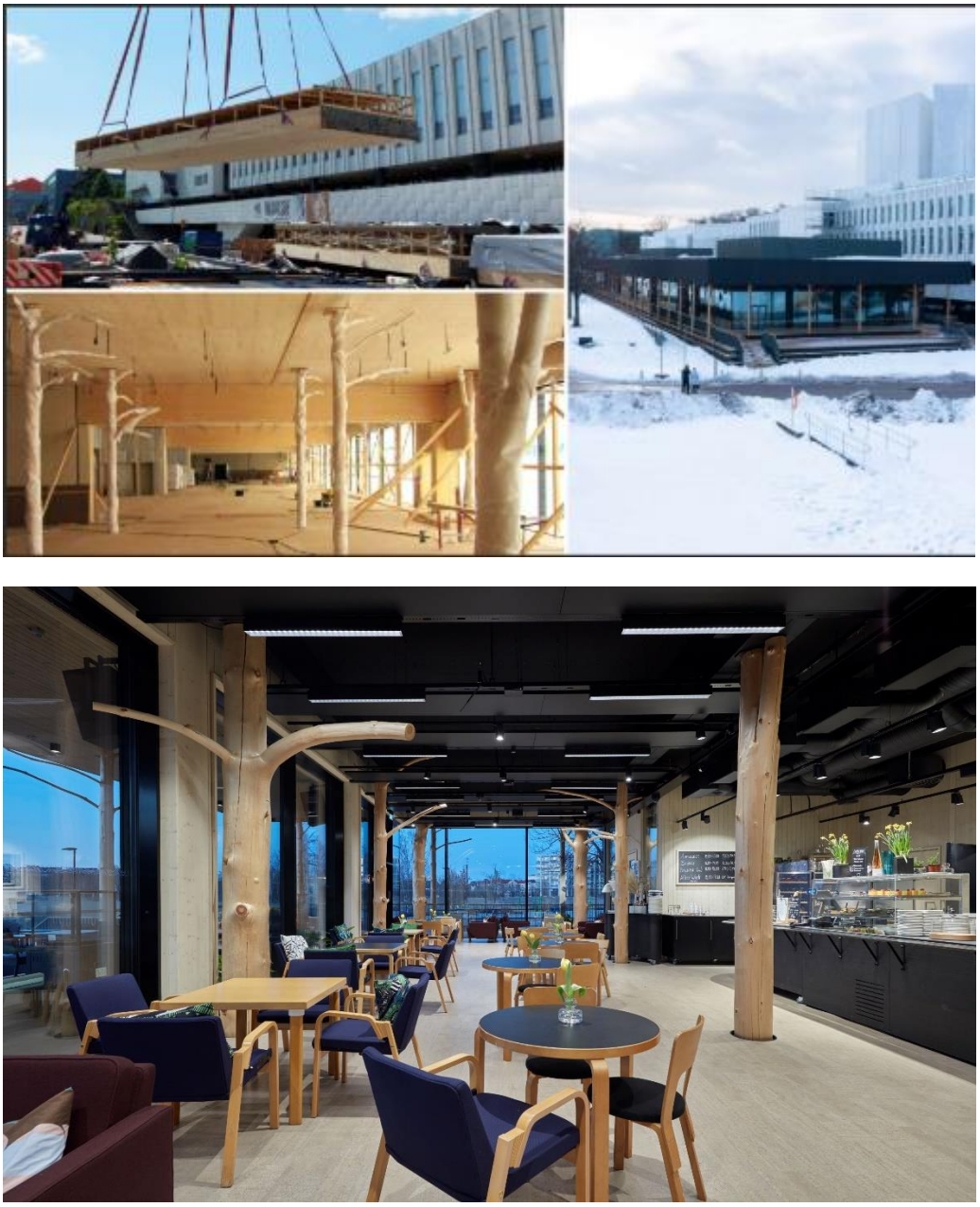


Figure 9. Circular building Pikku-Finlandia (Little Finlandia) in Helsinki, Finland

Pikku-Finlandia exemplifies how buildings can be designed from the outset for easy disassembly and relocation, promoting material reuse and reducing waste. The use of whole tree trunks and natural materials underscores the potential of timber in sustainable construction. The building's modular design and multifunctionality demonstrate how structures can adapt to different uses over time, aligning with circular economy principles.

Pikku-Finlandia serves as a model for circular timber construction, showcasing how thoughtful design and sustainable practices can create buildings that are not only functional and aesthetically pleasing but also environmentally responsible.

6. CONCLUSION

The environmental footprint of buildings and infrastructure is vast but not irreversible. By rethinking how we design, construct, and manage our built environment, we can significantly reduce these impacts. The transition to sustainable, circular, and low-impact construction and urban development is critical to achieving global climate and biodiversity goals.

The circular economy offers numerous benefits that make it an attractive solution for promoting sustainability and reducing waste. These benefits include environmental sustainability, economic opportunities, and social benefits. By adopting circular practices, stakeholders can minimise the environmental impact of production and consumption, stimulate innovation and economic growth, create job opportunities, improve resource access and affordability, and enhance community resilience [10].

One of the significant environmental benefits of implementing circular economy principles is that it can lead to a reduction in greenhouse gas emissions. By promoting the reuse of existing products and materials, the circular economy can curtail the need for extracting natural resources, reducing the associated carbon footprint. Additionally, by minimizing the use of virgin materials, the circular economy can help conserve natural resources and protect vital ecosystems such as soil, air, and water bodies. Moreover, circular practices and processes can lead to significant energy savings by reducing the need for resource extraction, manufacturing, and transportation of new products.

Another environmental benefit of the circular economy is that it can help to limit waste generation and reduce pollution. Circular economy practices such as recycling and remanufacturing can divert waste from landfills and incineration, thus promoting resource efficiency. This, in turn, can help protect ecosystems, limit biodiversity loss, reduce landscape and habitat disruption, and contribute to the global effort to combat climate change [10].

By adopting these principles, the circular economy can create a sustainable economic system that meets the needs of current and future generations while minimizing its environmental impact.

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