Chapter 4
Circular Manufacturing

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Abstract Circular Manufacturing (CM), understood as CE strategies adopted in manufacturing, takes a key position in decoupling industry growth from environmental impacts. To achieve a transition into circular economy in construction, a clear view on the state-of-the art is crucial. Construction materials such as concrete, cross-laminated timber or steel have an environmental impact during their production and circularity is not always given. Knowing that the design phase of a product defines a big part of its overall environmental footprint, this chapter discusses CM principles and most commonly pursued CM strategies for steel, concrete and timber. Effects and impacts on buildings and eventual challenges are discussed. Furthermore, Additive Manufacturing (AM), as a possible key driver of circularity is analysed. The

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reduction of material use is identified as key driver in order to reduce material flows, however structural safety and durability needs to be assured. The design and mixture of construction products and materials itself together with an efficient design process in the projects are essential pillars of CM. Prefabrication, modular construction as well as DfD and DfA are key principles that can be achieved with all the analysed construction materials but are more widespread in steel construction today.

Keywords Circular manufacturing · Construction materials · Additive manufacturing · Reduce · Reuse · Recycling

4.1 Definition and Principles

The past century has witnessed an alarming trend within industry: unbridled resource consumption coupled with a steep rise in CO_2 emissions. The negative impacts of resource depletion and the emission of greenhouse gases are obvious and numerous and could lead to planet collapse [1]. As described in the OECD, the scarcity of resources will exacerbate, while the consumption of those will double to 167 gigatonnes in 2060 [2]. Decoupling industry growth from environmental impacts is a major challenge and one of the key pillars to achieve the climate goals set in the EU Green Deal. Adopting CE principles in manufacturing represents an opportunity for industry stakeholders to reduce material consumption as well as resource toxicity, while maintaining and pursuing their business activities.

The implementation of CE concepts, which aim to minimise the use of (primary) resources, energy, and waste flows, hence narrowing down and closing material loops, is strongly encouraged by policy makers. In the EU, the recently updated Circular Economy Action Plan (CEAP) underlines the importance of this concept and the will to transition towards a regenerative growth model. The design phase holds critical influence over a product's environmental impact, with studies suggesting up to 80% of its detrimental footprint being determined at this stage (not specific for construction products). This emphasises the importance of the participation of the manufacturer in circular economy concepts [3]. When the CE philosophy is adopted in the manufacturing sector, it transforms into Circular Manufacturing (CM), highlighting the specific strategies and practices employed in production to minimise waste and maximise resource reuse. Acerbi and Taisch define CM as follows [4]: *"The concurrent adoption of different CM strategies, which enable to reduce resources consumption, to extend resources lifecycles and to close the resources loops, by relying on manufacturers' internal and external activities that are shaped to meet stakeholders' needs"*.

Circular manufacturing in construction refers to an approach that aims to minimise waste, reduce resource consumption, and increase the lifespan of construction materials and products through a circular economy model. This approach builds on the broader framework of the circular economy, which emphasises the elimination of waste by extending the lifespan of products and materials and keeping them in use for as long as possible.

Table 4.1 summarises circular manufacturing principles been adopted in construction and described in further detail in the text below (non-exhaustive list).

To drive the manufacturing sector's transition towards a circular economy, numerous strategies can be implemented, including circular design, disassembly, remanufacture, reuse, recycle, servitisation (manufacturing firms offering innovative services alongside their products), cleaner production, industrial symbiosis, resource efficiency, waste management, reverse logistics, and closed-loop supply chain.

Design for Recycling and Reuse: Sustainable construction practices prioritise designing and manufacturing materials and products with their end-of-life in mind (Fig. 4.1). This entails ensuring easy disassembly of components and facilitating their recycling or repurposing for other projects, thereby minimising the demand for virgin raw materials.

Moreover, the key sustainable construction principle for reducing the quantity of new materials used in the industry is to build less. This is most easily achieved by reusing existing building stock. Existing buildings have the potential to be refurbished by retaining existing building elements and improving them to suit future uses. If we have to build new buildings, we must consider how many of the materials can be from reused products, components or buildings. For example, where there are buildings being demolished on site or locally, materials can be sourced from these buildings, refurbished, and then used in the new building. Alternatively, a national circular economy should be developed to enable the sharing of good quality reused products.

Many structural elements, such as steel beams or concrete prefabricated floor slabs, have a life expectancy which far outlasts a building's lifespan. By knowing these products are going to waste through the demolition of existing buildings, designers can incorporate these components into their design from the outset, using fewer new natural resources and raw materials. Instead of breaking components into smaller pieces and recycling the individual materials, reusing a component in its primary form has a higher value for sustainable construction. It results in fewer

Table 4.1 Circular manufacturing principles in construction

1. Design for Reuse and Recycling Design with the EoL in mind	**5. Long-Term Building Planning** Lifespan of structures, Design for Adaptability (DfA)
2. Material Selection Choosing the right material	**6. Digital Technologies** 3D printing
3. Prefabrication and Modular Construction Reversible construction, Design for Deconstruction (DfD)	**7. Resource efficiency in manufacturing stage** Efficient use of raw materials
4. Resource Recovery and Recycling Salvage of materials, DfD	

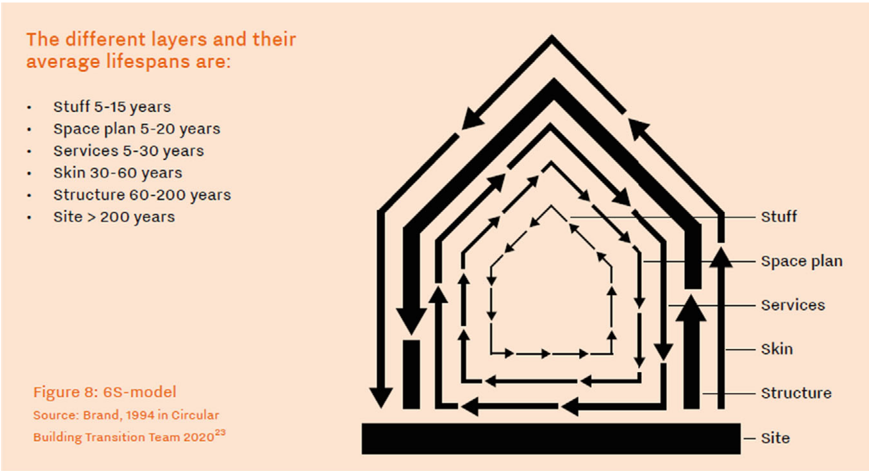

Fig. 4.1 Average lifespan of building layers [5]

modifications, and less manufacturing and construction. This uses fewer materials, less energy and minimises environmental impacts. The value of the item is retained with the potential to reuse it again in the future, thus enabling circular principles to continue in the future.

Material Selection: Choosing sustainable, renewable, and low-impact materials plays a vital role in circular manufacturing. Materials that are durable, easily repairable, and recyclable are preferred over those with limited lifespan and high environmental impact. Prioritise low-maintenance materials throughout the entire building to ensure long-term structural integrity and facilitate future reuse or recycling of valuable components. Implement distinct material strategies for each building layer, considering their individual lifespans (see Fig. 4.2).

Prefabrication and Modular Construction: Prefabricated and modular construction methods can enhance circular manufacturing by enabling easier disassembly and reassembly of building components, allowing for faster construction, and reducing waste during the building process. The design should accommodate reversible connections.

Resource Recovery and Recycling: Construction sites can integrate waste sorting and recycling processes to ensure that materials are recovered and reused whenever possible. This includes salvaging materials from deconstructed buildings and using recycled materials in new construction. Additionally, the use of recycled materials must be maximised without compromising the technical performance of the material. This can be achieved through innovative and efficient design solutions that minimise waste. The growing commercial interest in waste signifies a paradigm shift: waste is no longer solely viewed as a burden, but increasingly regarded as a potential "co-product" with considerable implications for environmental impact assessment. This

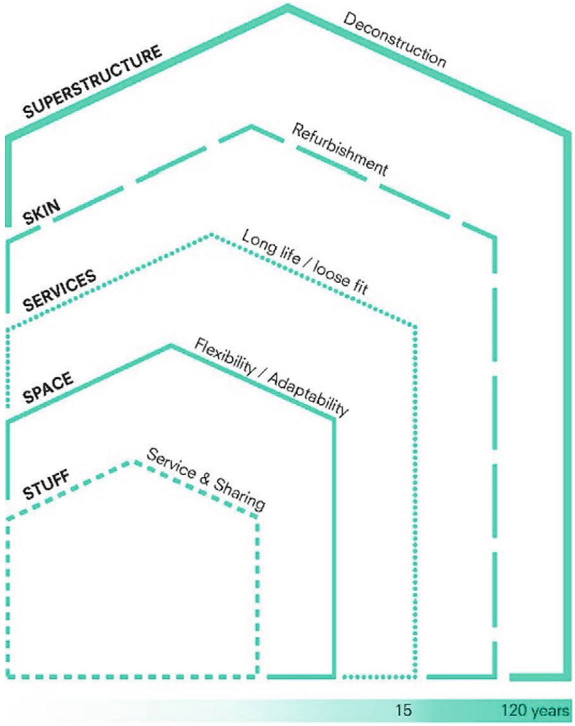

Fig. 4.2 Strategy needs to fit to the life expectancy of the layer [6]

is evident in the cement and concrete industry, where companies actively explore waste-based alternatives, such as industrial by-products, to replace Portland cement, with the aim of decreasing the environmental footprint of construction materials.

Long-Term Building Planning: Circular manufacturing also involves considering the long-term use and adaptability of structures. Designing buildings that can be easily modified or repurposed for different uses increases their lifespan and reduces the need for new construction. Sustainable construction extends the lifespan of buildings by prioritising flexible and adaptable design. This means considering potential future uses and designing features that can easily accommodate them, thereby minimising future material consumption and construction waste.

Digital Technologies: Building Information Modelling (BIM) and other digital technologies unlock a new era of construction efficiency. By streamlining processes, facilitating precise material tracking, and enabling optimised resource allocation, these advances contribute to a sustainable and cost-effective building environment. Integrating digital design tools into a sustainable construction strategy facilitates the precise calculation of material quantities, including the individual screws and bolts needed for a building. This meticulous approach minimises material ordering, resulting in reduced waste and a more environmentally responsible construction process.

By assigning each material in a building a digital "passport" containing its environmental and technical specifications, decision-makers can select materials based on their environmental impact. This transparency extends beyond construction, as material passports facilitate accurate identification and responsible reuse or disposal at the building's end-of-life, promoting a circular economy and minimising waste. 3D printing enables the manufacture of building components with precise, customised shapes, eliminating the need for excess material and reducing waste generation. Virtual Reality (VR) technology offers the ability to generate immersive replicas of buildings and spaces, allowing clients and users to virtually experience them before construction begins. This immersive experience facilitates informed decision-making and enables design modifications prior to physical construction, thereby minimising costly and resource-intensive post-completion changes.

Resource efficiency in the manufacturing stage: efficient use of raw materials and energy for the production of construction materials (e.g. cement, steel) is a main pillar of circular manufacturing. Circular manufacturing in construction has the potential to contribute to environmental sustainability, reduce the carbon footprint, and foster the development of a built environment characterised by enhanced resilience and resource efficiency. However, its successful implementation requires collaboration among all stakeholders, including designers, contractors, suppliers, and policymakers, to address challenges such as standardisation, regulation, and industry-wide adoption.

4.2 Steel

The most relevant CM strategies for steel in construction are presented in Table 4.2.

Steel is widely used in construction and infrastructure, as load bearing elements, façades or foundations. Due to its inherent properties, several CE strategies can be easily applied on steel elements in the built environment such as circular design, reduce, remanufacture, reuse, recycle, servitisation, industrial symbiosis, just to name some of them. In a first step, the use of material should always be avoided. If this is not possible, the use of materials should be reduced.

The reduction of material use is relevant mainly in the following stages of a steel element: 1. Design phase of product 2. Design phase of project. Resource efficiency

Table 4.2 CM strategies for steel

Steel	
1. **Reduction of material use** On product by project basis, DfA	3. **Recycling** Scrap-based steel production
2. **Reuse** Circular design and traceability, DfD	4. **Industrial symbiosis and efficient waste treatment**

for steel elements starts with efficient design of products. They should be designed to be lightweight and long-lasting, while still meeting the same structural and safety requirements. Over the last decades steel products were continuously improved and further developed. In general, high strength steel grades allow the choice of lighter sections, when talking about structural elements. The choice of lighter sections by designers results 1:1 in a reduction of required steel production, reducing the need for virgin raw materials and minimising greenhouse gas emissions during construction and operation. Hence, designers wield significant influence during the project's initial phase, as the decisions made then heavily impact its success and sustainability. Choosing the right solutions and implementing them efficiently are therefore critical for a positive outcome. Steel elements are prefabricated, hence allow a fast installation on the construction site. Further, steel elements can be designed to be modular and easy to dismantle. Design for Adaptability (DfA) represents a core strategy within the CE framework that allows to keep building stock longer in use, hence reduce the use of new raw materials. It has to be underlined that steel structures offer opportunities to follow this strategy, due to possibility of long spans and related opportunities on modularity.

Reuse, to extend the lifecycle of a product, is closely linked to circular design. Circular design strategy is one of the game changers in the construction industry, as the decisions in the Beginning-of-Life (BoL) of a product, influence the environmental impacts during the lifecycle and in the End-of-Life (EoL). To promote circular design in construction, manufacturers need to focus on product functionalities and features, efficiency, reuse possibility as well as durability and modularity. Availability of information and traceability of the products is crucial. Most of steel elements can be disassembled from the existing structures after their service life. In general, disassembly is straightforward when mechanical connections are used. (Read more about reuse of salvaged steel elements in chapter 5). Only if CE principles, especially circular design, are considered already in the manufacturing stage, a shift to CE in the construction industry is possible. Again, the design phase of a steel product, as well as the design phase of a project are relevant. Besides product specifications, the management at the end of life of these products needs to be considered. According to Acerbi et al., one of the main barriers for circular design in the construction sector are agency and ownership issues in the End-of-Life of materials [1].

Recycling of a construction material becomes relevant at its EoL. Strategies like reuse or remanufacturing should be chosen first, as they represent a higher level of circularity. Steel is infinitely recyclable and can be recycled to 100%. Besides reuse, recycling is the most adopted CE strategy for steel. The European Steel Association conducted a survey in 2012 that quantified the steel recovery rate from representative building demolition projects. The average recycling rate for steel across all products, was found to be 92% [7]. Taking all steel products into account, also those products that are not used in construction, a recycling rate of 85% is realised [8]. These numbers show that the recycling chain for steel is well established. The magnetic properties of steel allow an easy separation from other construction materials during the demolition or dismantling stage. Every steel plant that produces steel, is a recycling plant for End-of-Life steel. Two main production routes are currently used in steel production. The first one is the mainly iron-ore based production in a two-stage process—Blast Furnace/Basic Oxygen Furnace (BF/BOF). In the blast furnace, iron ore is turned into iron. In the second stage, iron is turned into steel. The second route is a scrap-based production in an Electric Arc Furnace (EAF). The iron-ore based steel production, called the primary route, relies on iron ore, coke (coal), limestone and up to 30% scrap input. Scrap-based steel production, called secondary production, uses up to 100% of scrap [9]. Scrap plays a major role in circular steel manufacturing, while each tonne of scrap used avoids 1.5 tons of CO_2 emissions, but also conserves critical resources such as iron ore (1.4 tonnes), coal (740 kg), and limestone (120 kg). End-of-Life scrap is a limited resource. Knowing that the average lifetime of a steel product is around 40 years, the End-of-Life scrap that is available today as a resource for new production, was produced around 40 years ago. Scrap availability will further increase in the next decades; hence double from around 450 Mt in 2023 to 900 Mt in 2050. In order to achieve complete circular manufacturing in steel, scrap recycling needs to be maximised, however due to limitations in scrap availability and a rising steel demand, a primary steel production will be needed until 2100 according to today's forecasts. Steel production over the (primary) Blast Furnace route currently accounts for 71% of the global steel production, which is mainly led by Chinese production. In Europe, 56% of the crude steel production is based on the primary route, which means that 44% is produced on the secondary route [8, 10].

Industrial symbiosis and efficient waste treatment are strategies that are closely linked to the recycling strategy in CE. Besides maximising scrap use in the steel production, there are also other ways to reduce environmental impacts of the primary production route and increase the circularity: (1) Biomass to replace fossil coal, (2) Direct reduced iron, (3) Use of renewable energy, (4) Carbon capture and usage, (5) Use of by-products. Steel manufacturers in Europe are currently undergoing a fundamental change by replacing Blast Furnaces into Direct Reduced Iron plants, in order to meet the targets, set by the Paris Agreement and the EU Green Deal. This cuts the GHG emissions by around 50% per ton of steel, while still meeting the steel demand. Direct Reduced Iron is a viable and already existing technology, that is used on industrial scale. Currently the iron ore is reduced with natural gas. In the future, this could be done with hydrogen, leading to a chemical reaction that only emits water as by-product, besides the iron. H2 Green Steel, in Boden, Sweden, are erecting a new primary iron ore plant powered by hydrogen, which eliminates the need for coke and hence eliminates greenhouse gas emissions for the primary generation of iron. This is highly reliant upon the large hydroelectric schemes nearby to make this viable. In a DRI plant in Germany, the switch to using hydrogen instead of natural gas in the iron ore reduction process is being prepared [11]. But also, the Blast Furnace route itself can become more efficient. Some manufacturers have launched promising pilot projects, that demonstrate the use of biomass, to replace fossil coal in the Blast Furnaces in an industrial scale. The biomass consists of waste wood and waste plastic. The EU Horizon 2020 funded project, 'Torero', also deals with carbon capture and usage. Hence, carbon monoxide from the Blast Furnace's exhaust fumes can be captured directly in the plant and microbially fermented to bioethanol, that can be used in gasoline or chemical industry. This allows material and energy loops to be closed to a large degree. This project allows the creation of a value chain of waste wood, which has currently no attractive applications [12].

During the steel making process, several co-products are generated. The BF/BOF route generates around 400 kg of solid co-products, whereas the EAF route produces only 200 kg. The main solid co-products are slag (90%), dust and sludge. These materials are considered as by-products, not as waste since they have an economical value and are used in other industries. Slag, for instance, is a welcomed resource in road construction and in cement industry, where it is used as roadstone or clinker replacement. The efficient use of steel co-products, in e.g. cement, road construction, metallurgical use, fertiliser and other areas, leads to an overall material efficiency in the steel industry of 97.5%. Furthermore, the use of slag in cement has an environmental value since it can reduce the embodied carbon of concrete up to 59%. Besides solid co-products, process gases from coke ovens and BFs and BOFs can be exploited. They are generally used to produce steam and to fuel reheating furnaces after they are cleaned. Process gases are also used as reducing agents in the BF. The exceeding heat of reheating furnaces, for instance, can be used for heat supply of entire districts. Obviously, using co-products from steel industry contributes to circular economy [10].

4.3 Concrete

The most relevant CM strategies for concrete in construction are presented in Table 4.3.

Concrete acts as both a composite material and a structural element, depending on the lifecycle stage. Its individual components, like cement and aggregates, can also be viewed as distinct products or integral parts of the concrete itself. In terms of Circular Economy strategies, two levels are identified [13].

Material-scale. The diverse material scales involved in concrete (angstroms to meters) and its chemically distinct components—aggregates and binders—restrict

Table 4.3 CM strategies for concrete

Concrete	
1. **Reduction of material use** On material and product scale	4. **Recycling** Downcycling–Crushing concrete
2. **Increasing longevity** DfA	5. **Resource efficiency in manufacturing** Biofuels, Supplementary cementitious materials
3. **Reuse and remanufacturing** DfD	

the feasibility of complete recycling. Consequently, it is typically reprocessed as components in new concrete or other products, limiting the ability to recapture its original material state. Concrete has remarkable versatility due to its ability to incorporate a wide range of materials such as aggregates, extending its functionality and performance. Few examples are the inclusion of fibre-reinforced polymers, rubber [14] or mixed plastic waste [15]. Although incorporating downcycled materials offers potential benefits both for the life cycle of the material and the specific properties of concrete, questions remain regarding their impact on future reuse or recycling options. However, the effectiveness of these materials in fulfilling their engineering function within the infrastructure is evident.

Product-scale. Where structural elements and whole buildings are considered, the remarkable tensile strength advantage of reinforced concrete over its unreinforced counterpart (which in design is assumed to be zero) becomes evident. This superior characteristic allows for its application in demanding structural components like beams and columns, solidifying its value and desirability for reuse compared to its unreinforced counterpart. Despite its superior strength and value for reuse, reinforced concrete constitutes a minority within the global concrete landscape. Estimations suggest that only 25% of globally produced cement ends up in reinforced concrete, highlighting the potential for expanding its utilization for more sustainable construction practices [16]. While reinforced concrete provides superior functionality, the incorporation of steel reinforcement creates new vulnerabilities that can impact its longevity. Specifically, exposure to atmospheric CO_2 and chlorides from de-icing salts or seawater can trigger corrosion of the steel, potentially compromising the structural integrity of the concrete. Concrete's interaction with the environment triggers degradation mechanisms that reduce its load-bearing capacity and lifespan, significantly impacting its performance and ultimately leading to costly repairs or replacements. These detrimental effects depend on the specific concrete mix and its exposure environment. Notably, the economic burden of steel corrosion in reinforced concrete is substantial, representing roughly 4% of GDP in industrialised nations [17]. The inherent differences in value and physical longevity between reinforced and unreinforced concrete significantly impact the effectiveness of various reuse and recycling strategies. This necessitates a nuanced approach considering these distinct characteristics to optimise resource recovery and minimise waste.

Circular Economy approaches for concrete encompass various strategies targets: minimising resource consumption through material reduction, designing for durability and resilience, extending lifespan through proper maintenance and repair, maximising value through reuse, and ultimately recovering resources via remanufacturing and recycling.

Reduction of material use in concrete construction starts with minimising material used in the design stage. This multi-pronged approach focuses on: (1) Structural optimisation—product scale (reducing the overall volume of concrete needed in structures while maintaining safety and functionality), (2) Material optimisation—material scale (lowering the amount of cement per cubic metre of concrete through innovative mix alternative materials), (3) Clinker optimisation—material scale (using alternative sources or minimising the clinker content within the cement itself, aiming at a smaller environmental footprint).

Increasing longevity represents another design-stage strategy within the Circular Economy for concrete. While the immediate reduction in the in-use concrete volume might be modest, the long-term benefits are substantial. Extending the lifespan of structures translates to reduced material flows and waste generation over time, consequently minimising environmental impact. Design for Adaptability (DfA) promotes a product-scale approach that prioritises designing products with inherent flexibility, enabling them to adjust to evolving needs and circumstances [18]. The principles of DfA extend beyond products and can also be effectively applied to infrastructure projects [19]. In-service strategies like maintenance, repair, and refurbishment play an important role in slowing resource flows, by extending the technical lifetime of products and components. However, these efforts must constantly evolve to 'keep up' with upstream innovations in the concrete lifecycle, such as the development of low-carbon novel concretes that require specific protective measures.

Reuse and remanufacturing constitute complementary end-of-use strategies that focus on slowing resource flows by extracting and re-integrating functional components from decommissioned concrete products into new applications, thereby minimising reliance on virgin materials. Reuse is defined as the act using again a component or product in its original or a similar function, potentially requiring preparatory steps such as inspection, cleaning, or repair [20]. In the context of concrete structures, a discrete concrete structural component can be considered a product offering. Refurbishment entails a meticulously documented process of disassembling a product offering into its constituent parts. These parts are then meticulously inspected, cleaned, repaired or replaced as necessary, and subsequently reassembled into the original product offering, while delivering an equivalent or enhanced warranty pertaining to the product's functionality [21]. Within the construction industry, a structure can be viewed as a complete product, comprised of numerous component parts, encompassing (but not restricted to) structural elements. Remanufacturing and refurbishment, while sharing similarities, represent distinct approaches to extending the functional lifespan of structures. Refurbishment focuses on replacing individual, end-of-life components within an existing structure to prolong its overall operational life. In contrast, remanufacturing involves the disassembly of a structure at its end-of-life, with the utilisation of still-functional components to construct a new structure entirely. Both methodologies align with the principles of Design for Disassembly (DfD). Within this framework, disassembly signifies the strategic removal of structural components with the intended purpose of their subsequent utilization in different structures.

Recycling constitutes an end-of-use strategy aimed at closing resource loops. This strategy entails the reprocessing of materials for integration into the creation of new products, thereby circumventing both waste generation and the extraction of virgin resources. In the context of concrete, recycling ranks as the second most prevalent Circular Economy strategy utilised. The typical recycling process for demolished concrete structures entails the fragmentation of the material at its end-of-use stage. This coarse aggregate is subsequently employed as a substitute for natural aggregate in the creation of new concrete. This method falls under the classification of downcycling, indicating that the recycled aggregate exhibits diminished value and functionality relative to the original concrete. Not all downcycling is equal. "Recycled concrete aggregate" boasts higher quality and finds application in structural concrete, while the more prevalent "recycled aggregate" exhibits lower quality and is typically confined to road sub-base construction [22].

Resource efficiency in manufacturing is key pillar in reducing the environmental impact in the cement industry: (1) the focus on improving the energy efficiency of cement plants primarily emphasizes optimising the thermal performance of their kilns; (2) substituting/decreasing the use of conventional fuels (coal and/or petcoke) in cement kilns with biofuels and other alternative fuels, (3) optimising the clinker-to-cement ratio through the strategic replacement of clinker with alternative materials or supplementary cementitious materials (SCMs), respectively reducing the clinker content of cement; (4) carbon capture, utilisation, and storage [23].

Currently, most cementitious binders in production already incorporate a small quantity of SCMs. In fact, the estimated global clinker factor was 0.77, indicating that out of the total 4200 million tonnes of cement produced in 2015, at least 800 million tonnes of SCMs were utilised [24]. Integrating alternative materials and lowering the clinker-to-cement ratio in cement production yields reductions in both emissions and energy consumption. Exploring the utilisation of waste products from various industries as alternative raw materials in construction presents an intriguing eco-friendly option and is widely used in the cement industry. Materials such as ground blast furnace slag (GBFS) from pig-iron/steel production process, coal fly ash (FA) from coal fired industries, natural pozzolanas (silica fume, rice husk ash) have proven to be effective in substantially reducing CO_2 emissions per tonne of cementitious materials. While GBFS and FA are the most widely used Supplementary Cementitious Materials (SCMs), their availability is projected to be limited. Currently, these materials account for only 17% of the global supply compared to current cement production. This supply is expected to decline to a mere 7% by 2050, driven by increased steel recycling and a shift away from coal usage. The restricted availability of established supplemental cementitious materials, such as slag and fly ash, in conjunction with the emerging potential for enhanced clinker substitution facilitated by calcined clay and limestone blends, is transforming the cement production landscape. A ternary blend (limestone-calcined clay cement, LC3) offers higher levels of substitution due to the synergistic effects among clays, limestone, and clinker. Clay, a widely abundant resource globally, serves as the primary raw material for LC3 production, alongside clinker. Clays with a substantial presence of kaolinite, a critical factor in determining clay quality for cement applications, have demonstrated exceptional pozzolanic properties when subjected to calcination within the temperature range of 700 to 850 °C [25]. Additionally, to address the increasing demand for cement and consequently concrete, considering the constraints on the availability of high-quality SCMs, research is now directed toward exploring alternative possible wastes as SCMs from the other industries such as red mud, incinerated sewage sludge ash, municipal solid waste (MSW) ash, wood biomass ash, construction and demolition waste powder and others. Currently most of these wastes are landfilled due to lacking technical solutions, symbiotic value chains, and coverage by the EU regulations. One of the critical aspects of using new waste materials in the cement production are standardisation and compatibility with the cement production process related specifically on maintaining consistent cement quality and performance. Establishing standards and guidelines will help to ensure the safe, reliable, and environmentally responsible incorporation of waste-derived materials into the cement manufacturing process. One of good example of activating value chain and foster industry-urban symbiosis is AshCycle project focused on use underutilised incinerated ashes as secondary raw materials in the construction and wastewater treatment sectors trough developing of technical guidance, requirements and specifications.

An alternative to traditional cement is the use of alkali-activated materials (AAM). Alkali-activated materials (AAMs) constitute a category of binding agents produced via the chemical interaction between an alkali metal activator and a solid silicate precursor [26]. The solid precursor can consist of materials rich in calcium silicate or aluminosilicate, including natural pozzolan, bottom ash, fly ash, or metallurgical slag. Activators are soluble substances that provide alkali metal cations, elevate the mixture's pH, and expedite the dissolution of the solid precursor. Despite significant potential, the global commercial adoption of these materials remains negligible compared to established alternatives [16]. Researchers are currently directing their attention toward innovative alternatives as precursor materials, including ferronickel slag, electric arc furnace slag, red mud, and calcined clay.

4.4 Timber

The most relevant CM strategies for timber in construction are presented in Table 4.4.

Although timber constructions offer significant potential to promote sustainable building practices, achieving a fully closed material cycle with negligible emissions remains a challenge. Although the inherent characteristics of timber enable partial carbon sequestration during growth and facilitate recycling, various aspects of the process, such as forestry practices, transportation, and processing, require further optimisation to fully realise the material's sustainability potential. As approximately half the dry weight of timber is composed of carbon and one kilogram of carbon is

Table 4.4 CM strategies for timber

Timber	
1. **Reduction of material use** Optimise building structures	3. **Recycling** To a small amount
2. **Reuse and remanufacturing**	

equivalent to 3.6 kg of CO_2, each kilogram of dry timber stores roughly 1.8 kg of CO_2. Despite its carbon storage potential, timber is a finite resource, and significant amounts of processed wood currently end up as fuel, releasing its stored carbon back into the atmosphere. Furthermore, at the end of its life cycle, through combustion or natural decay, timber releases its stored CO_2, limiting its positive long-term impact on climate change. To increase the volume of timber and wood-engineered construction, strategies should focus on maximising material efficiency and raw material utilisation through: (1) optimising structural design for material efficiency, (2) integrating secondary wood streams into construction components, and (3) establishing a circular economy framework that promotes the extended service life of timber products [27].

Despite the potential for circularity, timber *recycling* and closed-loop material use remain marginal practices. Most of the timber is still used for energy production, effectively eliminating it from the construction cycle and negating its long-term carbon storage potential. Several European research projects investigated specific aspects of wood recycling such as "WoodCircus!–Underpinning the vital role of the forest-based sector in the Circular Bioeconomy", or "CaReWood"–Cascading Recovered Wood providing the wood satisfies the requirement of being free of contamination [28]. In the latter case, the research focused on true timber recycling, using used timber from demolition projects instead of simply "downcycling" it. This is particularly relevant given the significant amount of high-quality construction timber discarded during demolition. Across Europe, the construction sector generates 70.5 million tonnes of waste timber annually, yet only one-third undergoes recycling processes [29].

The circular economy draws inspiration from nature's cyclical processes, emphasising resource optimisation and the continued circulation of materials within closed loops. Often described as a holistic approach, it embraces the "reduce, reuse, recycle" mantra. By prioritising reuse and reintegration of materials into new products, the circular economy strives towards eliminating waste as a concept, recognising its inherent resource inefficiency. Polymers and other fossil-based materials demand a transition from linear to circular economic models. Preventing their disposal in landfills or conversion into fossil fuels during energy recovery is crucial. The rise of industrialisation coincides with a dramatic increase in CO_2 emissions, demonstrably contributing to global warming [30].

Reuse and Remanufacturing: throughout its lifecycle, timber acts as a natural carbon sink. During photosynthesis, trees capture atmospheric CO_2 and store it within their cellular components, primarily cellulose, hemicellulose, and lignin. Upon harvesting and subsequent combustion, stored carbon is released back into the atmosphere, completing the cycle [31]. Direct combustion for energy accounts for roughly half of the globally harvested wood, resulting in the immediate release of its stored carbon back into the atmosphere as CO_2 [32]. Diversifying the energy mix with renewable sources such as solar could reduce the reliance on fuelwood, thus reducing carbon emissions. However, the immediate reduction of the use of fuelwood in developing countries remains a complex challenge due to its critical role in providing energy access. The other half of global timber harvest enters the industrial sector, where it is processed into valuable engineered wood products widely used in building applications. Contemporary timber construction primarily utilizes adhesive-bonded elements like glue-laminated timber (glulam) and cross-laminated timber (CLT), with minimal use of untreated solid timber. Strand-based products, such as Oriented Strand Board (OSB) and Parallel Strand Lumber (PSL), offer additional options for ceiling elements and solid wall, albeit to a lesser extent. One example among currently available products is the "Magnum Board," a solid element crafted from glued OSB panels, manufactured by Swiss Krono [33].

Instead of dismantling and recycling timber components, the most sustainable approach prioritises the reuse of entire buildings or their components whenever possible. The optimal waste management strategy in timber construction revolves around maximising reuse, starting with the entire building and progressing to individual components only when necessary. At the material level, shredding and reassembling timber particles into new products instead of direct thermal conversion should be preferred.

Hassan et al. identified wood chips, sawdust and bark as primary sawmill side streams, comprising 38.3% of log input, with wood particles and sawdust constituting the most significant volume. In particular, processing hardwood logs, often less straight, is expected to further increase this percentage. Although wood particles have diverse applications in energy (pellets), construction (concrete additives, particleboard), and agriculture (fertilisers), most of the waste wood still goes directly to energy production [34]. While regulations like the Renewable Energy Act (EEG 2017) and RE2020 promote resource efficiency through "cascading use", current practices like those in the particleboard industry often result in downcycling, ultimately diminishing material value and hindering true circularity. Downcycling is the current norm, but no technology exists to break down particleboards into their constituent materials because of the use of thermoset adhesives, whose irreversible curing process effectively "locks" the materials together, preventing efficient separation into their original components. Current "cascading use" systems remain ineffective, failing to meaningfully increase timber's market share against competitors. Only a true recycling process, epitomised by the cradle-to-cradle approach, can achieve a truly wasteless, circular economy.

Regarding the environmental footprint, the cradle-to-gate concept measures a product's environmental impact from raw material extraction to factory output, excluding use and end-of-life stages where producer responsibility ceases. Looking beyond production to the full product lifecycle, from cradle-to-cradle, requires the development of innovative material design approaches. These approaches must integrate recycling considerations from the outset, alongside primary material development, to achieve true circularity.

4.5 Additive Manufacturing

Additive manufacturing (AM) is a CM strategy that can be applied on different construction materials; hence, it is treated separately. Table 4.5 presents the key characteristics of additive manufacturing as a CM strategy.

Although additive manufacturing promises to be a pivotal pillar of Industry 4.0, driving the circular economy and reducing carbon through minimal material waste, its adoption in construction remains below its potential compared to other industries [35]. Utilising data from CAD software or 3D scanners, additive manufacturing builds objects iteratively, one layer at a time. It is also known as 3D printing. AM minimises energy consumption and waste by using only the precise amount of material needed for a design, eliminating the need for subtractive processes and scrap material. This process can be used to create new products from recycled materials, reducing waste and saving resources, and offering substantial environmental benefits for the construction sector [36–38].

As outlined by Gibson, Rosen and Stucker, the foundational steps of additive manufacturing comprise [39]:

- 3D model generation via either computer-aided design (CAD) software or 3D scanning;
- conversion of the model into an executable format specific to the intended 3D printer, typically involving slicing into 2D sections;
- object construction by the AM machine (3D printer) through sequential deposition of material layers based on the pre-generated slices;
- removal and potential post-processing of the printed object.

The main 3D printing methods used in construction are:

Extrusion: This approach creates objects by adding material in sequential layers, using one or more nozzles depending on the specific technology (e.g., fused deposition modelling uses a single nozzle, while multi-jet modelling employs multiple) mounted on a robotic arm, gantry system, or crane. The material can be concrete, cement, wax, foam or polymer. This is the most common and versatile method, as it can be used in almost any environment, including construction sites, and for various applications [40]. As technical challenges, the balance between printability and buildability becomes a crucial aspect during printing, since instability during manufacturing can induce zones of weakness in the extruded material [35].

Table 4.5 Key characteristics of additive manufacturing as CM strategy

Circular manufacturing	
1. **Main 3D printing methods** Extrusion, Power Bonding, Additive Welding	3. **Potential reduction of material waste, energy consumption and transport costs**
2. **Materials** Concrete/cement, polymer, metal a.o	4. **Barriers to overcome** Costs, Size and Dimension limitations a.o

Powder Bonding: This method creates an object by selectively bonding together layers of powdered material using a binder, a laser, or a chemical reaction. The material can be polymer, metal or sand. This method can produce complex and detailed shapes but requires a controlled environment and post-processing [40].

Additive Welding: This method creates an object by depositing droplets of molten metal or wire using an electric arc or a laser. The material is usually steel or aluminium. This method can produce strong, durable structures, but it requires high temperatures and skilled operators [40].

Due to their inherent fresh and hardened properties, the vast number of readily available raw materials and the flexibility in mix design, cement-based materials offer unmatched adaptability, making them the most studied option for widespread use in additive construction. Printable cement-based materials typically blend common construction materials (sand, soil, clay, crushed stone, recycled aggregates, etc.) with binders (cement, polymers, fly ash) and workability agents/additives, but there are no standard protocols for assessing printable cement-based mixes, leading to challenges in formulation and performance optimisation [41]. Additive manufacturing (AM) could unlock substantial incentives for polymer recycling and reuse within a circular economy framework. By enabling the creation of new products from used or recycled materials, AM offers a closed-loop approach that minimises waste and maximises resource efficiency. Pellets, as an example of polymer reuse, can be used as a raw material in additive manufacturing. Pellets are small cylindrical pieces of plastic that can be melted down and used to create 3D printed parts [42].

Polymers offer an attractive option for AM in construction due to their combination of affordability and lightweight properties, enabling the cost-effective and potentially faster construction of lighter structures, while allowing storage in a controllable, deposit-ready state, unlike that of cement-based raw materials. AM of polymers has attracted significant interest across various sectors. However, widespread implementation as functional, load-bearing components remains limited. While research explores various polymeric materials such as elastomer, photosensitive resin, acrylonitrile–butadiene–styrene (ABS), nylon, and wax, the resulting AM products often function primarily as conceptual prototypes due to limitations in strength and overall performance compared to traditional manufacturing methods [41].

Thus far, there have been no demonstrations of the production of building components using solely lignocellulosic resources or wood-based products, without the inclusion of any mineral or plastic binders. In their study, Lamm et al. provide a comprehensive analysis of the present state of 3D printing using wood and lignocellulosic materials (such as lignin, wood particles, nanocellulose, and cork). The authors delve into the examination of filament-based printing technologies and granulate-based extrusion processes, particularly in the context of large-scale printing [43].

In wood-based FDM/FFF printing, there is a trade-off between wood content and printability/strength. Increasing the wood content beyond 30% becomes difficult to manage successfully with current technology. Rosenthal et al. achieved an impressive 89% wood content in small-scale specimens using liquid deposition modelling.

Their key innovation was a paste-like methylcellulose suspension with ground beech sawdust [43]. Launched in 2020, the TU Dresden's "Addwood–3D printing of furniture " project demonstrated the potential of timber-based 3D printing using a layered particle-resin approach (this technique-built elements by layering sprayed timber particles and adding resin, achieving qualities similar to particleboards). However, existing patents reveal that a fully bio-based solution for the construction industry remains elusive.

Recent publications indicate an absence of discourse surrounding metallic structures in the context of additive manufacturing applications for construction [35]. An all-encompassing adoption of additive manufacturing techniques for large-scale structure printing can be realized once the current size and resolution limitations are overcome. Below are some practical examples of the use of AM parts in construction: steel structures for pedestrian bridge construction—which are 3D printed; new 3D printed steel structural elements and connectors [45–48]; 3D printed multi-binding geopolymer composites—which are a type of cementitious material that can be reinforced with nano additives to improve mechanical properties; 3D printed concrete houses using robotic concrete printing; among others.

Despite a diverse array of AM processes available for architectural and construction applications, many remain restricted to creating objects from single, homogeneous materials, hindering the exploration of more complex and versatile structures [36]. Though in its early stages, multi-material AM in architecture and construction shows promise, necessitating discussions about its potential advantages and drawbacks to accelerate its development. A 2022 study by Pasco et al. [35] suggests that by 2025, AM could significantly improve manufacturing sustainability. Qualitative assessments predict a 5% reduction in key sustainability criteria such as production costs, energy consumption, and CO_2 emissions.

Additive manufacturing can support the circular economy in several ways, such as described in [46, 48–51]:

- reduce material waste by using only the amount of material needed to create an object and reusing or recycling excess material;
- reducing energy consumption by using less energy-intensive processes and optimising the design and performance of objects;
- reducing transport costs and emissions by producing objects closer to the point of use or demand and enabling distributed and decentralised production networks;
- extending the useful life of products by allowing repair, refurbishment, remanufacturing or customisation using additive manufacturing techniques;
- create new business opportunities and value propositions by offering on-demand, customised or innovative products and services using additive manufacturing capabilities.

Since 2015, the ISO/ASTM 52900 international standard has brought clarity and consistency to the terminology used in the AM and ASTM community. This standardisation helps to distinguish AM from traditional techniques such as casting, machining, rolling, forging, and extrusion. However, a radical change in licencing structures, patents, trademarks, and copyrights is also expected. Sustainability policies that focus on technology, work, and regulation also need to be created [35].

To truly realise the environmental benefits of AM in construction, a comprehensive life-cycle assessment (LCA) approach is essential. This involves meticulous analysis of the entire lifecycle of the structure, from manufacturing to end-of-life, alongside the AM process itself. This holistic perspective is crucial for paving the way towards a circular economy within AM construction [52–56]. According to MTC, the following are some of the challenges that AM faces in a sustainability context:

- develop a greater understanding of the AM lifecycle and collect its data;
- identify how Design for the Environment (DfE) approaches can be adapted to Design for AM (DfAM);
- maximize resource recovery through efficient material recycling;
- enhanced safeguards for intellectual property (IP) and better control over regulated products;
- investigate the potential challenges and unforeseen expenses inherent to MA, among others [50].

Also, important barriers need to be overcome in the construction sector, such as:

- additive manufacturing machines are expensive;
- metal additive manufacturing has its benefits in cost when you need 1 to 100 prototypes.
- customising parts is very costly;
- parts have size and dimension limitations;
- using them to create large batch sizes takes more time than traditional manufacturing;
- many additively manufactured objects require some post-processing to clean up and smooth edges, among other things;
- ensuring the final part has good properties. From a materials science perspective, this is probably the greatest challenge in additive manufacturing [57].

In recent years, numerous initiatives have emerged in the development of materials and processes, in addition to designing strategies and applications specifically optimised for additive manufacturing. Large-format 3D printing is gaining traction in construction, with new suppliers emerging and established companies developing innovative solutions. Panjonk et al. highlight the increasing involvement of established construction companies in 3D printing, indicating a promising future for this technology in real-world applications [58].

The achievement of sustainable AM construction practices requires a rigorous and well-defined framework that addresses all key aspects. Continuous and consistent material delivery through optimised mixer and pump settings is paramount for uninterrupted printing and robust interlayer adhesion. This necessitates the precise selection of compatible material types and their specific formulations, including the appropriate incorporation of additives and compatibilizers (materials that allow two largely incompatible materials to mix together to form a new blend or alloy) for optimised interaction. To advance AM in construction, one need to focus on developing standardised performance criteria, material properties, methods to ensure strong layer adhesion and robust structural design approaches. The deployment of additive manufacturing (AM) as a leading technology within the circular economy (CE) model presents potential benefits including, but not limited to, shortened localized value chains and production costs, enhanced resource efficiency and environmental sustainability through the use of recycled materials, and reduced transportation-related emissions [41].

References

1. Acerbi F, Sassanelli C, Terzi S, Taisch M (2021) A systematic literature review on data and information required for circular manufacturing strategies adoption. Sustainability 13:2047. https://doi.org/10.3390/su13042047
2. OECD (2019) Global material resources outlook to 2060: economic drivers and environmental consequences, OECD Publishing, Paris. https://doi.org/10.1787/9789264307452-en
3. European Commission (2014) Directorate-general for energy, directorate-general for enterprise and industry. Ecodesign your future: how ecodesign can help the environment by making products smarter. European Commission. https://doi.org/10.2769/38512
4. Acerbi F, Taisch M (2020) A literature review on circular economy adoption in the manufacturing sector. J Cleaner Product 273:123086. ISSN 0959–6526, https://doi.org/10.1016/j.jclepro.2020.123086
5. Brand S (1994) How buildings learn: what happens after they are built? Penguin, New York
6. Brydenwood (2023) Value & reuse: sustainable construction and circular economy. https://www.brydenwood.com/sustainable-construction/s172998/
7. Sansom, M; Avery N (2014) Briefing: reuse and recycling rates of UK steel demolition arisings. Proc Inst Civil Engin Engin Sustain 167(ES3):89–94. https://doi.org/10.1680/ensu.13.00026.
8. Worldsteel (2021) Climate change and the production of iron and steel. Worldsteel Association. https://worldsteel.org/wp-content/uploads/Climate-change-and-the-production-of-iron-and-steel.pdf
9. Biljard R; Mulders P (2023) Steel, the perfect material for a sustainable, circular and re-usable economy. https://foundationreuse.com/wp-content/uploads/2023/06/Foundation-Reuse-Bijlard.pdf
10. Worldsteel (2021) Steel industry co-products. World Steel Association. https://worldsteel.org/wp-content/uploads/Fact-sheet-Steel-industry-co-products.pdf
11. ArcelorMittal (2021) Climate action report. https://corporate.arcelormittal.com/media/jv0jm0ok/car_2.pdf
12. Torero. Fueling a sustainable future. https://www.torero.eu/
13. Marsh A, Velenturf A, Bernal S (2022) Circular economy strategies for concrete: implementation and integration. J Cleaner Product. https://doi.org/10.1016/j.jclepro.2022.132486
14. Li X, Ling (Bill), Tung-Chai, Mo, KH (2020) Functions and impacts of plastic/rubber wastes as eco-friendly aggregate in concrete – a review. Construct Build Mater 240:117869
15. Saikia N, de Brito J (2012) Use of plastic waste as aggregate in cement mortar and concrete preparation: a review. Construct Build Mater 34:385–401. ISSN 0950–0618. https://doi.org/10.1016/j.conbuildmat.2012.02.066
16. Scrivener C, John V, Gartner E (2018) Eco-efficient cements: potential economically viable solutions for a low-CO_2 cement-based materials industry. Cement Concrete Res 114:2–26. https://doi.org/10.1016/j.cemconres.2018.03.015
17. Francois R, Laurens S, Deby F (2018) Steel corrosion in reinforced. Concrete. https://doi.org/10.1016/B978-1-78548-234-2.50001-9

18. Kasarda M, Terpenny J, Inman D, Precoda K, Jelesko J, Sahin A, Park J (2007) Design for adaptability (DFAD)—a new concept for achieving sustainable design. Robot Comput-Integrat Manufact 23:727–734. https://doi.org/10.1016/j.rcim.2007.02.004
19. Gilrein E, Carvalhaes T, Markolf S, Chester M, Allenby B, Garcia M (2019) Concepts and practices for transforming infrastructure from rigid to adaptable. Sustain Resilient Infrastruct 6:1–22. https://doi.org/10.1080/23789689.2019.1599608
20. den Hollander M, Bakker CA, Hultink E (2017) Product design in a circular economy: development of a typology of key concepts and terms: key concepts and terms for circular product design. J Ind Ecol 21:517–525. https://doi.org/10.1111/jiec.12610
21. Priyono A, Ijomah W, Bititci U (2016) Disassembly for remanufacturing: a systematic literature review, new model development and future research needs. J Indust Engin Manag 9:899. https://doi.org/10.3926/jiem.2053
22. Purnell P, Dunster A (2010). Recycling of concrete. https://doi.org/10.1533/9781845697662.5.569
23. IEA (2009) Cement technology roadmap 2009. https://iea.blob.core.windows.net/assets/897b7ad9-200a-4314-b870-394dc8e6861a/CementTechnologyRoadmap-CarbonEmissionsReductionsupto2050.pdf
24. Snellings R (2016) Assessing, understanding and unlocking supplementary cementitious materials. RILEM Tech Lett 1:50
25. Porikam Poil KR (2023) Development of high-performance concrete with lower ecological footprint, doctoral thesis. University of Zagreb Faculty of Civil Engineering
26. Rilem TCA (2014) Alcali activated materials. State-of-the-Art Report, RILEM TC 224-AAM. Springer
27. Mair C, Stern T (2017) Cascading utilisation of wood: a matter of circular economy? Curr Forestry Rep Bd 3. Nr 4:281–295. https://doi.org/10.1007/s40725-017-0067-y
28. Risse M, Richter K (2018) CaReWood – cascading recovered wood; Teilvorhaben: Ökologische und ökonomische Berwetung der kaskadischen Holznutzung, Technische Universität München, Lehrstuhl für Holzwissenschaft, https://www.ls.tum.de/fileadmin/w00bww/hfm/Bilder/Stoffstrom/20180130_abschlussbericht_carewood_wp6.pdf.
29. WoodCircus (2022) Underpinning the vital role of the forest-based sector in the Circular Bioeconomy. https://woodcircus.eu/
30. Ziska LH, Epstein PR, Schlesinger WH (2009) Rising CO_2, climate change, and public health: exploring the links to plant biology. Environ Health Perspect 117(2):155–158. https://doi.org/10.1289/ehp.11501
31. Geng A, Yang H, Chen J, Hong Y (2017) Review of carbon storage function of harvested wood products and the potential of wood substitution in greenhouse gas mitigation. Forest Policy Econ 85:192–200. https://doi.org/10.1016/j.forpol.2017.08.007
32. Ramage MH (2017) The wood from the trees: the use of timber in construction. Renew Sustain Energy Rev 68:333–359. https://doi.org/10.1016/j.rser.2016.09.107
33. SWISS KRONO for massive timber building (2023) https://www.swisskrono.com/global-en/products/building-materials/magnumboard-osb/#/
34. Hassan MdK, Villa A, Kuittinen S, Jänis J, Pappinen A (2019) An assessment of side-stream generation from Finnish forest industry. J Mater Cycles Waste Manag Bd 21, Nr 2, S 265–280. https://doi.org/10.1007/s10163-018-0787-5
35. Pasco J, Lei Z, Aranas C (2022) Additive manufacturing in off-site construction: review and future directions. Buildings 12:53. https://doi.org/10.3390/buildings12010053
36. Gardner L (2023) Metal additive manufacturing in structural engineering–review, advances, opportunities and outlook. Structures 47, 2178–2193. https://doi.org/10.1016/j.istruc.2022.12.039
37. Garg R (2023) Here's how to create a circular system for the built environment. Nov 2. https://www.weforum.org/agenda/authors/ritu-garg
38. Khan MA, Latheef A (2023) Metal additive manufacturing of alloy structures in architecture: a review on achievements and challenges. Mater Today Proc. https://doi.org/10.1016/j.matpr.2023.05.192

39. Gibson I, Rosen D, Stucker B (2015) Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing, 2nd edn. https://doi.org/10.1007/978-1-4939-2113-3
40. Baigarina A, Shehab E, Ali M (2023) Construction 3D printing: a critical review and future research directions. Progress Addit Manufact 8:1–29. https://doi.org/10.1007/s40964-023-00409-8
41. Ghaffar S, Corker J, Fan M (2018) Additive manufacturing technology and its implementation in construction as an eco-innovative solution. Autom Constr 93:1–11. https://doi.org/10.1016/j.autcon.2018.05.005
42. Mishra V, Negi S, Kar S (2023) Manufatura aditiva baseada em FDM de termoplásticos reciclados e compósitos associados. J Mater Cycles Waste Manag 25:758–784. https://doi.org/10.1007/s10163-022-01588-2
43. Lamm ME et al (2020) Material extrusion additive manufacturing of wood and lignocellulosic filled composites. Polymers (Basel) Bd 12, Nr 9 (2020). https://doi.org/10.3390/polym12092115
44. Rosenthal M, Henneberger C, Gutkes A, Bues C (2017) Liquid deposition modeling: a promising approach for 3D printing of wood. Europ J Wood Wood Products. https://doi.org/10.1007/s00107-017-1274-8
45. Wynne Z, Buchanan C, Kyvelou P, Gardner L, Kromanis R, Stratford T, Reynolds T (2022) Dynamic testing and analysis of the world's first metal 3D printed bridge. Case Stud Construct Mater 17:e01541. https://doi.org/10.1016/j.cscm.2022.e01541
46. Ye J, Kyvelou P, Gilardi F, Lu H, Gilbert M, Gardner L (2021) An end-to-end framework for the additive manufacture of optimised tubular structures. IEEE Access 9:165476–165489. https://doi.org/10.1109/ACCESS.2021.3132797
47. Erven M, Lange J (2022) Design of optimised 3D-printed steel nodes. In: Structures and architecture a viable urban perspective? CRC Press, pp 229–236
48. Kloft H, Schmitz LP, Müller C, Laghi V, Babovic N, Baghdadi A (2023) Experimental application of robotic wire-and-arc additive manufacturing technique for strengthening the I-beam profiles. Buildings 13(2):366. https://doi.org/10.3390/buildings13020366
49. Laghi V, Palermo M, Gasparini G, Trombetti T (2020) Computational design and manufacturing of a half-scaled 3D-printed stainless steel diagrid column. Addit Manufact 36:101505. https://doi.org/10.1016/j.addma.2020.101505
50. MTC (2023) Additive manufacturing in the circular economy: opportunities and constraints from a design perspective. NCAM National Center Additive Manufacturing; MTC Manufacturing Technology Center. https://ncam.the-mtc.org/media/gycaqkwb/am-in-circular-economy.pdf?download=AM%20in%20the%20circular%20economy [Accessed 15 August 2023]
51. CECIMO (2022) Publications: enabling the circular economy with additive manufacturing exploring best practices. 07 November 2022. CECIMO European Association of the Machine Tool Industries and Related Manufacturing Technologies. Available from: https://www.cecimo.eu/publications/enabling-the-circular-economy-with-additive-manufacturing-exploring-best-practices/
52. Reis RC, Kokare S, Oliveira JP, Matias JC, Godina R (2023) Life cycle assessment of metal products: a comparison between wire arc additive manufacturing and CNC milling. Adv Indust Manufact Engin 6:100117. https://doi.org/10.1016/j.aime.2023.100117
53. Shah IH, Hadjipantelis N, Walter L, Myers RJ, Gardner L (2023) Environmental life cycle assessment of wire arc additively manufactured steel structural components. J Clean Product 389:136071. https://doi.org/10.1016/j.jclepro.2023.136071
54. Tinoco MP, de Mendonça ÉM, Fernandez LIC, Caldas LR, Reales OAM, Toledo Filho RD (2022) Life cycle assessment (LCA) and environmental sustainability of cementitious materials for 3D concrete printing: a systematic literature review. J Build Engin 52:104456. https://doi.org/10.1016/j.jobe.2022.104456
55. Mohammad M, Masad E, Al-Ghamdi SG (2020) 3D concrete printing sustainability: a comparative life cycle assessment of four construction method scenarios. Buildings 10(12):245. https://doi.org/10.3390/buildings10120245

56. Campatelli G, Montevecchi F, Venturini G, Ingarao G, Priarone PC (2020) Integrated WAAM-subtractive versus pure subtractive manufacturing approaches: an energy efficiency comparison. Int J Precis Engin Manufact-Green Technol 7:1–11. https://doi.org/10.1007/s40684-019-00071-y
57. Tankova T, Silva L (2020) Robotics and additive manufacturing in the construction industry. Current Robot Rep 1:13–18. https://doi.org/10.1007/s43154-020-00003-8
58. Pajonk AM, Prieto Hoces AI, Blum U, Knaack U (2022) Multi-material additive manufacturing in architecture and construction: a review. J Build Engin 45:Article 103603. https://doi.org/10.1016/j.jobe.2021.103603