Review of the Circular Concrete Construction: CO2 Impact and Practice Concerns

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Abstract

This paper addresses the environmental impacts in terms of Carbon Dioxide (CO2) emission in circular concrete construction. Considering the existing buildings being one of the largest stocks of building materials for circular means representing a vast amount of embodied energy, extending, repairing, and reprogramming becomes the prime circular design strategy. From full preservation to demolition buildings can be reused, components can be salvaged, and materials can be reprocessed into new products. But doing so often requires new material and equipment deployment and, therefore, energy consumption, hence, the presented research will explore CO2 emissions related to these various circular approaches to identify the lowest CO2 in circular concrete construction. By comparing building components such as columns constructed by different circular means, in this case reuse and reprocess, the study identifies the energy and materials input at component scale, which could inform and enhance the redeployment of multi-lifecycle building construction.

Keywords

Circular Concrete, Embodied Emission, Reused Components, Recycled Materials, Reprocess, Life Cycle Analysis.

1. Introduction

The Architecture, Engineering, and Construction (AEC) sector represents the largest emitter of Greenhouse Gas[1] (GHG) and accounts for a vast amount of resource consumption and waste generation[2]. In order to mitigate both climate issues and resource challenges, a Circular Economy (CE) is slowly replacing the take-make-use-discard linear approach with circular practices involving reuse repair, reuse, and recycle strategies, benchmarking the relevance of Embodied Carbon (EC) associated with building materials (Röck et al., 2020).

Concrete, among others, is the most employed anthropogenic material in the built environment reaching a total volume of 14 billion cubic meters[3] and rising (*Cement and Concrete around the World*, n.d.). Despite its numerous advantages, including superior durability, strength, fire resistance, affordability, and versatility in design, the ecological impact of concrete is severe due to its profound demands for natural resources and energy during production, as well as large waste after demolition. Various strategies, including enhanced energy efficiency,

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[1] *Building Materials and the climate: Constructing a new future*. (n.d.). UNEP - UN Environment Programme. https://www.unep.org/resources/report/building-materials-and-climate-constructing-new-future#:~:text=The%20buildings%20and%20construction%20sector,have%20a%20significant%20carbon%20footprint.

[2] *Buildings and construction*. (n.d.). Internal Market, Industry, Entrepreneurship and SMEs. https://single-market-economy.ec.europa.eu/industry/sustainability/buildings-and-construction_en

3 *Cement and concrete around the world - GCCS | Staging*. (n.d.). GCCS | Staging. https://gccassociation.org/concretefuture/cement-concrete-around-the-world/

alternative fuels for clinker production, substitution of cementitious material (Lashari et al., 2023), and improved material design through digital fabrication (Muñoz et al., 2021), have successfully reduced the EC within concrete's life cycle (Marsh et al., 2022; Habert et al., 2020; Nielsen & Glavind, 2007), etc.

Circular concrete strategies, on the other hand, target the post-use and re-use of concrete components and materials as substitutions for new concrete in concurrent life cycles. They safeguard embodied carbon, diminish new emissions, limit resource depletion and waste accumulation (Reference), and are seen as imperative ways to achieve decarbonization. Adapted from the waste management ladder (Marsh et al., 2022; Hendriks & Janssen, 2003), three distinct strategies are identified: retaining, reutilizing, and reprocessing, referring to the reuse of concrete at a building, component, and material scale, respectively, as explained in fig.1. This paper focused on a comparative study of the latter two, concrete reutilizing and reprocessing, as they involve various levels of reuse (Reference) and negotiate between donor, receiver structures, initial, and concurrent life cycles, bringing in new design mechanism, as well as new material and energy consumption across different stages.

In this study, A Life Cycle Analysis (LCA) is conducted to evaluate the global warming potential of two hypothesis concrete components constructed through different circular strategies. First is a reutilized column extracted from nearby structures, and second is a reprocessed column that is 3D-printed with Recycled Concrete (3DRCP). Specifically, the interconnected phase of the initial and concurrent life is investigated, involving deconstruction (re-extraction), reproduction, reconstruction, and transportation of the circular building components and materials. The results offer insight into the technicality and potential environmental impact of circular strategies to better assess circular design decisions from a sustainability point of view.

The paper includes a review of existing environmental assessments for circular concrete products as opposed to linear methods in Section 2 and the methodology of comparative analysis in Section 3. In sections 4 and 5, results and discussions are presented. Lastly, the content of this paper is summarized in section 6.

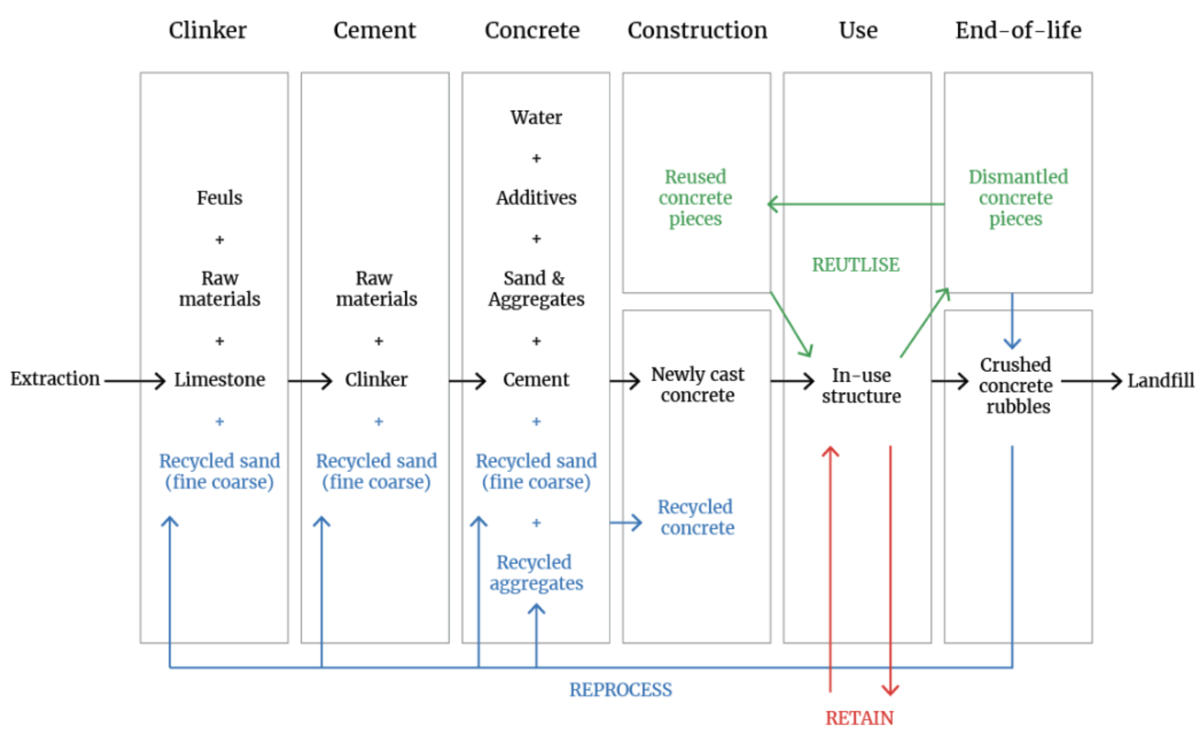


Fig. 1. Concrete value chain (adapted from Habert et al., 2020): conventional concrete production and service cycle (black) and

circular concrete strategies (colored: retain in red, reutilize in green, and reprocess in blue); related strategies identified in each building stage: concrete production, construction, use, and end-of-life (in gray).

2. State-of-the-Art

While concrete reutilization refers to the reassembly of a dismantled or salvaged component sourced from the building deconstructions, it aims at keeping the intrinsic values of hardened concretes through direct reuse or refurbishment of the components. Reprocessing, in contrast, breaks down reclaimed concrete components into material stages, i.e., Recycled Aggregates (RA), reintegrates them into new components, and installs them in new buildings. The main distinction between the two is the irreversibility of the latter. For example, the adhered quality of RA, separated from old cement and adhesive, largely influences the material performance of new Recycled Concrete (RC) components (Xing et al., 2022; Marinković et al., 2010). On top of that, they also bring in different materials and energy flows, resulting in different decarbonization effects. To compare the two distinct strategies, their technicalities regarding design and construction, and associated impact assessment methods are reviewed in this section.

2.1 Reutilization of concrete components

Component reutilization, considered common practice before industrialization, has lost its interest along with the mechanization of construction sites and the rise of labor costs. Recently,
It has regained awareness as an imperative way to simultaneously limit waste, greenhouse gas emissions, and the demand for new raw materials by extending the component's use with its initial or redesigned function. Precedents of concrete reutilization since the 1970s have been identified by (Küpfer et al., 2023), revealing niche and experimental circular construction. However, they are also challenged by its unconventional design mechanism that involves multiple life cycles. (Fig) (Küpfer et al., 2023). This demands selective deconstruction tools and reusability assessment (Devènes et al., 2024), which is sensitive to specific material technicality and pre-existing compositions of components.

Re-extraction

As concrete elements are often cast together, separating them for reuse without damage is impossible. With traditional demolition methods, i.e., hydraulic crusher or jackhammer, the concrete remains are left with irregular dimensions, making it harder to reuse, especially with the existence of reinforced steel. In contrast, dismantling allows structures to be systemically taken apart with controlled processes and precise dimensions. Tools are primarily diamond saws, hydro-jetting, or piece lifting when connections are loose. Specific processes such as shoring, lifting, storage, and early deconstruction planning are necessary to ensure a good dismantling workflow as well as the quality of circular products (reference).

Transportation

Another challenging aspect of concrete reutilization is transportation and storage, as they involve various locations of donor and receiver buildings, and the different schedules of deconstruction and new construction. Moreover, unlike cast-in-situ concrete, reutilized concrete is transported at the component stage, which is often bulky and heavy. It was highlighted in (Devènes et al., 2022) that the transportation of reclaimed concrete blocks was the largest global warming impact contributor (34%) in the studied reutilization case, whereas concrete sawing-related emissions are neglectable. In short, the limitation for components' size and shape to be moved or stored encourages reutilization to be planned locally (reference). Besides transportation distance, other factors affecting transportation emissions, i.e., vehicle type, road conditions, average speed, and temperature, request further research efforts for real-time analysis (Wang et al. 2021).

Environmental impact

Despite multiple trends and diverse strategies, precedents of concrete reutilization cases have demonstrated significant carbon savings (40%-97%) compared to conventional constructions (Küpfer et al., 2023; Eberhardt et al., 2019). In addition, (Küpfer et al., 2022) further evaluated
using various alternative (circular) materials to construct the same reutilized components, an arch bridge, and parking pavements. The former showed a 63% reduction of global warming impact compared to a monolithic recycled-concrete arch, 75% to a steel arch, but a slightly higher impact than a timber arch. Likewise, the other case showed an 82% carbon savings compared to the other two alternatives composed of recycled concrete and bituminous surfacing. While both cases support concrete realization as an effective decarbonization method, it was reported that the energy requirement for excessive cutting could sometimes overrule the total emission in specific conditions (REBEAUTY), hence requiring comprehensive assessment prior to circular design and construction decision-making.

2.2. Reprocessed concrete materials and composite through 3D-printing.

Traditionally, concrete reprocessing refers to casting with Recycled Concrete, which is proven to offer little to negative carbon savings due to the excessive new cement requirements when achieving similar structural performance (Lei et al., 2022; Zhang et al., 2019). The present study aims to leverage the advantages of the existing 3D-concrete printing (3DCP) technique for constructing circular concrete components with RC, namely 3DRCP, to understand its sustainable potential and design feasibility addressing functional changes between the initial concrete component and its concurrent life. The environmental impact of 3DRCP could be assessed in two parts, the material acquisition phase and the construction phase, referring to the embodied emissions of 3DRCP materials and operational emissions from the printers (Agustí-Juan & Habert, 2017). While 3DRCP distinguishes 3DCP with the deployment of circular materials, the printing technology and process are somewhat similar, and both materials need to be formulated to achieve rheological status and design requirements after hardening (Anton et al., 2020; Reiter et al., 2020). As there is currently little research effort on the environmental impact of 3DRCP, the review is largely based on the existing knowledge of 3DCP.

Machines

Initiated with the work of Pegna (reference), a large variety of printing technologies have been developed, including the pioneering three, Contour Crafting, Loughborough systems, and the D-shape system (Ghaffar et al., 2018), equipped with various machine set-ups, including the robotic printers, mixers, extensive tools, cables, and gantry structures. The operation of these machines guarantees the printing workflow with controlled hardware specifications, i.e., nozzle head size, print speed, print length, and build-up rate, allowing the concrete filaments to be placed as designed. Regarding environmental assessments for the 3DCP construction phase, it was reported that the operational energy consumption, including both machine and building operations, does not significantly increase environmental costs as it typically contributed up to 10% of the total emissions in the worst case (Saade et al., 2020). However, some other research also considered the production emission outlay of the machines in the LCA of 3DCP components, taking into account the embodied carbon, life span, and operating hours of robotic printing systems, which could lead to a higher impact on the machines (Kuzmenko et al., 2020).

Materials

Compared to standard C25/30 concrete for conventional casting, 3DCP concrete typically contains more fine aggregates (sand) as no large aggregates (gravel) for reinforcements are printable with current technologies. Likewise, 3DRCP concrete formulation consists of water, Recycled Fine Aggregates (RFA) in replacement of natural sand, cementitious materials, additional sand if needed, and additives. From a sustainability point of view, recycled aggregates limit waste and have lower embodied carbon[4] primarily due to their availability and accessibility in urban areas, which largely reduces transportation needs (Lei et al., 2022). Whereas natural gravel or sand is extracted from riverbeds. However, structurally speaking, under the same water-to-cement ratio, recycled concrete's compressive, tensile splitting, and flexural strengths are relatively lower than conventional cast samples (Plaza et al., 2021; Ding et al., 2020), resulting in a higher cement and additives content to achieve equivalent structural performance for 3DRCP components. Nevertheless, it was confirmed that the higher the RFA replacement rate in 3DRCP concrete formulation, the lower the total embodied emissions at the material acquisition phase regarding the simultaneous increase of cement content (Han et al., 2021).

Environmental impact assessment at component scale

As 3DCP has not been largely applied at the building scale, existing LCA studies mainly focus on the fabrication of 3DCP components, bringing in external resources and energy consumption other than 3DCP materials and machines, i.e., cast concrete, steel reinforcement, polishing, and transportation of various materials. (Agustí-Juan et al., 2017) reported potential carbon savings of digitally fabricated concrete walls (with no formwork required) compared to conventionally constructed ones when wall components have high design geometric complexity or extreme dimensions. (Mohammad et al., 2020) pointed out that when 3DCP is used with reinforced elements, it is associated with higher GWP emissions than the studied conventional method, indicating further research on 3DCP structure strength and safety, as well as developing novel reinforcement techniques suitable for 3DCP rather than adopting reinforcement techniques specifically meant for conventional concrete construction methods (Ahmed et al., 2022; Anton et al., 2020). Lastly, (Muñoz et al., 2021) reported a 40% reduction in carbon emission for a 3DCP structural pillar over a traditionally cast one. This is mainly due to the replacement of formwork with 3DCP mould, which served as a permanent case for additional concrete pouring. Despite inconsistent decarbonization effects from various design approaches for 3DCP components, they all confirm that GHG emissions for 3DCP constructions were consistently dominated by materials production rather than the manufacturing process itself (Kuzmenko et al., 2020). This highlights the search for alternative material solutions, including using a high-performance concrete mix (Gosselin et al., 2016), printing with (recycled) coarse (Liu et al., 2022), and using locally sourced materials (Aslaminezhad et al., 2024; Bai et al., 2021; Yao et al., 2020).

2.3 Research gap and contribution

As most research on concrete reutilization and reprocessing through 3DRCP have been individually studied, there were no systematical reviews or comparative assessments of the two paralleled strategies regarding the reuse or post-use decisions for obsolete (donor) structures, and the existing material solutions for new (receiver) structures. Hence, despite many other indicators i.e. cost, that might suggest different conclusions, this paper focused on the LCA study in terms of GHG (carbon) emissions to evaluate which strategy could achieve effective decarbonization and how the allocated impact informs about circular designs and constructions.

3. Methodology and Approach

With the main purpose of achieving decarbonization through circular construction, the presented study systemically reviews two cases: A. a reutilized concrete column and B. a 3DRCP column (Fig.), under Life Cycle Analysis (LCA) framework. The former represents one of the 54 concrete columns dismantled from a parking structure and reassembled as load-bearing columns in a new housing complex Elementa in Basel, and the latter refers to one of the twelve 3DCP columns originally designed and fabricated at ETH Zurich, Switzerland, with the consideration of

[4] the embodied emission of recycled aggregates included the energy involved production and the transportation.

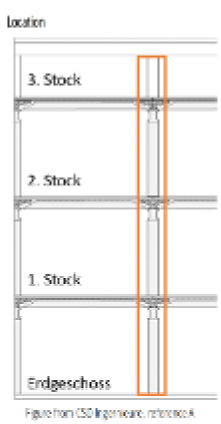
using recycled materials made of demolition concrete waste, see 3.1 for detailed presentations. Through Life Cycle Inventories (LCI), the paper aims to compare the environmental footprint for constructing a hypothesis concrete column in a concurrent life cycle with the two identified circular strategies. Therefore, the LCA calculations consider only the GHG emissions generated additionally after the initial life cycle.

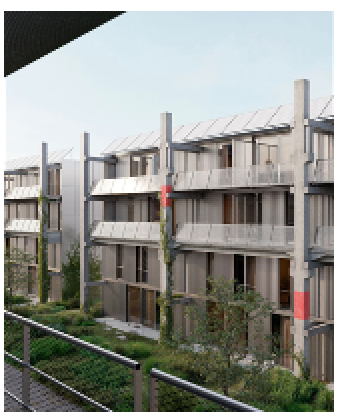
3.1 Case study presentations

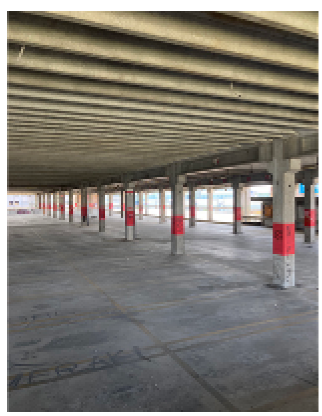
Scenario A: Reutilized pre-cast reinforced concrete columns.

Elementa is the winning proposal of an open international architectural competition for the 20,000 sqm public housing and integration center for migrants in Basel, Switzerland. The project convinced the interdisciplinary jury with its strong aesthetics generated through the systematic use of reused building components as part of the load-bearing structure of the new buildings. Among the 2680 building components reused, the reutilization of the concrete load-bearing components – structural columns, transversal beams, and ribbed slab – reclaimed from the nearby obsolete Lysbüchel car park building, is significantly recognized. As they were dismantled strategically and designed to be reused as close to their original state, minimal component remanufacturing was conducted.

Constructed in 1970, the precast reinforced concrete columns had a dimension of approximately 470*470*20110 mm, and a total weight of 11898 kg, accommodating a 4-story parking structure. The intended compressive strength was not specified; however, its density (2,530 kg/m3) resemblances the density of the typical C25/30 concrete (2,400 kg/m3), hence, a 30mPA compressive strength was assumed. Each unit is reinforced with 20 of D20 rebars and D8 stirrups at 250 mm spacing. The columns were finished with exposed concretes as they were not directly exposed to rain. During dismantling, diamond saws were used to extract the columns by removing the ribbed slabs and supporting beams in advance since the connection types were unknown. The columns were then transferred and stored at a nearby site for one year. Meanwhile, component testing and additional treatment such as water-repellent coating was applied, as the reutilized columns were reconfigured as exterior structure. (see fig.) The columns would be later be transported and installed at new project site that was 5 km apart.







Scenario B: Reprocessed 3DCP columns

The 3DCP bespoke columns were originally designed within the Concrete Choreograph studio as part of the Master of Advanced Studies in Architecture and Digital Fabrication 2018-2019 at ETH Zurich (ETHZ) (Ana et al.). Nine out of twelve columns were successfully fabricated, exhibiting unique ornamentation and details that are impossible to reproduce with other fabrication methods. Column number 7 was further chosen for demonstrating LCA calculation as it was considered the most successful specimen regarding efficiency and stability of the printing process, and it accounts for the largest material usage among all. While the column was 3D printed with Natural Aggregate Concrete (NAC), the calculation is made for a reprocessed column that is 3D printed with Recycled Aggregate Concrete (RAC), which replaces sand with RFA extracted from donor structures.

The column reaches a height of 2.75 m and consists of an outer shell and an inner core. The outer shell displays highly differentiated ornamental exteriors with dimensions ranging from 250 to 600mm. Meanwhile, the inner core houses a cylinder shaft of 250 mm in diameter, which serves as a permanent formwork for inserting reinforcing rebar cage and concrete casting. The cage is made of 12 d12 steel rebars and stirrups positioned every 200mm. As the 3DCP shell and core were not structurally tested, this comparative study only considered the compressive strength of the internal cast reinforced concrete, which is reported to be 30 mPA. Within each extruded layer, the shell and core were connected by optimized print paths, providing printing stability and supporting adjacent overhanging geometric features (Fig. 5). The concrete filament has a cross-section of 25*5 mm^2, print speed at 180 mm/s, and extruder flow rate at 22550 mm^3/s. (reference), resulting in the printing process of 163 minutes and material consumption of 264.3 liters of concrete.

The concrete formulation consists of calcareous crushed sand with 0-2 mm grain sizes, Ordinary Portland Cement (OPC) based binder at a water-to-cement ratio of 0.4, containing 15% substitution of limestone powder and 8% substitution of micro silica. A liquid superplasticizer is dosed at 0.7% by weight to improve extrudability and proper interlayer bonding of the 3DCP mix. A sucrose solution is applied as a retarder to ensure an open time of 8 hours and prevent hardening before extruded. A commercial thickener (viscosity modifier) is used to facilitate the workability of concrete. Accelerators are dosed at the nozzle head to activate the hardening of concrete after being expelled. This ensures fresh concrete's buildability and minimizes subsequent layers' deformation during printing (Gebhard et al., 2021; Anton et al., 2020).

The construction of the R3DCP column contains two stages: off-site printing and on-site casting. RFA is extracted from the demolishing site and transported to the fabrication warehouse, which is assumed to be 5 km away. Then the printed component is transported 5 km to the new project site to be reinforced and assembled on new foundations.

Fig. 3: Concrete Choreography

3.2 LCA methods

Cut-off method

The Life Cycle Analysis was carried out with the European Norms EN 15804 and Swiss Norms SIA 2031 as methodological guidelines. Stage A1-3 is known as the production stage, A4-A5 the construction stage, B1-B5 the embodied use stage, B6-B7 the operational use stage, and C1-C4 the end-of-life stage. In addition, module D is defined to account for potential circular strategies such as reuse and recovery. Nevertheless, LCA for concurrent life has not been well established nor defined since the main characteristic of reuse is that the lifespan of a component is distributed over multiple life cycles. While several authors and standards proposed various methods to assess the environmental footprint of circular products (De Wolf et al., 2020; Eberhardt et al., 2019), the cut-off method (BSI, 2008), also known as the 100:0 approach is adopted in this paper, to focus on the comparative analysis of two circular scenarios after their initial life by allocating the environmental impacts load and credits, i.e. CO2 emission, of each stage within the life cycle in which they actually occur.

System boundary (R1-R5): cradle-to-gate

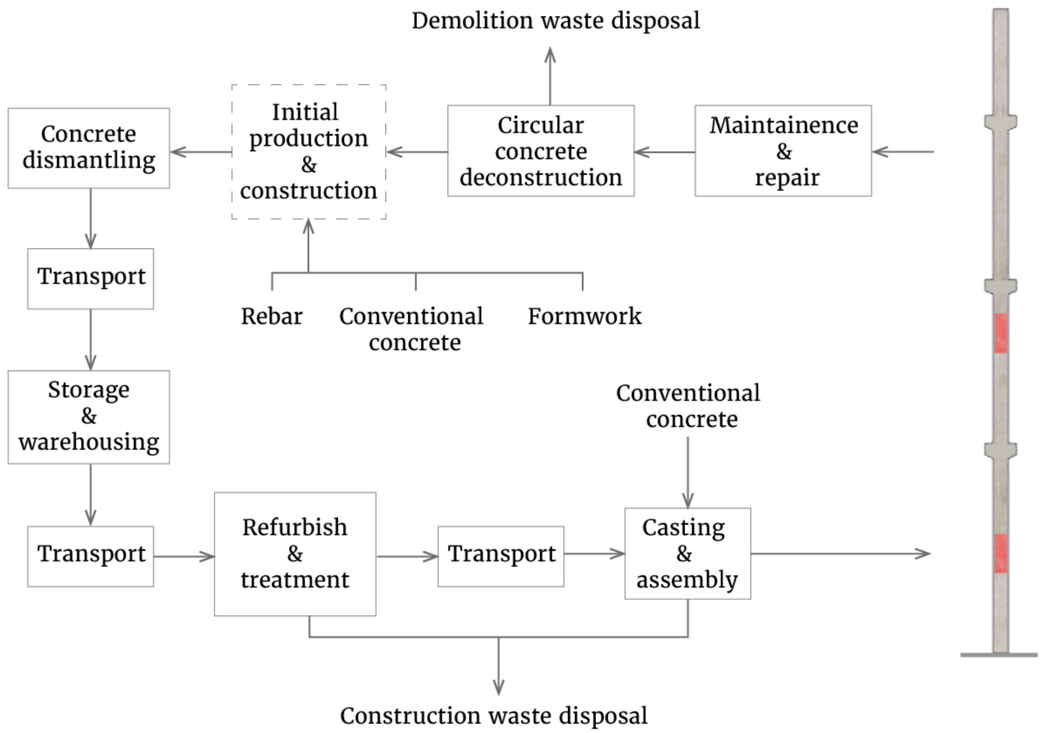
Followed by and excluding the end-of-life stage of the initial life cycle, the system boundaries include the re-extraction of existing building components and materials (R1) from donor buildings, transportation to manufacturing site (R2), remanufacture and refurbishment of circular components (R3), transportation to new project site (R4), and lastly their assembly and installation in receiver buildings (R5). The assessment of the new use and EoL stages afterwards are not included in this paper. However, they require future studies and attention regarding the quality, maintenance, repair of circular products at use, and their end-of-life strategies and multi-use evaluation (Devènes et al., 2024; Burger et al., 2023; Ding, Xiao, Zou, et al., 2020).

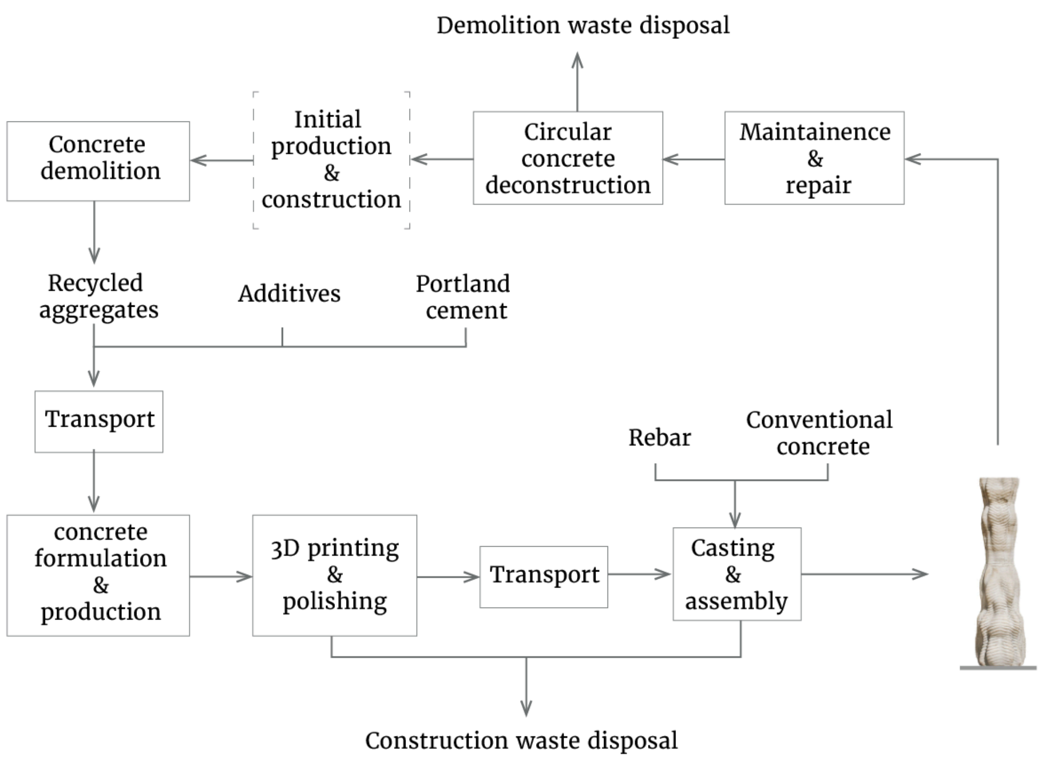
Functional unit

While the LCA calculation is made for one component, which is one column unit for both cases, the functional unit is defined as 1 cubic meter (m3) of, both reinforced, reutilized concrete, and reprocessed 3DCP concrete, respectively, considering the inconsistent design approach and function of the two separated cases.
(for example, the first column is designed with a beam resting while the R3DCP is not designed with consideration to connect to a beam…)

3.3 Life Cycle Inventories (Data collection)

In the life-cycle inventory analysis, the emission data were collected through various literature, norms, and standards. Since the two cases are both presented in Switzerland, Swiss data was mainly adopted for calculation in the next step. By cradle-to-gate, the emission inventory was calculated as follows where R1 accounts for the dismantling of the concrete component in Case A, and deconstruction of concrete into materials (aggregates) in Case B, respectively; R2 and R4 consider the weight, distance, and emissions factor depending on the type of vehicles; R3 includes the embodied emissions of additional materials and operational emissions such as 3D printers and lighting etc. during fabrication; R5 represents the emissions from materials and energy use during the assembly. The calculations and source could be found in Table., and analysis presented in next section.


Demolition waste disposal
Concrete dismantling
Initial production & construction
Circular concrete deconstruction
Maintainence & repair
Transport
Rebar
Conventional concrete
Formwork
Storage & warehousing
Conventional concrete
Transport
Refurbish & treatment
Transport
Casting & assembly
Construction waste disposal


Demolition waste disposal
Concrete demolition
Initial production & construction
Circular concrete deconstruction
Maintainence & repair
Recycled aggregates
Additives
Portland cement
Transport
Rebar
Conventional concrete
concrete formulation & production
3D printing & polishing
Transport
Casting & assembly
Construction waste disposal

4. Results

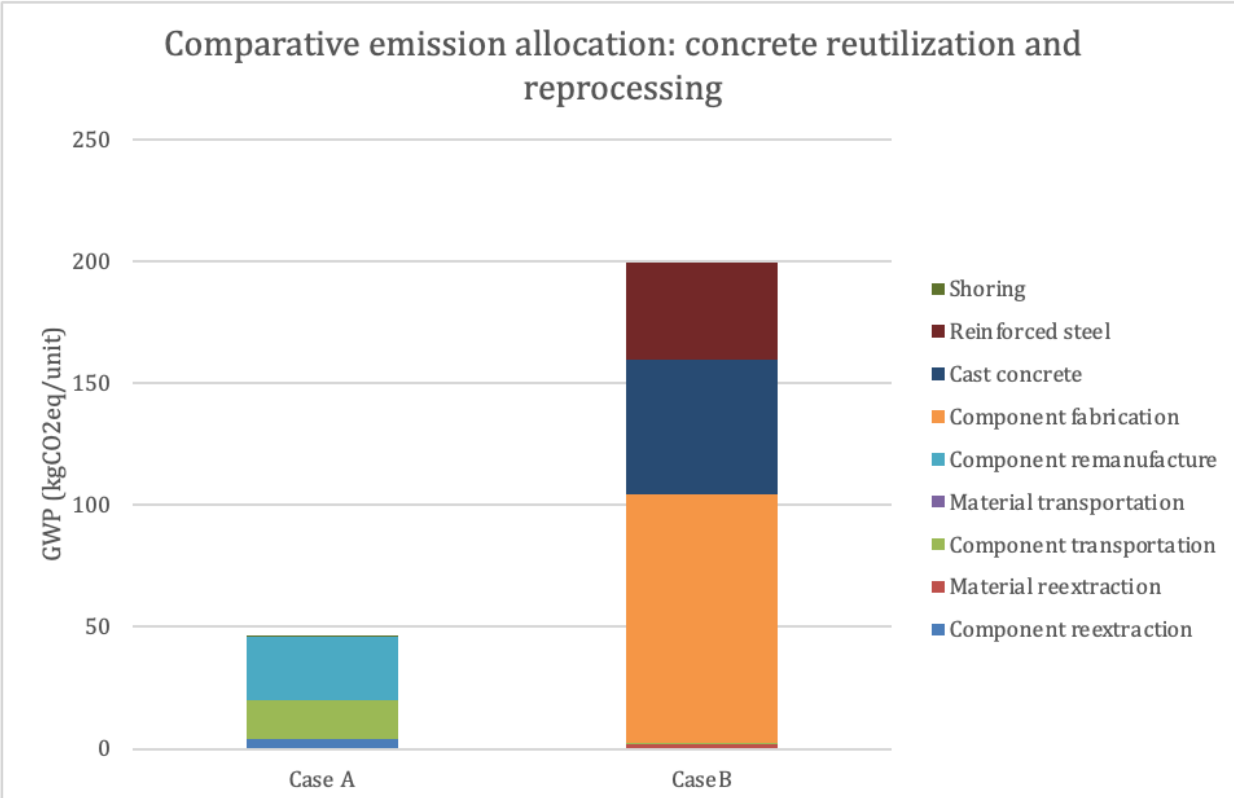


Fig.

The total emissions of Case A and B are 46 kgCO2eq and 199 kgCO2eq respectively, with reutilization of the concrete column showing 77% carbon savings potential compared to the reprocessed one. Regarding the allocation, Case B's emission results largely from two parts, first, the component fabrication (51,2%) which includes the embodied carbon of 3DCP concrete mixture materials as well as the operational emission during printing, and second, the assembly stage (47,5%) which involves the production and construction of other materials such as cast concrete and reinforced steel. The following are concrete aggregate extraction (1%), and material and component transportation (0,3%). Interestingly, the embodied carbon of new materials summed up 97% of the R3DCP while the emissions from printing cells and building operations accounted for merely 1,5% of the total GHG emission. Since the result excludes the embodied emission of the robotic cells, it is worth mentioning that Munoz et al. () have pointed out that the 3DCP process including printing, polishing, and the entire life cycle of the machines appears to be almost negligible, representing less than 1% of the total GHG emissions in their case. Despite the slight difference from case to case, we can conclude that the majority of GHG emissions of the R3DCP column are contributed by new material production. In other words, potential carbon reduction could be achieved by largely incorporating recycled materials (Reference).

In Case A, the embodied carbon of water-repellent coating solely contributed to emissions at the component remanufacture stage, representing 56.5% of the total results, followed by component transportation (35.5%), component re-extraction (8%), and re-installation (1%). Note that for the assessment, we excluded the emissions generated from component testing, and it was assumed that there was no other excessive processing, such as resizing, in Case A. Interestingly, transportation-related emissions remain a critical GWP contributor in concrete reutilization and largely depend on two factors: the weight and the transportation distance between deconstruction sites, warehouses, and construction sites. In Case A's conditions, where components are already bulk and heavy, with each unit reaching almost 12 tons, the transportation distance became even more dominant than in Case B, as shown in Figure 3. We conducted a sensitivity analysis and found out that with the premised condition of the two cases, when the total component transportation distance exceeds 125 km, the final GWP of Case A would surpass Case B. In other words, concrete reutilization no longer shows carbon-saving advantages over reprocessing; breaking or crushing concrete components into aggregates and refabricating them as new components through 3DCP or other methods becomes a more suitable option for decarbonization. The heavier the component weight is, the more sensitive the total emissions become to transportation distance, and hence, the location and distance between donor and receiver buildings should be considered thoroughly, as reutilization shows much more positive carbon-saving impacts when components are sourced locally.

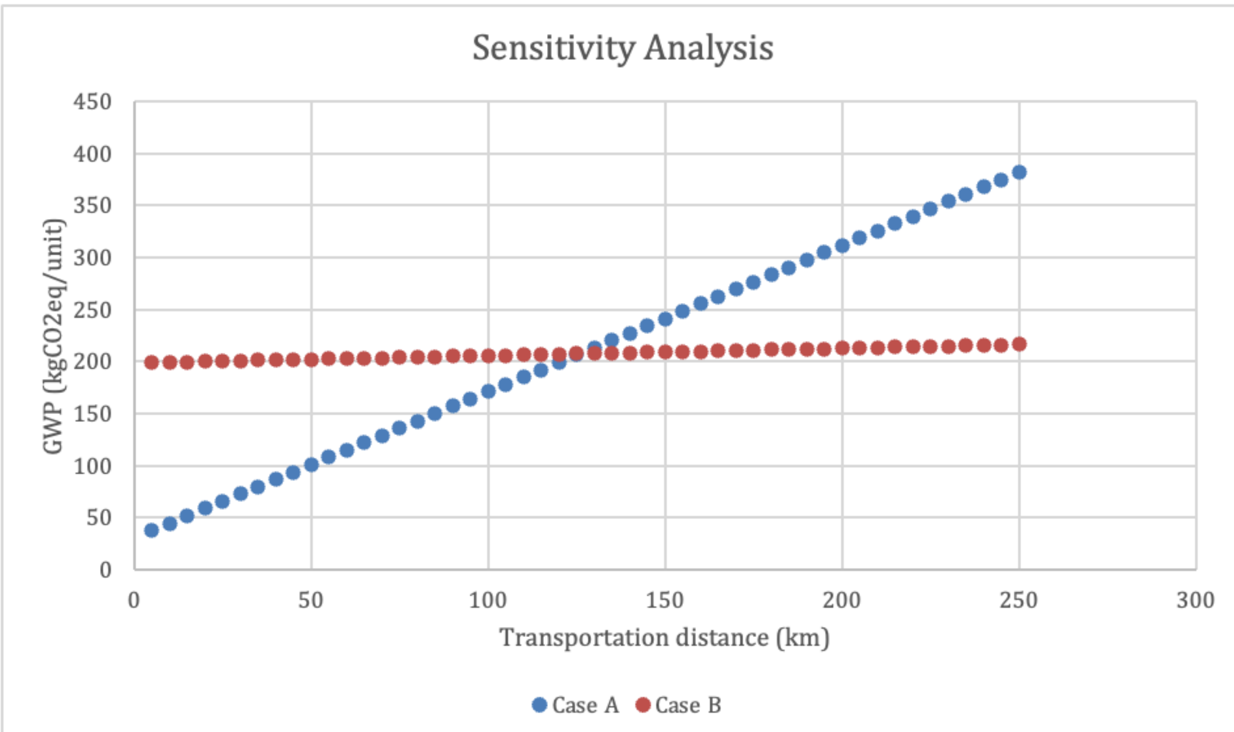


Fig.

5. Discussion

Despite the tendency to prioritize concrete realization over reprocessing, as confirmed in this study, there are other hidden aspects that are not considered but should not be neglected when it comes to circular design assessments. For instance, when a concrete column originally designed for carloads is reused as a column for a housing complex, this results in a loss of (structural) function due to a downgrade reuse approach in case A. However, concrete reprocessing allows circular components to break free from their initial form and use and remanufacture the components with the intended design requirements to achieve material efficiency. Hence, the results of decarbonization should be re-evaluated, considering both initial and concurrent lifecycles regarding their design approach and level of reuse. In other words, concrete reutilization and reprocessing offer different mechanisms to reduce environmental impacts, requiring further research efforts for LCA for circular products across multiple stages, life cycles, and at building scales.

6. Conclusion

This study demonstrates that the environmental impact of concrete construction approaches differ depending on the methods used. The reutilization of concrete columns in case A shows 77% carbon saving compared to case B, where reprocessing is used. However, the carbon saving greatly depends on the transportation distances. Hence, for long distance transportation, the benefits of using reutilization are offset and reprocessing is more preferable.
Moreover, the structural capacity of the reprocessed 3DCP column is more than the concrete reutilization which leads to a higher material efficiency and sustainability.
In conclusion, both concrete reutilization and reprocessing methods offer sustainable approaches for minimizing environmental concerns; however, the efficiency varies based on contextual dimensions, building scales, design and structural requirements, and operational stages.

References

Agustí-Juan, I., & Habert, G. (2017). Environmental design guidelines for digital fabrication. *Journal of Cleaner Production*, *142*, 2780–2791. https://doi.org/10.1016/j.jclepro.2016.10.190

Agustí-Juan, I., Müller, F., Hack, N., Wangler, T., & Habert, G. (2017). Potential benefits of digital fabrication for complex structures: Environmental assessment of a robotically fabricated concrete wall. *Journal of Cleaner Production*, *154*, 330–340. https://doi.org/10.1016/j.jclepro.2017.04.002

Ahmed, G., Askandar, N., & Jumaa, G. (2022). A review of largescale 3DCP: Material characteristics, mix design, printing process, and reinforcement strategies. *Structures*, *43*, 508–532. https://doi.org/10.1016/j.istruc.2022.06.068

Anton, A., Reiter, L., Wangler, T., Frangez, V., Flatt, R., & Dillenburger, B. (2020). A 3D concrete printing prefabrication platform for bespoke columns. *Automation in Construction*, *122*. https://doi.org/10.1016/j.autcon.2020.103467

Antunes, A., Silvestre, J., Costa, H., Carmo, R. do, & Júlio, E. (2024). Reducing the environmental impact of the end-of-life of buildings depending on interrelated demolition strategies, transport distances and disposal scenarios. *Journal of Building Engineering*, *82*, 108197. https://doi.org/10.1016/j.jobe.2023.108197

Aslaminezhad, A., Hidding, A., Bier, H., & Calabrese, G. (2024). In-Situ vs. Prefab 3D Printing Considerations for CO2-free Pop-up Architecture. *SPOOL*, *11*(1), 71–80. https://doi.org/10.47982/spool.2024.1.05

Bai, G., Wang, L., Ma, G., Sanjayan, J., & Bai, M. (2021). 3D printing eco-friendly concrete containing under-utilised and waste solids as aggregates. *Cement and Concrete Composites*, *120*, 104037. https://doi.org/10.1016/j.cemconcomp.2021.104037

Burger, J., Lloret-Fritschi, E., Akermann, M., Schwendemann, D., Gramazio, F., & Kohler, M. (2023). Circular Formwork: Recycling of 3D Printed Thermoplastic Formwork for Concrete. *Technology|Architecture + Design*, *7*(2), 204–215. https://doi.org/10.1080/24751448.2023.2245724

De Wolf, C., Hoxha, E., & Fivet, C. (2020). Comparison of environmental assessment methods when reusing building components: A case study. *Sustainable Cities and Society*, *61*, 102322. https://doi.org/10.1016/j.scs.2020.102322

Devènes, J., Bastien-Masse, M., & Fivet, C. (2024). Reusability assessment of reinforced concrete components prior to deconstruction from obsolete buildings. *Journal of Building Engineering*, *84*, 108584. https://doi.org/10.1016/j.jobe.2024.108584
Devènes, J., Brütting, J., Küpfer, C., Bastien-Masse, M., & Fivet, C. (2022). Re:Crete – Reuse of concrete blocks from cast-in-place building to arch footbridge. *Structures*, *43*, 1854–1867. https://doi.org/10.1016/j.istruc.2022.07.012

Ding, T., Xiao, J., Zou, S., & Wang, Y. (2020). Hardened properties of layered 3D printed concrete with recycled sand. *Cement and Concrete Composites*, *113*, 103724. https://doi.org/10.1016/j.cemconcomp.2020.103724

Eberhardt, L., Birgisdottir, H., & Birkved, M. (2019). Comparing life cycle assessment modelling of linear vs. Circular building components. *IOP Conference Series: Earth and Environmental Science*, *225*(1), 012039. https://doi.org/10.1088/1755-1315/225/1/012039

Fivet, C., & Masse, D. M. B. (2022). *Case study of a residential building structure and comparison to conventional construction method*.

Gebhard, L., Mata-Falcón, J., Anton, A., Dillenburger, B., & Kaufmann, W. (2021). Structural behaviour of 3D printed concrete beams with various reinforcement strategies. *Engineering Structures*, *240*, 112380. https://doi.org/10.1016/j.engstruct.2021.112380

Gosselin, C., Duballet, R., Roux, Ph., Gaudillière, N., Dirrenberger, J., & Morel, Ph. (2016). Large-scale 3D printing of ultra-high performance concrete – a new processing route for architects and builders. *Materials & Design*, *100*, 102–109. https://doi.org/10.1016/j.matdes.2016.03.097

Grangeot, Parascho, & Fivet. (2023). From concrete waste to walls: An investigation of reclamation and digital technologies for new load-bearing structures. *Journal of Physics: Conference Series*, *2600*, 192019. https://doi.org/10.1088/1742-6596/2600/19/192019

Habert, G., Miller, S. A., John, V. M., Provis, J. L., Favier, A., Horvath, A., & Scrivener, K. L. (2020). Environmental impacts and decarbonization strategies in the cement and concrete industries. *Nature Reviews Earth & Environment*, *1*(11), Article 11. https://doi.org/10.1038/s43017-020-0093-3

Han, Y., Yang, Z., Ding, T., & Xiao, J. (2021). Environmental and economic assessment on 3D printed buildings with recycled concrete. *Journal of Cleaner Production*, *278*, 123884. https://doi.org/10.1016/j.jclepro.2020.123884

Hendriks, Ch. F., & Janssen, G. M. T. (2003). Use of recycled materials in constructions. *Materials and Structures*, *36*(9), 604–608. https://doi.org/10.1007/BF02483280

Küpfer, C., Bastien-Masse, M., Devènes, J., & Fivet, C. (2022). Environmental and economic analysis of new construction techniques reusing existing concrete elements: Two case studies. *IOP Conference Series: Earth and Environmental Science*, *1078*(1), 012013. https://doi.org/10.1088/1755-1315/1078/1/012013
Küpfer, C., Bastien-Masse, M., & Fivet, C. (2023). Reuse of concrete components in new construction projects: Critical review of 77 circular precedents. *Journal of Cleaner Production*, *383*, 135235. https://doi.org/10.1016/j.jclepro.2022.135235

Kuzmenko, K., Gaudillière-Jami, N., Feraille, A., Dirrenberger, J., & Baverel, O. (2020). *Assessing the Environmental Viability of 3D Concrete Printing Technology* (pp. 517–528). https://doi.org/10.1007/978-3-030-29829-6_40

Lashari, A. R., Kumar, A., Kumar, R., & Rizvi, S. H. (2023). Combined effect of silica fume and fly ash as cementitious material on strength characteristics, embodied carbon, and cost of autoclave aerated concrete. *Environmental Science and Pollution Research*, *30*(10), 27875–27883. https://doi.org/10.1007/s11356-022-24217-9

Lei, B., Yang, W., Yan, Y., Tang, Z., & Dong, W. (2023). Carbon Emission Reduction Evaluation of End-of-Life Buildings Based on Multiple Recycling Strategies. *Sustainability*, *15*(22), Article 22. https://doi.org/10.3390/su152215711

Lei, B., Yu, L., Chen, Z., Yang, W., Deng, C., & Tang, Z. (2022). Carbon Emission Evaluation of Recycled Fine Aggregate Concrete Based on Life Cycle Assessment. *Sustainability*, *14*(21), 14448. https://doi.org/10.3390/su142114448

Liu, H., Liu, C., Wu, Y., Bai, G., He, C., Yao, Y., Zhang, R., & Wang, Y. (2022). 3D printing concrete with recycled coarse aggregates: The influence of pore structure on interlayer adhesion. *Cement and Concrete Composites*, *134*, 104742. https://doi.org/10.1016/j.cemconcomp.2022.104742

Marinković, S., Radonjanin, V., Malešev, M., & Ignjatović, I. (2010). Comparative environmental assessment of natural and recycled aggregate concrete. *Waste Management*, *30*(11), 2255–2264. https://doi.org/10.1016/j.wasman.2010.04.012

Marsh, A., Velenturf, A., & Bernal, S. (2022). Circular economy strategies for concrete: Implementation and integration. *Journal of Cleaner Production*, *362*, 132486. https://doi.org/10.1016/j.jclepro.2022.132486

Mohammad, M., Masad, E., & Al-Ghamdi, S. G. (2020). 3D Concrete Printing Sustainability: A Comparative Life Cycle Assessment of Four Construction Method Scenarios. *Buildings*, *10*(12), Article 12. https://doi.org/10.3390/buildings10120245

Monteiro, P. J. M., Miller, S. A., & Horvath, A. (2017). Towards sustainable concrete. *Nature Materials*, *16*(7), 698–699. https://doi.org/10.1038/nmat4930

Motalebi, A., Khondoker, M. A. H., & Kabir, G. (2024). A systematic review of life cycle assessments of 3D concrete printing. *Sustainable Operations and Computers*, *5*, 41–50. https://doi.org/10.1016/j.susoc.2023.08.003
Muñoz, I., Alonso, J., Menéndez-Muñiz, M., Uhart, M., Martin, C., Fabritius, M., Calvo, L., Poudelet, L., Cardona, R., lombois-burger, H., Vlasopoulos, N., Bouyssou, C., Dirrenberger, J., Papacharalampopoulos, A., & Stavropoulos, P. (2021). Life cycle assessment of integrated additive–subtractive concrete 3D printing. *The International Journal of Advanced Manufacturing Technology*, *112*, 1–11. https://doi.org/10.1007/s00170-020-06487-0

Nielsen, C., & Glavind, M. (2007). Danish Experiences with a Decade of Green Concrete. *Journal of Advanced Concrete Technology*, *5*, 3–12. https://doi.org/10.3151/jact.5.3

Plaza, P., Sáez del Bosque, I. F., Frías, M., Sánchez de Rojas, M. I., & Medina, C. (2021). Use of recycled coarse and fine aggregates in structural eco-concretes. Physical and mechanical properties and CO2 emissions. *Construction and Building Materials*, *285*, 122926. https://doi.org/10.1016/j.conbuildmat.2021.122926

Reiter, L., Wangler, T., Anton, A., & Flatt, R. J. (2020). Setting on demand for digital concrete – Principles, measurements, chemistry, validation. *Cement and Concrete Research*, *132*, 106047. https://doi.org/10.1016/j.cemconres.2020.106047

Röck, M., Saade, M. R. M., Balouktsi, M., Rasmussen, F. N., Birgisdottir, H., Frischknecht, R., Habert, G., Lützkendorf, T., & Passer, A. (2020). Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. *Applied Energy*, *258*, 114107. https://doi.org/10.1016/j.apenergy.2019.114107

Saade, M. R. M., Yahia, A., & Amor, B. (2020). How has LCA been applied to 3D printing? A systematic literature review and recommendations for future studies. *Journal of Cleaner Production*, *244*, 118803. https://doi.org/10.1016/j.jclepro.2019.118803

Xing, W., Tam, V. W. Y., Le, K. N., Butera, A., Hao, J. L., & Wang, J. (2022). Effects of mix design and functional unit on life cycle assessment of recycled aggregate concrete: Evidence from CO2 concrete. *Construction and Building Materials*, *348*, 128712. https://doi.org/10.1016/j.conbuildmat.2022.128712

Yao, Y., Hu, M., Di Maio, F., & Cucurachi, S. (2020). Life cycle assessment of 3D printing geo-polymer concrete: An ex-ante study. *Journal of Industrial Ecology*, *24*(1), 116–127. https://doi.org/10.1111/jiec.12930

Younes, A., Elbeltagi, E., Diab, A., Tarsi, G., Saeed, F., & Sangiorgi, C. (2024). Incorporating coarse and fine recycled aggregates into concrete mixes: Mechanical characterization and environmental impact. *Journal of Material Cycles and Waste Management*, *26*(1), 654–668. https://doi.org/10.1007/s10163-023-01834-1

Zhang, Y., Luo, W., Wang, J., Wang, Y., Xu, Y., & Xiao, J. (2019). A review of life cycle assessment of recycled aggregate concrete. *Construction and Building Materials*, *209*, 115–125. https://doi.org/10.1016/j.conbuildmat.2019.03.078