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## Research Article

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# Lightweight 3D Printed Concrete Beams Show an Environmental Promise: A Cradle-to-Grave Comparative Life Cycle Assessment

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## ABSTRACT

Despite the increasing interest in 3D Concrete Printing (3DCP) in construction, limited research has quantitatively investigated the environmental impact that 3DCP brings. The existing Life Cycle Assessment (LCA) studies in the field can be criticized for a lack of clearly defined functional units of comparison, especially considering load-bearing structures. This paper investigates the potential environmental benefits of 3DCP over conventional concrete construction in a case study of structural beams based on a cradle-to-grave comparative LCA. Unlike in the existing LCA studies on 3DCP, this paper employs a carbonation model to account for the potential carbon offsetting from the use-stage of 3DP concrete, which showed to be significant for the results. The assessment includes three-beam designs, each analyzed for both prefabrication and on-site construction scenarios. While 3DCP generally has a higher environmental impact due to the larger quantity of cement employed in the process, the reduction of materials through shape and infill optimization results as valid design principles to reduce emissions. Results show that, while standard designed 3DCP beams perform worse than their equivalent cast beams, lightweight designs for printed beams are promising in terms of reducing the environmental impacts from construction. The paper draws recommendations for future research on material development, e.g. integration of larger aggregates and low-clinker cement, and carbonation-efficient 3DCP design of load-bearing structures, e.g. considering the environmental benefits of recarbonation in the design optimization process.

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## 1. Introduction

### 1.1 Global Environmental Impact of Concrete Construction

The construction industry is estimated to be responsible for 33% of greenhouse gases (GHG) emissions and 40% of the global resource use and waste generation (Eberhardt et al. 2020). On average, 7% of global anthropogenic CO<sub>2</sub> emissions are attributed to construction using concrete (IEA 2018; Miller et al. 2016). The global production of cement, the fundamental constituent of

concrete, has been steadily increasing and was estimated to be 4.1 Gt in 2020 (Hatfield 2021) with a projection above 4.7 Gt in 2050 (IEA 2018). The majority (77%) of the GHGs caused by cement production is carbon dioxide (CO<sub>2</sub>) emissions attributable to the clinker production, which requires heating at around 1400 degrees Celsius. This results in high Embodied Energy (EE) that ranges from 0.6 to 2.0MJ/kg in the produced concrete (Barcelo et al. 2014).

Current EU policies target a 40% CO<sub>2</sub> emissions reduction by 2030 compared to the 1990-level, with a suggested proposal of raising the target to 55% (European Commission 2021). The IEA and key cement companies created a shared objective to target a 20-25% reduction in carbon emissions by 2030 (IEA 2020). This points towards a growing interest in sustainable alternatives to conventional construction methods and materials.

Together with the development of more sustainable materials, an increasing body of research is revolving around digital and automation strategies for sustainable design and manufacturing technologies. The optimization of structural design has been reported to result in 18% to 24% reductions in cost and carbon emissions in concrete structures (Gan et al. 2019). The increased fabrication freedom and automation potential unfolded by digital fabrication techniques can lead to a further reduction in GHG emissions and costs (Agustí-Juan et al. 2017).

Among emerging automation technologies for sustainable construction, Additive Manufacturing (AM) occupies a fundamental role, enabling strategic material placing (Naboni et al. 2019). Research in AM-enhanced concrete construction is mainly distinguished between (i) indirect applications for Additive Formwork Manufacturing (AFM) to produce elements of variable complexity (Naboni and Breseghello 2019, Naboni and Breseghello 2020) and structural elements (Burger et al. 2020); and (ii) direct 3D printing of construction elements (Buswell et al. 2018). Within these application fields, 3D Concrete Printing (3DCP) is the main AM technique that has attracted the interest of both research (Labonotte et al. 2016, Perrot 2019, Buswell et al. 2020) and innovative practice (COBOD 2021, XTreeE 2021, CyBe 2021, Icon 2021, Winsun 2021).

In this framework, this paper focuses on the use of Life Cycle Assessment (LCA) for critical analysis of the environmental impacts of 3DCP for the manufacturing of reinforced concrete horizontal structures (Fig. 1), which accounts for almost 43% of the concrete use in a reinforced concrete construction (Cho et al. 2004). The aim is evaluating the readiness of the current state-of-technology and state-of-design in 3DCP as a valuable solution to reducing GHG emissions.



Fig. 1. Robotic 3DCP process of a full volume benchmark beam at the CREATE Lab (SDU)

### *1.2 3D Concrete Printing for Structural Applications*

3DCP is an AM technique where semifluid cement mortar is deposited in subsequent layers following a computer-generated path to creating a solid structure. To date, most research and industry projects employ mortar mixes with very fine aggregates and accelerating and plasticizing admixtures that are continuously extruded through a nozzle controlled by an industrial robotic arm or gantry system (Bos et al. 2016). The key benefits of this technology are that the material can be programmatically placed only where needed, and that no formwork is in principle required, increasing the material efficiency and the design freedom with reduced costs (Allwood et al. 2011, Mani et al. 2014). 3DCP enables the adoption of complex structures obtainable from structural optimization and functional hybridization (de Schutter et al. 2018). The reduction of concrete material usage through structural optimization as well as the reduction of auxiliary operations promise a large environmental impact in the construction industry (Chandra Paul et al. 2018; Vantghem et al. 2020).

Despite the growing number of research studies and early applications, the full adoption of 3DCP in civil uses is still limited due to the infancy of the technique. Vertical elements, i.e. walls and columns, are the structural typology where 3DCP is most often employed in the industry, and particularly, for on-site applications, but also widely explored in research with a focus on aesthetics

(Anton et al. 2020) and structural (Suiker et al. 2018) possibilities. Short span post-tensioned pedestrian bridges (Salet et al. 2018) have been tested and built, demonstrating advantages in customization and material savings (Vantghem et al. 2020). Research was carried out on prefabricated beam elements, with explorations on reinforcement integration strategies (Gebhard et al. 2021) and code compliance (Mesnil et al. 2020), and material saving. However, challenges in modeling the anisotropic mechanical behavior (Panda et al. 2017), in the simulation of printed structures, the inherent limitations of the layered manufacturing process, and the difficulties in integrating reinforcements, currently bound 3DCP to often simplistic solutions.

To further enhance the effectiveness of 3DCP as an environmentally sustainable construction practice, it is crucial to jointly investigate the development of structural design models and the study of their environmental implications. In this light, this work introduces a novel method for designing and manufacturing lightweight load-bearing horizontal structures with 3DCP and analyzes its potential environmental impacts through a cradle-to-grave life cycle assessment.

### *1.3 Life Cycle Assessment of 3DCP*

The current research focus regarding emissions in concrete construction is on GHGs. Multiple LCAs for cement production reports high variance in the amount of GHG emissions, in the range of approximately 500 to 950 kg of CO<sub>2</sub>eq per ton of cement produced (Lei et al. 2011).

In the literature are found three comparative LCAs on 3DCP of relevance for this study. Weng et al. (2020) compared prefabricated bathroom units and reported lower environmental impacts associated with 3DCP due to the assumptions formulated about the reuse of formworks used in their analysis. Their sensitivity analysis shows that a breakeven of emissions is reached at around 25 reuses, which results in traditional manufacturing being most beneficial when considering extensive reuse of the formworks. Alhumayani et al. (2020) carried out a comparative LCA study where unreinforced 3DCP walls are compared to reinforced cast-concrete walls. Comparing it to cast concrete, the study reports 27.2% higher climate change potential for 3DCP, indicating relatively higher impacts from GHG emissions for 3DCP, while all other impact categories resulted lower. Mohammad et al. (2020) compared a conventional reinforced concrete wall to a 3DCP reinforced wall, as well as to two different unreinforced 3DCP load-bearing walls of 1 m<sup>2</sup>. The study presents significantly lower impacts from the unreinforced walls. The reinforced walls show a higher climate change potential for the 3DCP, but a lower potential in terms of acidification, eutrophication, and smog formation.

These valuable studies lack the definition of a clearly identified Functional Unit (FU), arguably a significant factor that could affect the results of an LCA (Panesar et al. 2017). Furthermore, the literature review highlighted limitations in their system definition, i.e. adopting a cradle-to-gate system boundary, ending at the manufacturing stage. Furthermore, to the best of our

knowledge, no existing LCA has yet focused on evaluating the environmental impact of horizontal load-bearing structures realized with 3DCP.

The presented work aims at addressing the above-mentioned gaps and answering the following three research questions:

- (1) What are the main parameters that influence the environmental impacts of the 3DCP technology, and which of these are associated with the most uncertainty?
- (2) What is the magnitude of the environmental impact of 3DCP beams compared to traditional cast-concrete beams in a cradle-to-grave comparison?
- (3) Given the modeling assumptions considered in this study, how do prefabrication and on-site manufacturing compare for both 3DCP and cast beams?

## **2. Materials and Methods**

### *2.1 Experimental Studies on 3DCP at SDU CREATE*

The CREATE Group at the University of Southern Denmark is currently investigating novel design and manufacturing strategies that take advantage of 3DCP to fabricate high-resolution lightweight structures in concrete. Preliminary works consisted in the development of a fabrication setup, of a specific material mix and its characterization (Joergensen et al. 2021), and a digital simulation and visualization tool to predict the material behavior of the 3DCP process and its outcome (Breseghello and Naboni 2021a) These tools have been exploited in a design and fabrication experiment where the printing path and robot code are programmatically manipulated (Breseghello and Naboni 2021b).

The design scenario of the presented paper is that of structural reinforced concrete beams for civil uses to be placed below a slab, characterized by a similar boundary volume of 3.00 x 0.30 x 0.16 m, but differing in their internal material layout. The outcomes are a series of elements with different levels of porosity, and consequently volume of material and weight (Fig. 2, left). For comparability with conventional beams, the shape and the section of the beams are set as a standard rectangular, and any possible functional integration, e.g. with the slab or with installation conduits, is avoided. Structural optimization and smart toolpath planning were integrated into the workflow to optimize the design and fabrication processes, as well as the structural performance of the manufactured beams.

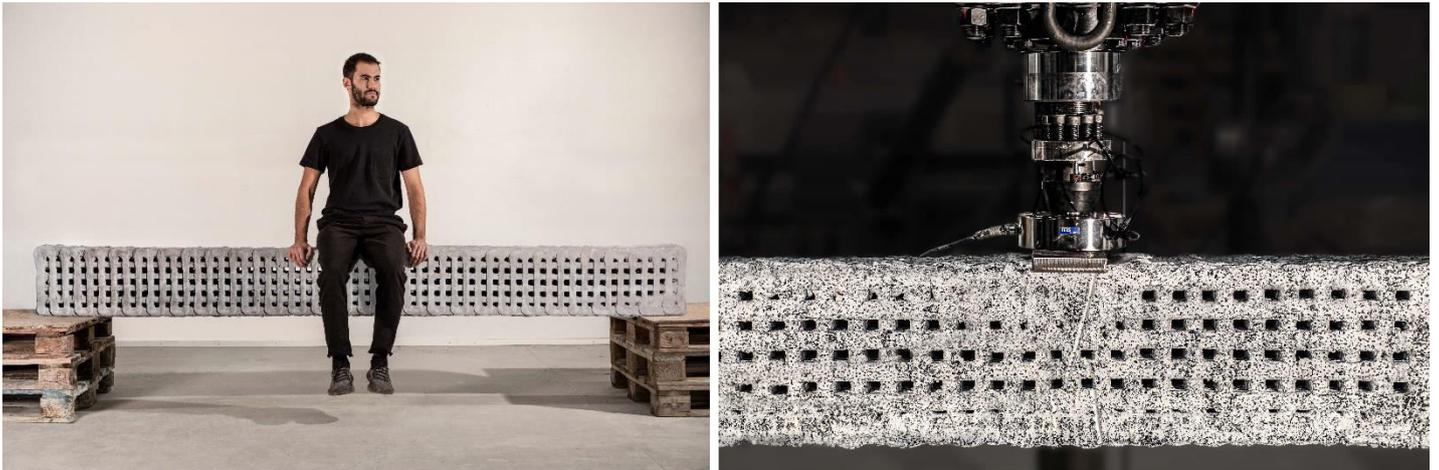


Fig. 2. Porous beam prototype, i.e. Grid 3DCP Beam (left) and three-point bending structural testing of the 3DCP reinforced concrete lightweight beams (right), from the 3DLightBeam project by CREATE (SDU).

The printed elements were designed as simply supported beams of 3 m, i.e. with a vertical point load in their middle at 1.5 m, and characterized by a span of 2.76 m, with supports at 0.12 m from each longitudinal edge. The beams were subsequently tested structurally via a three-point bending test (Fig. 3, right). The results from the fabrication and the subsequent testing proved the viability of the approach in terms of strength and reduced material use.

## 2.2 LCA Goal and Scope

The LCA presented in this study has been conducted based on the ILCD handbook and following the international standards such as ISO14040, ISO14044, and EN15804 (i.e. a standard on the sustainability of construction works) to ensure the standardization and replicability of the results. All modeling assumptions are based on the relevant scientific literature, empirical data, and expert testimony from industry and academia (Table S.1). The EC-JRC impact assessment method, also known as EF 3.0, has been adopted as recommended by the 15804 standards. SimaPro 9.1 and EcoInvent 3.6 cut-off databases (Ecoinvent, 2020) were utilized for the inventory modeling and impact assessment. Hotspot and sensitivity analyses have been carried out to discover the main sources of emissions, and understand which parameters would be subject to a high degree of variance in the results.

The goal of the LCA conducted in this study is to unveil the potential life cycle environmental impacts of two load-bearing beam designs, i.e. a *Solid 3DCP Beam (B1)* (Fig. 3a) and a *Grid Beam (B2)* with about 25% material reduction characterized by an orthogonal grid layout (Fig. 3b). Both the designs are developed and printed by the CREATE Group at the University of Southern Denmark (SDU). Taking from the results of the structural tests performed on the printed specimens, the Functional Unit (FU) has been formulated as a function of failure in three-point bending for two beams, and it is given as the following:

*Beams of 3m length with a span of 2.76m in a simply supported beam setup, tested in three-point bending with a failure of 43.7kN and an estimated lifetime of 50 years.*

The FU has been set to equal the load-bearing capacity achieved from the test results of (*B1*). The strength of 43.7 kN is the average failure load of the conducted tests. The chosen data for comparison is Ultimate Limit State (ULS). Based on Eurocode2, an alternative FU could be based on the Service Limit State (SLS), i.e. the load at maximum admissible deflection of the beam, which for this used span is equal to about 11 mm (Dansk Standard, 2008). However, given the proportional outputs of the two calculations, the former has been selected.

A third theoretical *Cast Beam (B3)*, representative of a conventional concrete structure, was designed using standard engineering procedures as a 3m element with the same functional characteristics described above (Fig. 3c). It was designed considering the same rebar arrangement as *B1* with a 40MPa concrete mixture. The calculations for *B3* are based on the work of Wight and Macgregor (2011) and verified by the software Polybeam (PolyStruc 2021).

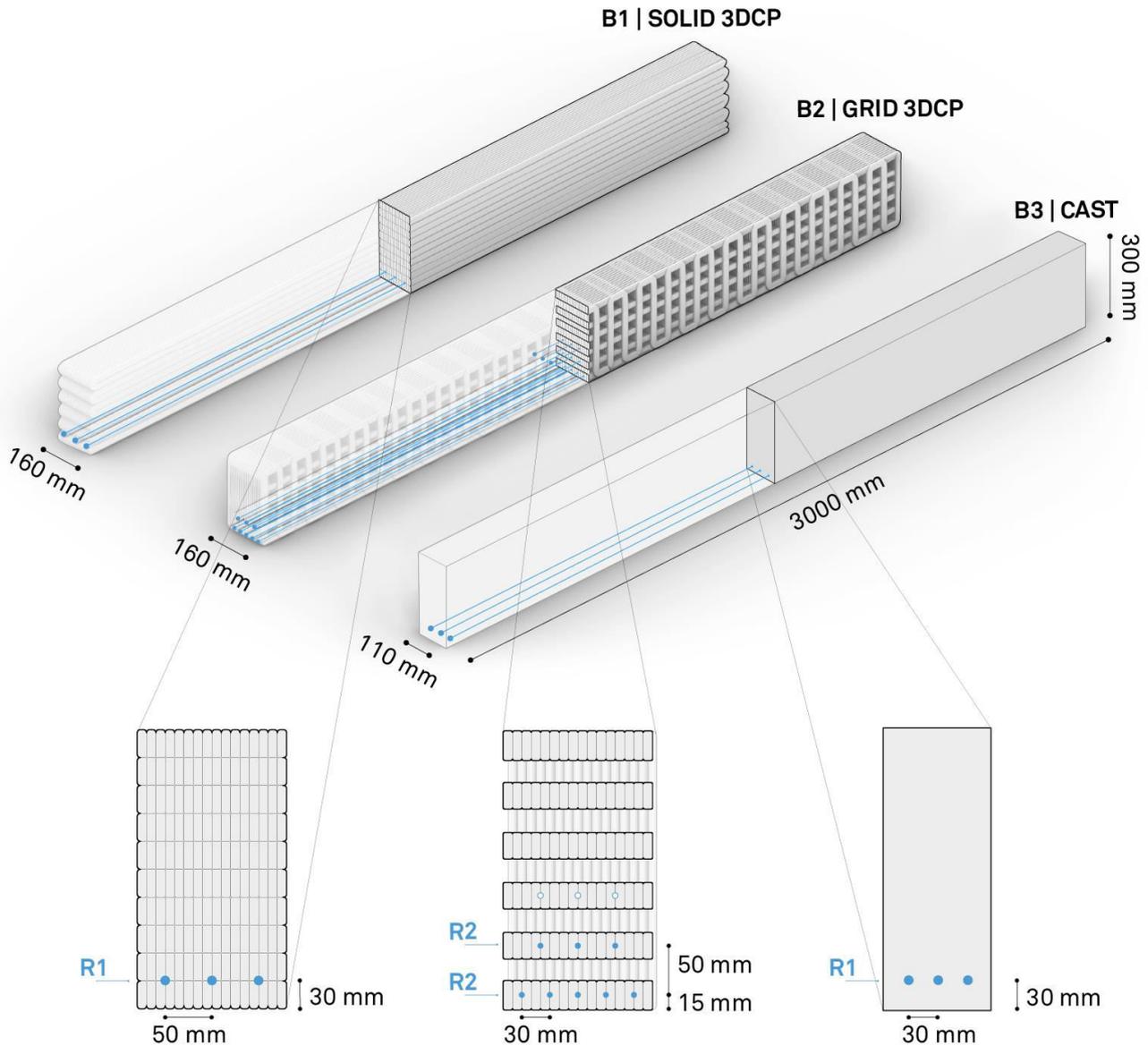


Fig. 3. Axonometric and section view of the three studied beams: (B1) Solid 3DCP beam; (B2) Grid 3DCP beam; (B3) Cast beam

Considering the defined FU, a reference flow of 0.87 for the *B2* and of 1 for *B3* are applied to provide the same load-bearing capacity owing to their higher performance. The LCA considers beams produced at the current time and disposed of 50 years in the future. The geographical scope is limited to Denmark. No multifunctionality was identified in the foreground system. The compared systems are summarized in Table S.2.

The system boundary includes all the life cycle tiers of the studied beams, i.e. material extraction, manufacturing, use, transportation, and disposal (Fig. 4). Additionally, the system boundary has been extended to include the life cycle environmental impacts of essential manufacturing equipment (i.e., the robotic arm and pump) to account for the effect of its reuse, accurately. The entire lifecycle of the manufacturing equipment has been assumed to be a part of the production process, which means the disposal of the manufacturing equipment will be attributable to the manufacturing stage when considering a hotspot analysis.

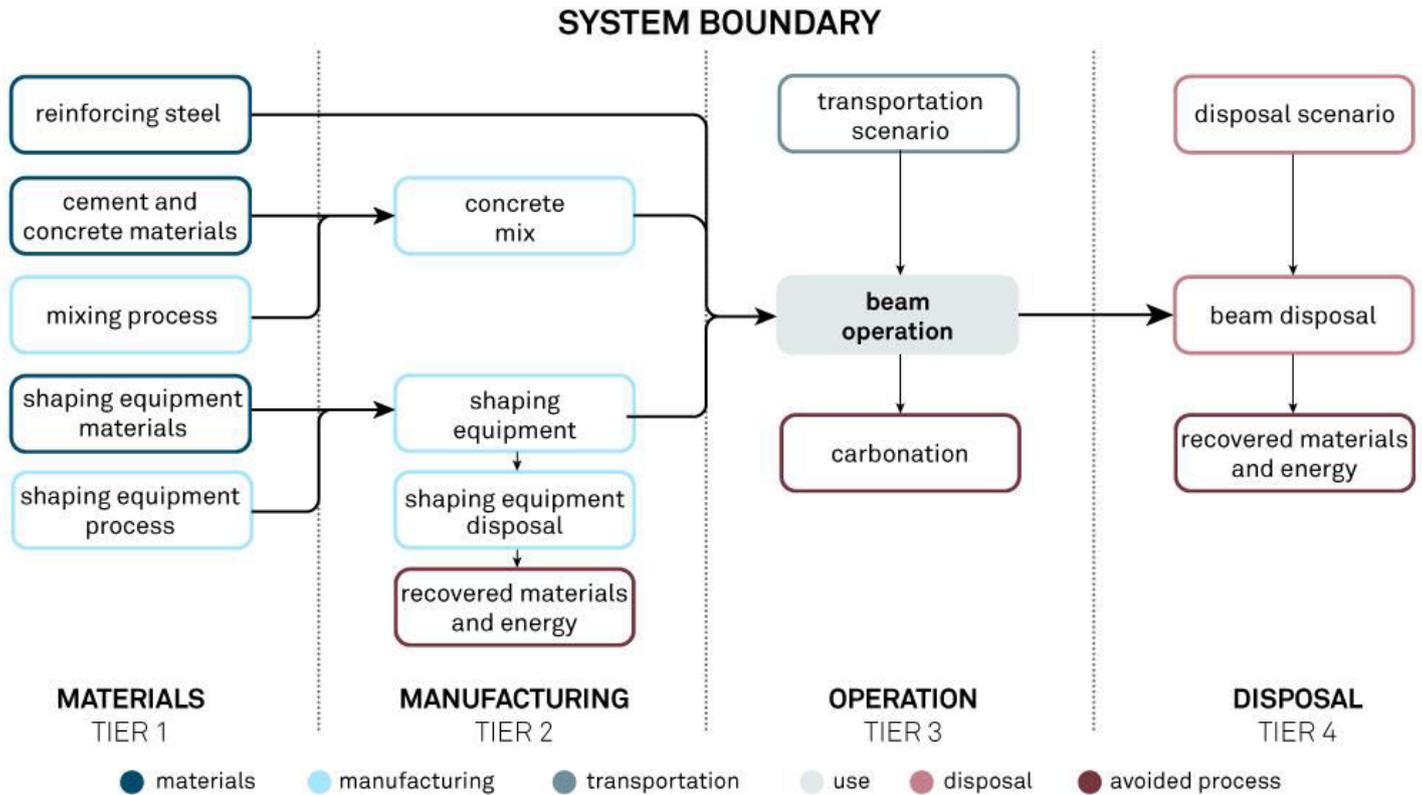


Fig. 4. The system boundary of the LCA model

In compliance with EN15804, the LCA reports the impact categories as seen in Table S.3 at characterized midpoints. Furthermore, an aggregated single score will be reported for a more straightforward evaluation of all impact categories.

## 2.3 Life Cycle Inventory

### 2.3.1 Materials

The composite nature of reinforced concrete consists of different components: the concrete mix, i.e. aggregates (gravel and sand) bound together with a cement matrix and mixed with water, and steel rebars. Reinforcing steel for concrete is generally of a low grade and not subject to variability, resulting in a uniformity of the material profiles for the 3DCP and cast-concrete beams. Compared to casting processes, 3DCP currently requires a concrete mix with smaller aggregates to be pumped through the system, and accelerator admixtures for faster hardening rates that allow withstanding the load of the subsequent layers.

*B3* is considered to be produced with a 40MPa strength concrete mix, and all the related data were obtained from the EcoInvent 3.6 database. To better represent the high variability of the concrete mixes for 3DCP found in the literature, the process *3DCP mixture* presented in Table S.4 was defined as the average between the mixtures used at SDU and two other mixtures from (Anell 2015; Nerella and Mechtcherine 2019). For the modeling of the 3DCP concrete mixture, the specific unit process, Concrete 45MPa (RoW) was obtained from the EcoInvent database and modified to represent the averages previously mentioned.

### 2.3.2 Manufacturing

Three manufacturing systems were identified for the following processes: i) a robotic 3DCP cell, consisting of a medium payload 6-axis industrial robot and a concrete pump; ii) a wooden formwork for on-site cast-concrete fabrication, and iii) a steel formwork for cast-concrete prefabrication (Table 1). Adequate formwork materials and amounts were estimated based on an interview with Spaencom A/S, a Danish concrete prefab elements manufacturer. The reuse of the formwork was selected similarly and included in the sensitivity analysis.

The robotic cell was modeled based on the current 3DCP cell at the SDU CREATE Lab, which includes a 6-axis ABB IRB 6650S robotic arm, and a PFT ZP 3 XL conveying pump (Fig. 5). The technical data available from the manufacturers were utilized along with the estimates of the parts and processes required for the manufacturing of the robotic cell. The amount of energy necessary for operating the robotic arm was calculated utilizing the Pareto principle (Slack et al. 2013), which assumes that the robotic arm is used at 80% of its maximum capacity for 20% of the time and operated at 20% of its full capacity for the remaining 80% of the time. It was also assumed that 75% of the pump and the robotic arm are repurposed at the end of life.

Table 1. Modeling assumptions for manufacturing equipment

	Pump (PFT ZP3XXL)	Robot (ABB IRB6650S)	On-site Formwork	Prefabrication Formwork
Total weight	240kg	2250kg	33.2kg	200kg
Materials & processes	55kg electric motor 51 kg frequency inverter 114kg low-alloy steel 114kg Metalworking, 20kg ABS plastic 20 kg injection molding	50kg e-motors 30kg cables 20kg electronics PCB 2100kg steel 1600kg casting 10 kg steel machining 500 kg die stamping 20m welding	33.2kg Plywood 0.332h power sawing	200kg Stainless Steel 200kg Metalworking processes
Operation	2.4 kWh	0.768 kWh	None	None
Reuse	35.000 hours	35.000 hours	5 castings	2000 castings
Disposal	75% component reuse	75% component reuse	Incineration	Scrap steel



Fig. 5. 3DCP fabrication setup at the CREATE Lab

### 2.3.3 Transport

Market mix processes were utilized for the assumption of transportation of raw materials to a specific location in Denmark. In contrast, two different transportation scenarios were identified for the on-site and prefab units. The transported weight consists either of raw materials and manufacturing equipment for on-site construction or of the manufactured beam in the prefab production system. The prefabrication assumes that the final product is transported to the construction site from a single facility in Denmark that is 250 km far from the site. The on-site scenario assumes that more facilities are present, with a 50 km distance to the construction site, and a 50 km return of the manufacturing equipment (Fig. 6).

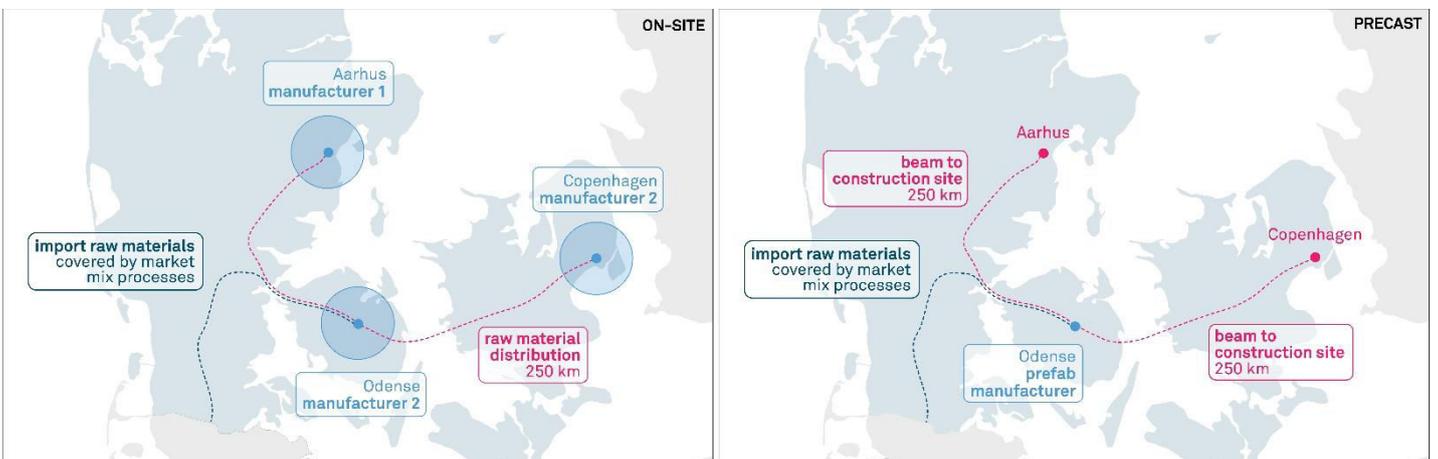


Fig. 6. Transportation flows for the on-site (above) and precast (below) production processes. Copenhagen, Odense, and Aarhus are considered for this study as the three major Danish cities, and strategically located in the national territory.

### 2.3.4 Use Stage

Given its potential to offset CO<sub>2</sub> emissions from concrete production (Xi et al. 2016, Cao et al. 2020), concrete recarbonation has been included in the assessment. The modeling of recarbonation can be complex as it relies on multiple environmental, physical, and material parameters (Venkat Rao and Meena 2017). The Lagerblad model was employed for its simplicity of application, introducing constants for environmental conditions and concrete mixtures (Lagerblad 2005). The following steps were accordingly implemented:

1. Assess the depth of recarbonation based on the parameters presented:

$$d = k * \sqrt{t}$$

2. Assess the volume (m<sup>3</sup>) of the concrete based on the exposed surface area:

$$m3 \text{ carbonated} = \sum A * d$$

3. Assess the CO<sub>2</sub> amount based on the carbonized volume based on the material profile:

$$kgCO_2 \text{ per } m^3 = 0.75 * C * CaO * \frac{MCO_2}{McaO} \left( \frac{kg}{m^3} \right)$$

4. Assess the total kg of CO<sub>2</sub> uptake of the concrete element by multiplying results from steps 2 and 3

$$m3 \text{ carbonated} * kgCO_2 \text{ per } m^3 = kgCO_2 \text{ carbonated}$$

Where:

$d$  is the depth of recarbonation,  $k$  is a constant for environmental effects (3.5 for this study),  $t$  is years of recarbonation (50 for this study),  $A$  is the area in m<sup>2</sup> exposed to air,  $C$  is the mass of portland cement clinker per m<sup>3</sup>,  $CaO$  is the amount of CaO in cement (weight %),  $Mco2$  is the molar mass of CO<sub>2</sub>,  $McaO$  is the molar mass of CaO

### 2.3.5 Disposal

Currently, 89% of concrete is recycled as road filling in Denmark, while the remaining 11% is estimated to be landfilled (EEA 2020). The disposal is assumed to occur 50 years in the future, where improvements are to be expected. Hence, it was assumed that while no landfilling occurs (Zhang et al. 2019), 50% of concrete waste is processed for high-grade recycling for aggregates in new concrete, and the remaining 50% is to be used for low-grade recycling for road filling (Pedersen and Ottosen 2019).

### 2.4 Sensitivity Analysis

A sensitivity analysis was conducted on the parameters identified as uncertain in values or likely subject to variation during the inventory modeling. The parameters were grouped into six categories, resulting in six uncertainty assessments considering the best- and worst-case estimates of parameter values (Table 2). The six cases identified were the recarbonation amount, clinker content, transportation, reuse of manufacturing equipment, recycling efficiency, and energy use of 3DCP cells. The results were compared for midpoint categories for the varying scenarios.

Table 2. Uncertain parameter values were grouped into categories, and sensitivity was assessed in worst and best cases compared to the best estimates of the inventory model. More information in S.5.

	Worst-case	Realistic case (inventory model)	Best-case
Category 1: recarbonation of concrete	Correction factors lowest values	Best estimate of correction factors	Correction factors highest values
Category 2: Clinker content	Cast: 95% 3DCP: 95%	Cast: 62% 3DCP: 95%	Cast: 62% 3DCP: 62%
Category 3: Transportation distance to the construction site	250 km 500 km	50 km 250 km	10 km 50 km
Category 4: Reuse and lifetime of manufacturing equipment	1* 1 000** 10 000h***	5 2000 35 000h	100 10 000 100 000h
Category 5: Recycling (EoL) of manufacturing equipment and beams	89% recycled to road filling 11% landfilled 25%	50% recycled to new concrete aggregate 50% recycled to road filling 75%	100% recycled to new concrete aggregate 100%
Category 6: Energy use of 3DCP robot and pump	2.4 + 7.5 kWh	0.768 + 2.4 kWh	0.48 + 1.5kWh

\* reuse of plywood formwork. \*\* reuse of steel formwork. \*\*\* lifetime of 3DCP equipment

## 3. Results

### 3.1 Midpoint Impact Categories

All the midpoint impact results, except for particulate matter, human toxicity (e.g., cancer), land use, and water use impact

categories display higher impacts for the *Solid 3DCP Beam (B1)* (Fig. 7). The climate change potential of the *B1* results is 300% higher than the *Cast Beam (B3)* and 180% higher than the *Grid 3DCP Beam (B2)*.

As presented in Table S.6, minimal differences were observed in the life cycle impacts of on-site 3DCP and prefab systems. However, significant differences in various impact categories were observed for the cast systems due to differences in manufacturing equipment. Overall, the *Grid 3DCP Beam (B2)* was found to have a 20% higher impact on average in the on-site and 40% in the prefab systems when compared to the corresponding cast concrete beams.

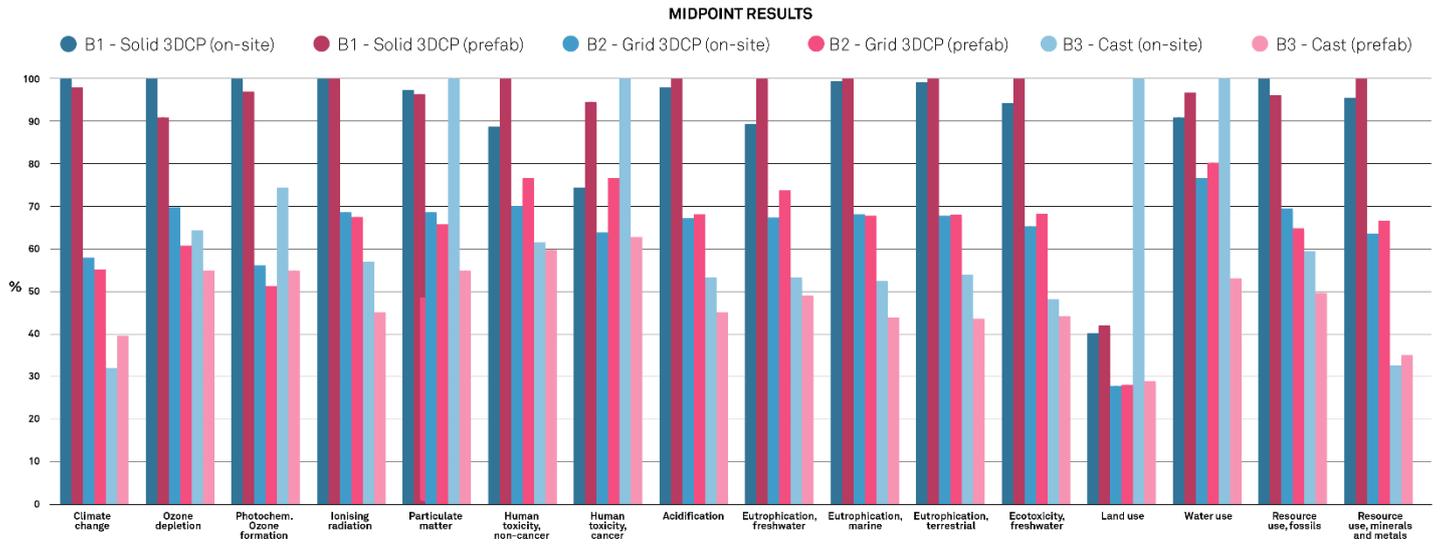


Fig. 7. Relative midpoint results of the compared systems

A single score comparison i.e. aggregated and weighed midpoints, is displayed in Fig. 8. *Cast Beam (B3)* is characterized by the lowest emissions 5.8 and 6.1 mPoints for prefab and on-site respectively), followed by the *Grid 3DCP Beams (B2)* (9.2 and 9.3 mPt), and finally the *Solid 3DCP Beams (B1)* with the highest single score (14.3 and 13.9 mPt). The results show most of the impacts are highly influenced by the three beam designs. The climate change potential and the fossil and mineral resource use contribute to most of the single score associated with the beams.

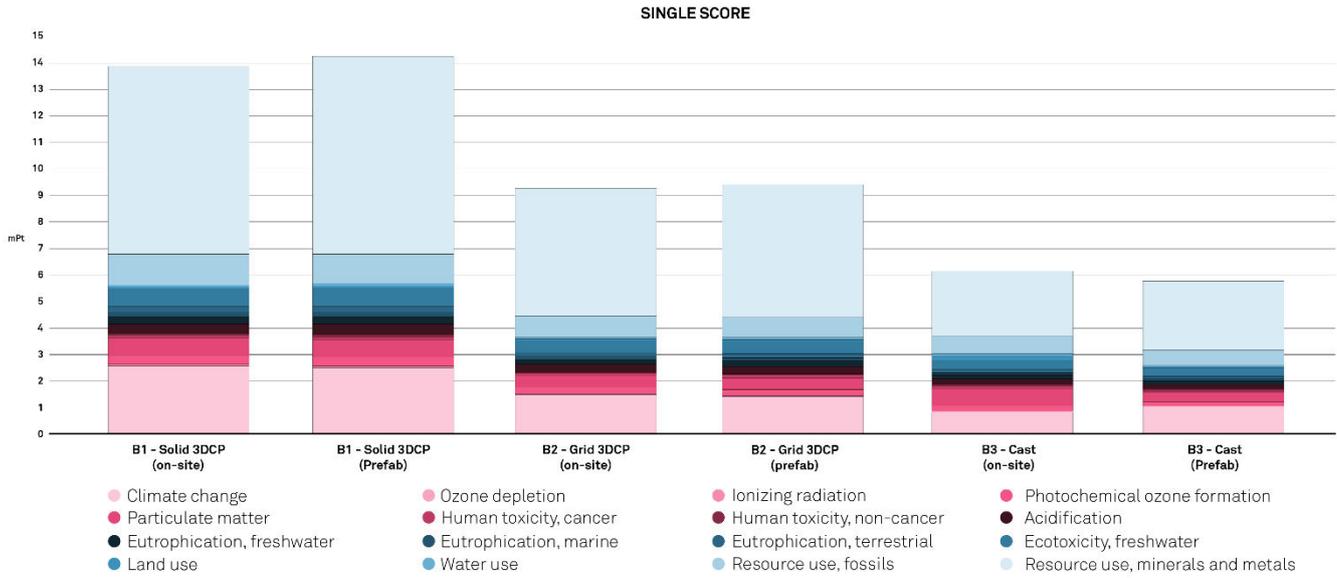


Fig. 8. Single score results, aggregation of the weighted midpoints.

### 3.2 Hotspot analysis

The hotspot analysis of the midpoint impact categories reveals that most of the impacts can be traced back to the material extraction stage (Fig. 9). Depending on the product system, the contribution of the manufacturing stage is generally minimal at around 2-15% of the total impact, except for the on-site cast-concrete system, which is due to the low reuse of plywood formwork that increased the contribution to the impact. Transportation contributes to a minimal amount of around 2-15%, although generally higher values are observed for the 3DCP on-site systems due to transportation requirements for the 3DCP cell. The use stage results in an offset of approximately 10% for the Climate Change impact category due to recarbonation. The disposal is found to prevent impacts due to material substitution from recycling, resulting in negative impacts in various categories, the highest of which is the carcinogenic human toxicity which reduces approximately 40% of the total impact from the other stages (Fig. 9d).



Fig. 9. Hotspot analysis of different product systems: B1 - Solid 3DCP on-site; B1 - Solid 3DCP prefab; B3 - Cast on-site; B4 - Cast prefab.

A detailed review of the raw material acquisition stage revealed that cement production accounts for most of the impacts, ranging from 58 to 76% of the single score. This is followed by the production of reinforcing steel which ranges from 11% to 27%. The remainder is the sum of other materials and processes, which contributed to roughly 15% of the total impact of the materials stage (Fig. 10).

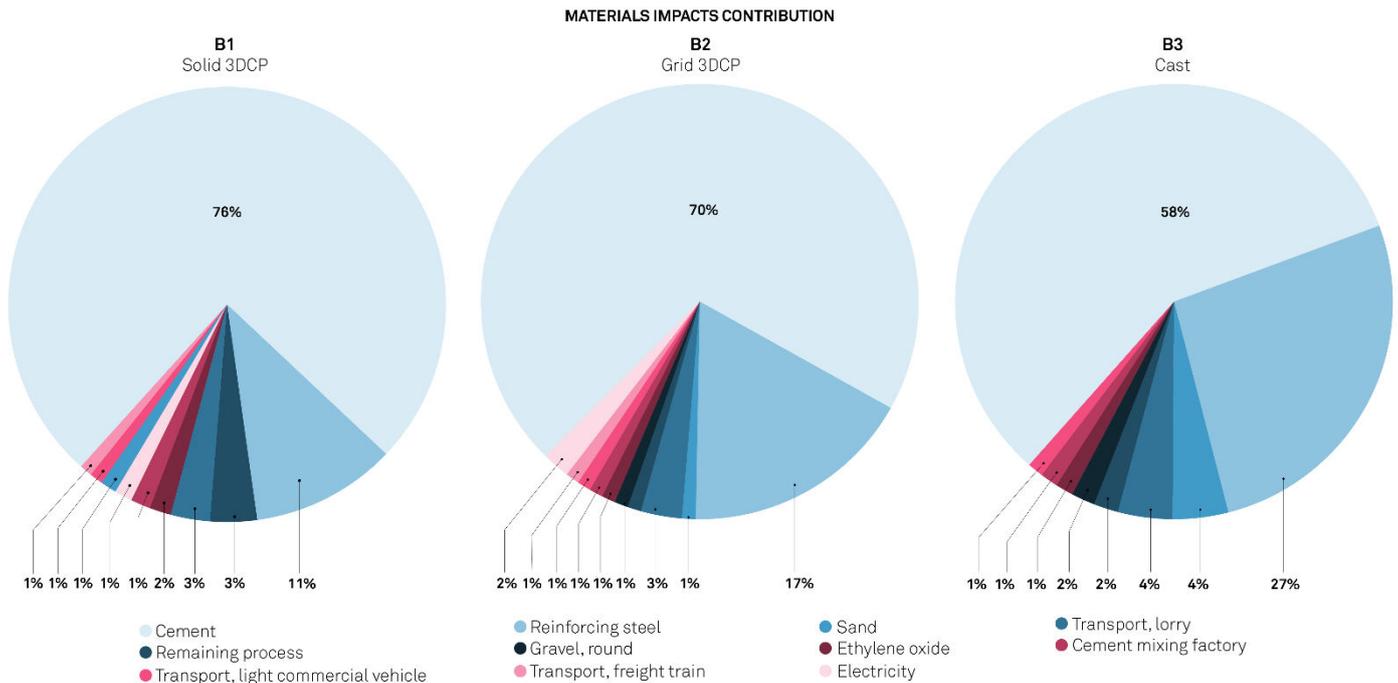


Fig. 10. Single score contribution from materials and materials production processes.

### 3.3 Sensitivity Analysis

According to the sensitivity analysis results (Fig. 11), the impact of recarbonation varies approximately between 7% and 34% based on the correction factors assumed in the recarbonation model proposed by Lagerblad (2005). As the maximum recarbonation is reached in the assumed lifetime for B2, no improvement can be outlined in the best-case scenario.

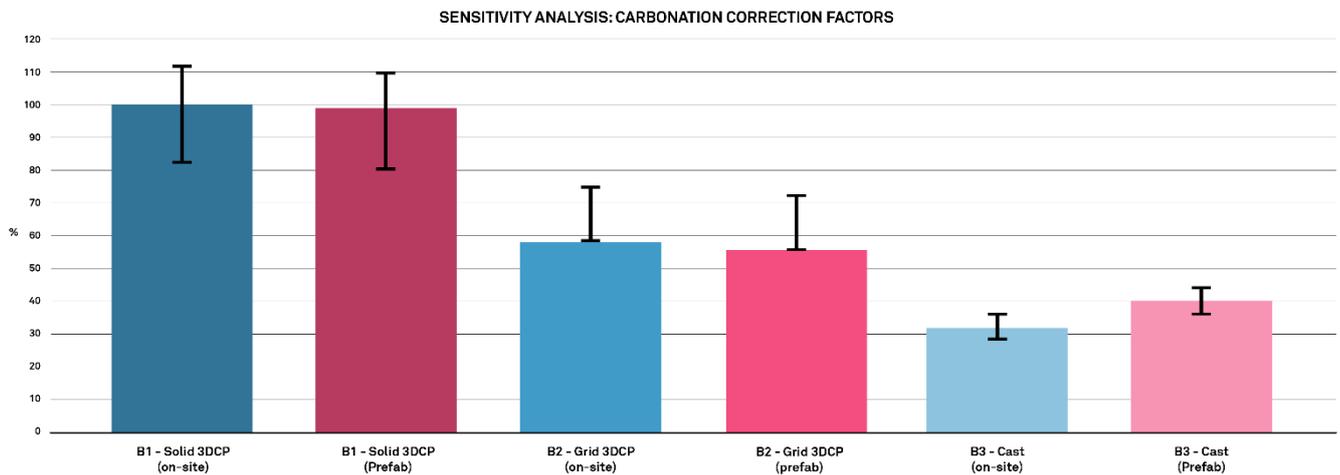


Fig. 11. Variation in climate change impacts in best and worst-cases of recarbonation correction factors compared to reference results

The clinker content has a high effect on the impacts, e.g. approximately 20% on climate change. Certain categories, e.g. land use, display a relatively low impact variation (Fig. 12a). Overall, the solid 3DCP beams present high variation, with specific impact categories more sensitive for all beams, such as the mineral resources use impact category.

The transportation distance from manufacturer to construction site has a great influence on the systems, with the highest magnitude on the *on-site beams*, which is due to the transportation of 2.5 tons of manufacturing equipment. GHG emissions show an increase of up to 30% in the worst-case, whereas the best-case leads to a decrease of up to 10% (Fig. 12b).

The reuse of manufacturing equipment is generally insignificant for the results. However, the on-site cast beam has a high environmental impact in the worst-case scenario, where the formwork is not reused. In the best case of 100 reuses, the on-site cast beam is comparable to the other beams (Fig. 12c). Recycling the manufacturing equipment has a relatively low impact in most categories, with the exceptions of water use and land use. The energy use for the robot and pump has a negligible effect when comparing the best and worst-case scenarios.

Current environmental climate change potential issues associated with the 3DCP technology lie in the higher use of cement, which results in required material savings of 59% for prefabricated beams and 63% for on-site produced beams to reach a breakeven of emissions compared to traditional cast beam. Overall, a cast beam made from reusable steel formwork presents the lowest total potential environmental impact. B2 beams have a 43% lower climate change impact than B1.

According to the sensitivity analysis results, the clinker content variation is one of the main factors influencing the impact assessment. For recarbonation, the differing cases alter the offset of CO<sub>2</sub>eq. emissions up to 30%, which indicates that more accurate modeling of recarbonation in concrete is essential to be considered in the LCAs of concrete construction elements. Transportation mainly affects the 3DCP on-site systems, only partially affecting the other comparisons. The end-of-life and reuse of the manufacturing equipment do not have a significant effect in any but one situation, i.e. on-site cast-concrete formwork. For the reuse of plywood formwork used for on-site cast-concrete, the difference in the number of emissions, when comparing the low (1) and average (5) reuse scenarios, is increased in the single score from 6.13 to 9.59 mPt.



Fig. 12. Variation in midpoint results considering best and worst-cases of uncertainty within categories: a) clinker content in cement; b) transportation distance; c) reuse of manufacturing equipment; d) recycling of concrete and manufacturing equipment.

#### 4. Discussion

The results of this study show that for geometrically standard short-span reinforced concrete beams, conventional casting has lower emissions compared to the current state of reinforced 3DCP. The hotspot analysis of the midpoint impact categories for 3DCP highlights that manufacturing and transportation combined accounts for only approximately 10% of the impacts, while the remaining amounts are due largely to the cement and its production. Given the achieved structural performance and the proportionally larger amounts of clinker present in the 3DCP mix, i.e. 33% more than for the cast beams in the current work, material savings of approximately 60% for both on-site and prefabricated 3DCP beams are required to reach a breakeven of emissions with

conventionally cast beams. Nevertheless, the results highlight that, from a single score perspective, the gap in global impacts between 3DCP and cast beams is reduced by up to about 30%, with disposable formworks in a single score perspective.

The lightweight 3DCP beam solution introduced in this study shows potential in terms of overall environmental impact. *B2 - Grid 3DCP*, in a weighted single score comparison, presented about 45% less global impacts when compared to *B1 - Solid 3DCP*. This is explained by the lower amount (approximately 25%) of cement employed, but also by the positive effects of recarbonation, which can reduce the carbon emissions by up to 30% more than the solid design. This is achieved thanks to the porous design made possible by the specific control on the material deposition offered by 3DCP.

Overall, the impacts from onsite and prefab productions have been found to be equivalent on a single score perspective for both production technologies. Nevertheless, the *Midpoint Analysis* results show, on average, about 20% higher impacts for the on-site construction process as compared to prefab for the conventionally cast beams.

The results highlight the relevance of including the *Use* and the *Disposal* stages into a Cradle-to-Grave LCA for concrete structures. The hotspot analysis (Fig. 9) shows that the *Use Stage*, through recarbonation, has impacts for -10% on climate change, which can become as high as -30% from the results of the *Sensitivity Analysis* (Fig. 11). The *Disposal* phase brings an impact of approximately 10-20% in most categories, however as low as -58% for *human toxicity, cancer*. This is due to the assumed partial recycling of the used materials, i.e. steel and gravel, overperforming the impact of transport and processing of the disposed of elements. The impacts of the *Use and Disposal* stages are novel findings that are not included in the results of the existing literature at the time of writing. Nevertheless, some general environmental considerations found in the literature regarding the application of 3DCP are confirmed. The results of this study align with Alhumayani et al. (2020) and Mohammad et al. (2020) both reporting 75-80% of the impact attributed to cement, which corresponds to the 76% of B1 assessed in this work. Moreover, they also highlight 25% higher CO<sub>2</sub>eq emissions generated by the 3DCP process altogether, which corresponds to the prefab results found in this research and are only slightly lower than that of the on-site approach (33%).

#### 4.1 Limitations of the study

The requirement of a well-defined FU in comparative LCA implied the use of a simple beam geometry for a fair comparison between the 3DCP and a formwork-based technique that would allow its reuse. As the main competitive advantage of 3DCP lies in its capability to design relatively more complex and customized solutions, the current setup limits the potential of 3DCP for better environmental performance. This is because the innovative nature of the 3DCP process potentially brings hybrid functional possibilities, e.g. integration of beam and slab, integration of technical cavities, that would exploit even further the technology and emphasize its positive environmental impacts.

The specific testing campaign performed on the 3DCP beams and the general lack of simulation and calculation models for this new technology poses a degree of uncertainty in comparison to the well-established cast-concrete structural element taken into account for the assessment. As the FU of comparison is based on the test data, this could have an influence on the results.

The sensitivity analysis highlights that the main uncertainties in climate change related to the clinker content of the cement with the best-case having 23% lower climate change compared to the worst case. The largest uncertainties for the cast beams lie in the reuse of manufacturing equipment, e.g. land use, that can increase up to 400%. A better definition of the clinker content amounts and of the reuse scenario would benefit from a statistical analysis of real-case applications.

The modeling of recarbonation was calculated through a simplified model, which carries a level of uncertainty in the results dependent on the applied constants (about -18% to +12%). Given the impact of recarbonation revealed by the results, accurate modeling of this phenomenon should be paid due attention in future research.

As disposal is expected at the end of the beam lifetime, the characterization factors and impacts may have changed. This is an inherent methodological limitation of LCA.

## **5. Strategies for enhancing the environmental sustainability of 3DCP**

The findings of the presented work indicate that the largest environmental impact of 3DCP is due to the use of materials, and reducing the related emissions requires improvements in design and material development.

Guidelines for material development encompasses:

- *Development of reinforcements methods for 3DCP:* As an upcoming and developing construction technique, methods for reinforcing printed concrete structures are still experimental. The use of conventional steel rebars, which account for up to 23% of the material impact, proved to generally fulfill structural requirements. Future studies on reinforcements should focus on enhancing the structural efficiency of reinforced 3DCP, and in turn, reducing the use of both concrete and steel to achieve optimal structural performance.
- *Concrete aggregates:* Cement has the highest environmental impact on the LCA of 3DCP. Future research should study manufacturing processes for the extrusion of cement mixes with larger aggregates, to reduce the clinker content.
- *Low-carbon concrete:* Sustainable low-clinker cement alternatives (Bhattacharjee et al. 2021) that reduce the environmental impact of the 3DCP material are strategic. Current studies are already focusing on this area ranging from limestone-calcinated clay-based cementitious mixes (Chen 2021) to the recycling of concrete as aggregates (Bai 2021).

Guidelines for the design advancements in 3DCP structures include:

- *Design for recarbonation:* This paper introduced a strategy for lightweight concrete structures based on a porous grid design. This design increases the exposed surface area by 300% in *B2 - Grid 3DCP* compared to the B1 and B3, favoring the recarbonation process. If correctly addressed in the design process, layer-based porous structures shall be taken into account as a long-term carbon sequestration strategy that fits well with the expected lifetime of concrete structures (Fig.13).
- *Shape optimization:* In this study, we have adopted a regular beam shape with a constant section to reduce the number of design variables in comparison. In principle, shape optimization can be both performed with printing and casting. However, 3DCP has much higher fabrication flexibility for almost no cost, while cast beams demand custom disposable formwork accounting for up to 75% of the concrete structure's cost (García de Soto 2018). This practically translated into much higher design freedom achievable through 3DCP, which points to a large potential for future investigation in the shape optimization of horizontal structures, targeting a reduction of the concrete mass to about 60% to outperform casted beams.
- *Bespoke Design:* The use of 3DCP generates a lower environmental impact when employed for manufacturing custom or non-standard concrete elements. In such cases, cast concrete involves a specific formwork design with an increase of ten times in *land use*, about six times in *particulate matter*, and between 100 and 1 reuses in climate change under the on-site scenario. The prefab casting scenario assumes that the use of steel formworks is hardly feasible for one-off applications.



Fig. 13. Detail of optimized toolpath layouts of beam prototypes from the 3DLightBeam project from CREATE

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## Data Availability Statement

The datasets generated during and/or analysed during the current study are partially included as Supplementary Information to the manuscript, and fully available from the corresponding author on reasonable request.

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