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Life-Cycle Assessment of a Concrete Pedestrian Bridge: A Comparative Analysis of 3D Printing and Precast Techniques

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This study aims to compare the environmental impact of precast and 3D concrete printing (3DCP) techniques with a pedestrian bridge case study. A detailed cradle-to-site life cycle assessment has been performed from the standpoint of material, construction, and installation stages. The results showed that the concrete used in 3DCP has a higher negative environmental impact compared to the precast method due to the higher percentage of cement used in printable concrete. However, since C3DP used less material than the precast technique, there is no significant difference in the environmental impact of the total concrete used between the 3DCP and precast bridges. In addition, due to the use of reinforcement and formwork in the precast technique, the environmental impact of the total materials used in the precast bridge was more adverse than the 3DCP bridge. Notably, due to using electricity for printing, the negative environmental impact of the construction process in 3DCP was significantly higher than in the precast technique. Finally, the total carbon dioxide equivalent emitted during the construction of the 3DCP bridge was 80% of the precast bridge.

Key Words: LCA, Environmental Impact, Concrete, Bridge, 3DCP

Introduction

The environmental impact of buildings' construction and operation is enormous. The built environment contributes 40% of global energy consumption, 28% of global greenhouse gas (GHG) emissions, 12% of global potable water consumption, and 40% of solid waste creation (Agustí-Juan and Habert 2017). Concrete and cement-based products are at the heart of the building industry, and their use has expanded exponentially in recent decades (Scrivener, John, and Gartner 2018). Concrete production has a significant carbon footprint, accounting for 4-5% of global CO_2 emissions (Zhang et al. 2014). Furthermore, in concrete construction, a substantial amount of waste is usually generated, mostly from formwork wastes (Mohammad, Masad, and Al-Ghamdi 2020). It has previously been demonstrated that conventional casting technologies have a very low carbon footprint compared to concrete. In particular, the contribution of concrete processing (i.e., transportation, mixing, and pumping) has been less than 1% of concrete's environmental impact (Kuzmenko et al. 2022). Furthermore, concrete shaping through the use of standard formwork along with on-site energy consumption was shown to represent less than a couple of percent of concrete's environmental impact (Hong et al. 2015). The low contribution is due to the low-tech, low-energy nature of these processes and high reuse rate of casting equipment.

Over the past few decades, there has been an increasing interest in automated construction. The present work is focused on extrusion-based additive manufacturing with cement-based materials, referred to as 3D Concrete Printing (3DCP). 3DCP consists of a successive layer-by-layer stacking of concrete filaments contouring an object with no formwork, i.e., by direct material placement. It is thus usually associated with a vision of a so-called “free-form construction” (Tuan et al. 2018). The 3DCP technology, developed around 20 years ago (Khoshnevis 2004), offers potential constructability benefits, including reduced waste, design freedom, reduced human error, and fast production in construction projects (Davtalab et al. 2022). However, limited studies are focusing on sustainability performance and the environmental impact of this new technology (Tuan et al. 2018; Liu et al. 2022).

The adoption of 3DCP in the construction sector was accelerated in recent years. Although there are several applications of 3DCP technology in building construction (Tuan et al. 2018), the use of this technology in bridge construction is still at a primitive stage. C3DP technology has been used for small bridge construction in a few demonstration projects in different countries, mainly pedestrian and bicycle bridges (see Table 1). Detailed information on these bridges can be found in the work of (Miryousefi Ata, Kazemian, and Jafari 2021). Concrete 3D printing allows for a great deal of geometric customization, allowing the bridges to have various expressions (Tuan et al. 2018). It may be possible to use 3D-printed elements in a circular economy since they can be printed, mounted on-site, clamped together and tensioned, and then disassembled anytime to be reused or recycled (Tuan et al. 2018). Although 3DCP is in the early stages of commercialization, the rapid advancements made in this technology indicate its great potential for automating bridge construction in the near future.

Table 1

A summary of 3D Printed Bridges

No	Year	Location	Robotic Printer	Length	Width	Reference
1	2016	Spain	Gantry Printer	8 m	1.75 m	(Mechtcherine et al. 2018)
2	2017	Netherland	Gantry Printer	8 m	3.5 m	(Wolfs and Suiker 2019)
3	2019	United States	Gantry Printer	10 m	0.9 m	(Buswell et al. 2018)
4	2017	China	Robotic Arm	26.3 m	3.6 m	(Xu et al. 2020)
5	2020	Belgium	Robotic Arm	27 m	3 m	(Vantyghem et al. 2020)

This study aims to perform a comparative Life Cycle Assessment (LCA) to investigate the environmental impact of two construction methods, 3DCP and precast, using a bridge construction case study. This study mainly focuses on greenhouse gas emissions from the material extraction and during the construction phase, using a cradle-to-site LCA. The case study is an 8-meter-long, 3.5-meter-wide pedestrian bridge built in 2017 in the Netherlands (known as the 3DCP bridge). For the construction of this bridge, a novel method was used for integrating steel wire reinforcement into the print filament. In addition, a bridge with the same geometry is designed based on the cast-in-place concrete box girder technique (known as the precast bridge). Separate system boundaries are designed based on the construction methodology of each bridge to be used in LCA. Both the 3DCP and precast bridges are modeled in OpenLCA, an open-source software, for a detailed life cycle assessment. The results of this study contribute to the relatively new and understudied field of 3DCP by providing a detailed environmental impact of the material and construction process of a 3D-printed small-scale bridge. It also highlights the importance of adopting 3DCP technology with more sustainable printable concrete.

Literature Review

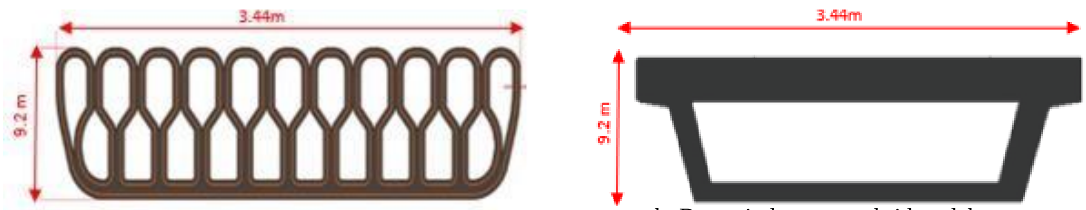
Although there have been numerous studies on 3DCP, the environmental impacts of this technology in construction have remained insufficiently explored (De Soto et al., 2018). A few studies have investigated the environmental impacts of 3DCP technologies using different projects and LCA methods. For example, Weng et al. (2020) evaluated prefabricated bathroom units using several construction techniques and found that 3DCP had lesser environmental impacts due to formwork-free construction. Alhumayani et al. (2020) performed a comparative LCA to compare the environmental impact of a load-bearing 3DCP wall with a reinforced cast-concrete wall and found out that the 3DCP wall has 27.2% higher GHG emissions due to the amount of cement used to produce printable concrete. Mohammad et al. (2020) conducted LCA on four load-bearing wall case scenarios of conventional concrete, 3DCP with reinforcement elements, 3DCP without any reinforcement, and 3DCP without any reinforcement and utilizing a lightweight printable concrete material. They concluded that 3DCP reduced environmental effects in terms of global warming potential as compared to conventional construction methods. Furthermore, Faludi et al. (2015) compared the environmental impacts of two types of additive manufacturing machines versus traditional numerical (CNC) milling machines and showed a reduction in energy use and waste in additive manufacturing machines. With respect to the contribution of the above studies, a comparative assessment is lacking to evaluate the environmental performance of the 3DCP and precast technique in terms of constructing a small-scale bridge. Therefore, this work has been conducted to fill the research gap by investigating the environmental impact of these two construction methods using a bridge construction case study.

Case Study

A small-sized concrete pedestrian bridge is used as a case study in this paper. The bridge was built in 2017 at the university of Eindhoven University of Technology (TU/e) using extrusion-based additive manufacturing with cement-based materials. The bridge was built using a gantry printer. In this gantry printer system, concrete was mixed with water and pumped into a hose by a mixer pump located on the side of the set-up. The hose was connected to the printer head situated at the end of the vertical arm of a motion-controlled 4-degree-of-freedom (4DOF) gantry robot serving a print area of 9 × 4.5 × 2.8 m (Bos et al. 2016). The total bridge dimensions are 8 m in length and 3.5 m in width, featuring 535 printed layers, with a length of 25.1 m of printing for each slab (a total printing path length of 13.4 km). The total printing time was 48 hours. With an average estimated power of 7kWh for a typical 4DOF gantry printer, a total of 336 kW of electricity is estimated for the printing process. The 3DCP technology used in this bridge features a reinforcement technique for extrusion-based 3DCP longitudinal filament by directly entraining a high-strength steel wire into the filament, actively fed from a spool by a small servo motor with an appropriately flexible cord (Bos et al. 2017). This technique allowed a fully automated process that does not reduce the geometrical possibilities of the 3DCP technology (Bos et al. 2017). The printing procedure, final slabs, and final bridge are shown in Figure 1.

Figure 1. The case study bridge and printing process at TU/e (Bos et al. 2017)

To compare the C3DP technique with the precast method, a similar bridge was designed based on the cast-in-place post-tensioned concrete box girder technique. The designed precast bridge had the exact geometry as the C3DP bridge and was designed based on the American Association of State Highway and Transportation Officials (AASHTO 2022) standard. The slab layout and dimensions of the designed precast bride and the C3DP bridge are shown in Figure 2. The total concrete used for both bridges is calculated based on the measurements: the 3DCP bridge requires 11.7 m^3 of concrete, which is 76% of the concrete needed for the precast bridge (15.3 m^3 of concrete). In addition, material wastage is considered in this study, which is typically between 1% and 13% of the total concrete required in conventional methods based on the type of project (Tam, Shen, and Tam 2007; Formoso Carlos et al. 2002). The concrete waste percentage can be calculated as the ratio of the volume of concrete purchased to the volume of concrete measured from the project drawing (Kazaz et al. 2015). The literature suggests an average of 9% waste for the precast technique, while this number can be up to 50% less in 3DCP. Based on the TU/e reports, the total waste calculated for the 3DCP bridge is around 6%. Assuming 33% less waste in the C3DP bridge compared to the precast bridge, the total volume of concrete required for the case study is estimated to be 12.4 m^3 and 16.7 m^3 for the C3DP and precast bridges, respectively. It illustrates that the concrete needed for the C3DP bridge is around 74% of the precast bridge.



a. 3DCP bridge slab (Salet et al. 2018) b. Box grinder precast bridge slab

Figure 2. The designed slab for the box grinder precast and 3DCP bridge slab

In addition to the amount of concrete required, the types of concrete used in the studied bridges differ. The concrete used in 3DCP usually has stricter requirements for fluidity, extrudability, and printability; The printing material not only needs to have enough fluidity to ensure the smooth pumping of the material and continuous extrusion from the nozzle, but also needs more water retention to avoid the clogging of the pumping tube due to material segregation. It also needs to have enough hardening speed to maintain the stable accumulation of subsequent layers to build (Lyu et al. 2021). For the 3DCP bridge, the printable material developed by SG Weber Beamix was used, comprising Portland cement (CEM I 52,5 R), siliceous aggregate with an optimized particle size distribution, and a maximum particle size of 1 mm, a small amount of polypropylene fibers for reducing crack formation due to early drying, and added accelerators (Bos et al. 2016; Kuzmenko et al. 2022). For the precast bridge, an M40 grade concrete, applicable to most precast slabs, is assumed with a compressive strength of 40 N/mm^2. The concrete mixture used in 3DCP and precast bridges are shown in Table 2.

Table 2

Concrete properties and volumes for 3DCP and precast bridges

3DCP Bridge Components	**1m^3 Concrete (Kg)**	**Whole Bridge (Kg)**	**Precast Bridge Components**	**1m^3 Concrete (Kg)**	**Whole Bridge (Kg)**
Cement: CEM I	540.0	6,697	Cement	400.0	6,671
Silica Fume	480.0	5,953	Coarse Aggregate	1,006.0	16,777
Sand	1,033.0	12,811	Fine Aggregate	800.0	13,342
Free Water	212.0	2,629	Free Water	180.0	3,002
Superplasticizer	8.8	109	Superplasticizer	2.0	33
Accelerator	6.0	74			
Polypropylene fibers	1.2	15			
Total Weight	*2,281.0*	*28,289*	*Total Weight*	*2,388.0*	*39,825*

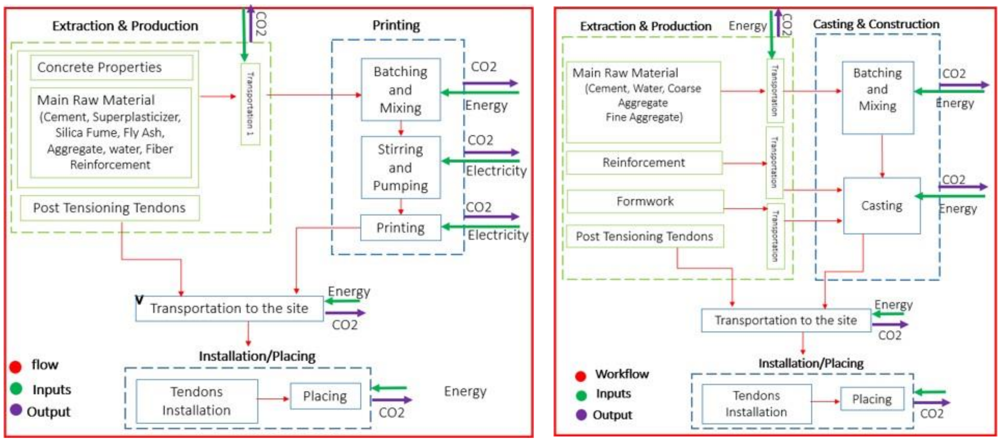
In addition to the type and amount of concrete, the type and method of reinforcement are different in the 3DCP and precast bridges. For the 3DCP bridge, high-strength steel Bekaert Syncrocord wires were used for reinforcement. Compared to ordinary reinforcement steel, the ductility of steel wires is limited. Wires with a diameter of 0.97 mm were considered for the 3DCP bridge (Bos et al. 2017). The total steel wire is calculated based on the total printing length (13.4 km) and specific weight of 7850 kg per m^3 for the steel wire (a total of 6.6 kg). On the other side, the specifications required by the American Society for Testing and Materials (ASTM) are used to design the reinforcement needed in the precast bridge. In precast concrete, the maximum quantity of steel required for a 1 m^3 concrete slab is typically 1.5%, resulting in a total of 118 kg of steel reinforcement in this study. This value is significantly higher than the total of 6.6 kg steel wire required for 1 m^3 of 3D-printed concrete. Finally, a Post-tensioning technique with 16 Dywidag-system tendons was applied to the bridge with the prestress to an initial load P0 of 150 kN (Salet et al. 2018) is assumed for both bridges.

Research Methodology

LCA has become an essential tool for minimizing the environmental impacts of construction and enabling the construction sector to move toward sustainability (Fenner et al. 2018). LCA methods can assess and enhance the construction processes by taking a comprehensive and systemic approach to environmental assessment. Depending on the level of assessment required, there are several approaches to LCA in construction, including cradle-to-gate, cradle-to-site, cradle-to-grave, and cradle-to-cradle (Zheng and Chini, 2017). The present research methodology is based on the environmental LCA method framed by the international standards ISO 14040 (ISO, 2006). Following the LCA methodology presented in Yan et al. (2010), A cradle-to-site LCA was performed that included raw material extraction, bridge construction (precast vs. 3DCP), and installation for the studied bridges. First, the system boundaries and function units are defined for the LCA analysis. Then, several inventory data were collected using OpenLCA, open-source and free software for sustainability and life cycle assessment. Although various environmental impact categories are considered in this study, the main focus was given on Global Warming Potential (GWP), a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2). In this study, A carbon dioxide equivalent (CO_2-eq) metric is used to compare the emissions from various GHG on the basis of their GWP.

For each designed bridge, a separate system boundary was defined in this study (see Figure 3). Three main stages of the construction process for cradle-to-site LCA were considered in this study (1) material extraction, (2) construction, and (3) placing and installation. To compare the two bridges, similar values are assumed for most of the inputs, including the material transportation distance, water resources, and post-tensioning procedure.

The estimated inputs in the defined system boundaries were modeled in OpenLCA. All the required inventory was selected from the EcoInvent 3.2 cut-off database within OpenLCA. Following the same method used by Agustí-Juan and Habert (2017), a ReCiPe Midpoint calculation method is used for the environmental impact calculation for each bridge (GreenDelta 2020). In addition, the IPCC 2013 GWP 100a method, based on data published by the Intergovernmental Panel on Climate Change, was selected as the environmental assessment method.



a. 3DCP bridge construction *b. Precast bridge construction*

Figure 3. Designed system boundaries for construction of the case study bridges

Results and Discussion

First, the GPW impact analysis was performed using generated CO_2-eq amount based on the concrete used in each bridge. The results showed that the extraction of the materials needed for 1 m^3 of concrete would result in generating 425 kg and 315 kg of CO_2-eq for 3DCP and precast bridges, respectively. In both scenarios, the contribution of cement to GWP impact is 85%. Figure 4 shows the LCA result regarding the GWP impact assessment of the concrete used in the case study. With respect to the GWP impact of 1 m^3 of concrete, the results indicated that the concrete mixture used in 3DCP generates 35% more CO_2-eq compared to the concrete mixture used in the precast bridge. The main reason is the higher amount of cement used in the 3DCP concrete mixture (almost 35% more cement compared to the precast concrete mixture). Because of the significant impact of cement production on generated GHG, it can be concluded that printable concrete with a high amount of cement would not be environmentally sustainable. In addition, the results showed that the 3DCP technique could reduce the concrete needed for the same bridge by 35% compared to the precast method in this case study. Therefore, as Figure 4 illustrates, the GWP impact of the total concrete used in each bridge does not significantly differ; i.e., the lower materials and lower waste associated with the 3DCP technique can even out the adverse environmental impact of the higher cement used for construction.

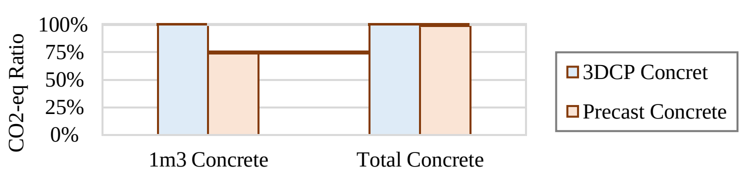
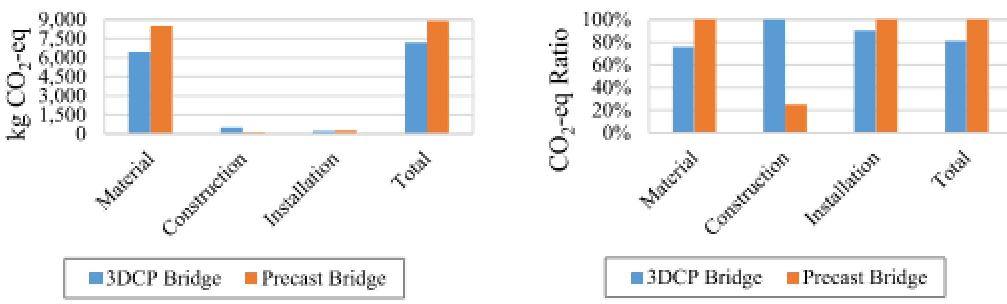


Figure 4. The GWP impact assessment of concrete used in the case study

Figure 5.a illustrates the amount of CO_2-eq generated in the bridge construction using 3DCP and precast methods. As the results show, the contribution of material extraction to total CO_2-eq generated is significantly higher than the construction and installation stages in both 3DCP and precast bridges (89% and 95% of total CO_2-eq emissions come from the material extraction in 3DCP and precast bridges,

respectively). In addition, Figure 5.b shows the ratio of the generated CO_2-eq in each stage in both 3DCP and precast bridges. As the results show, the GWP impact of the total materials used in the 3DCP bridge is 76% of the precast bridge. Although the amount of CO_2-eq generated from the extraction of concrete components was almost the same in both scenarios, the higher volume of reinforcement materials in the precast bridge (compared to steel wire in the 3DCP bridge) significantly increased the generated CO_2-eq. In addition, even though the 3DCP is a free-form technique, the precast method requires formwork, which increases the GWP impact. Regarding the construction stage, it is shown that the GWP impact of the 3DCP technique is four times higher than the precast method. Although both techniques require energy to be consumed for transportation, batching, mixing, and pumping concrete, the C3DP technique needs a significant amount of electricity for the 3D printer. The higher amount of electricity needed in the 3DCP technique would significantly increase the generated CO_2-eq during construction. Finally, since the same post-tensioning technique is assumed in both bridges, the GWP impact of the installation stage is almost the same in both scenarios. The slight differences are shown in Figure 5.b is due to the differences in the weight of the bridges as they need to be transported to and installed on the site. The precast bridge is heavier than the 3DCP bridge due to the higher amount of materials, resulting in a slightly higher generated CO_2-eq in the installation stage.



a. Total CO_2 Eq amount *b. CO_2 Eq ratio*

Figure 5. The GWP impact of each stage in bridge construction

Figure 6 shows comparative LCA results of the 3DCP and precast bridges in various environmental impact categories. As it is stated, the GWP impact of the 3DCP bridge is 80% of the precast bridge. As the results show, the 3DCP bridge reduced environmental effects regarding water consumption (due to removing the curing process) and ecotoxicity and acidification potentials (due to removing the need for reinforcement and formwork). On the other hand, the precast bridge performed better in the impact categories of land use and mineral resource scarcity compared to the 3DCP bridge, mainly due to the use of a smaller amount of cement in the concrete mixture.

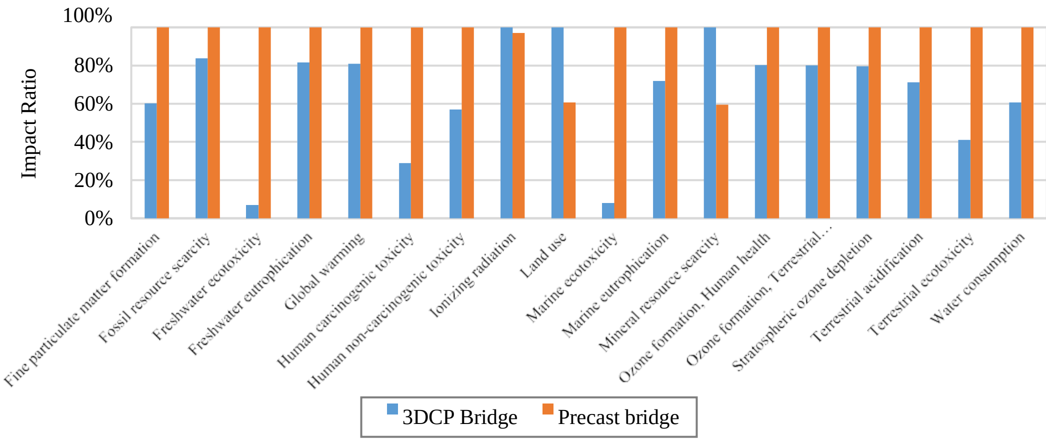


Figure 6. The comparative ratio of environmental impact assessment in bridge construction

Conclusion

This study compared the environmental impacts between precast and 3DCP techniques with a pedestrian bridge case study. The case study was a small concrete pedestrian bridge built in 2017 in the Netherlands using extrusion-based 3DCP with cement-based materials. Using the information of this bridge, a similar bridge was designed with a concentration on the cast-in-place post-tensioned concrete box girder technique. The designed precast bridge had the exact geometry as the C3DP bridge and was designed based on AASHTO standards. The cradle-to-site LCA results showed that cement was responsible for 85% of the generated CO2-eq regarding concrete used in the bridge. In addition, the concrete used in the 3DCP bridge had a higher GWP impact than the precast bridge due to a higher amount of cement in printable concretes. However, since C3DP used less material than the precast technique, there was no significant difference between the GWP impact of the concrete used in the whole bridge in both scenarios. In addition, due to the use of reinforcement and formwork in the precast technique, the GWP impact of the total materials used in the precast bridge was higher than the 3DCP bridge. Notably, due to using electricity for printing, the GWP impact of the construction process in 3DCP was also higher than the precast technique. Finally, the total generated CO_2-eq in the construction of the studied bridge using the 3DCP method was estimated to be 80% of the precast method.

Overall, the results of this study showed no significant difference on the environmental impact of constructing a small concrete bridge using 3DCP or precast methods. The significant difference between the two methods is during the construction, where 3D printers usually require a significant amount of electricity for printing concrete, resulting in four times more CO_2 generation. However, switching to other energy sources, such as renewables, can address this issue in the future. Furthermore, although the current printable concrete requires a higher amount of cement, resulting in higher environmental impact, 3DCP can significantly reduce the need for materials. By improving the printable concretes and replacing cement with environmental-friendly substitutes, the environmental impact of constructing infrastructure using 3DCP could be dramatically improved. Knowing that 3DCP allows for a great deal of geometric customization, reduces the construction time, requires minimum human labor, and is less expensive, the rapid advancements and significant investments in this technology indicate its great potential for automating bridge construction in the near future.

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References

AASHTO: The American Association of State Highway and Transportation Officials. 2022. Span CIPPTCBGB. In *Span Cast-in-Place Post-Tensioned Concrete Box Girder*.

Agustí-Juan, Isolda, and Guillaume Habert. 2017. "Environmental design guidelines for digital fabrication." *Journal of Cleaner Production* 142 (4).

Alhumayani, Hashem, Mohamed Gomaa, Veronica Soebarto, and Wassim Jabi. 2020. "Environmental assessment of large-scale 3D printing in construction: A comparative study between cob and concrete." *Journal of Cleaner Production* 270:122463.

Bos, F., R. Wolfs, Z. Ahmed, and T. Salet. 2016. "Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing." *Virtual and Physical Prototyping* 11 (3).

Bos, P Freek, Y Zeeshan Ahmed, R Evgeniy Jutinov, and A. M. Theo Salet. 2017. "Experimental Exploration of Metal Cable as Reinforcement in 3D Printed Concrete." *Material* 10 (11).

Buswell, R. A., W. R. Leal de Silva, S. Z. Jones, and J. Dirrenberger. 2018. "3D printing using concrete extrusion: A roadmap for research." *Cement and Concrete Research* 112:37-49.

Davtalab, Omid, A. Kazemian, X. Yuan, and B. Khoshnevis. 2022. "Automated inspection in robotic additive manufacturing using deep learning for layer deformation detection." *Journal of Intelligent Manufacturing* 33 (3):771-784.

De Soto, B.G., I. Agusti-Juan, J. Hunhevicz, S. Joss, K. Graser, G. Habert, and B. Adey. 2018. "Productivity of digital fabrication in construction: Cost and time analysis of a robotically built wall." *Automation in Constructio*n, 92.

Faludi, J., C. Bayley, S. Bhogal, and M. Iribarne, 2015. "Comparing environmental impacts of additive manufacturing vs traditional machining via life-cycle assessment." *Rapid Prototyping Journal*, 21(1).

Fenner, A., C. Kibert, J. Woo, S. Morque, M. Rezkenari, H. Hakim, and X. Lu. 2018. "The carbon footprint of buildings: A review of methodologies and applications." *Renewable & Sustainable Energy Reviews*, 94.

Formoso C., L. Soibelman, C. De Cesare, and L. Isatto Eduardo. 2002. "Material Waste in Building Industry: Main Causes and Prevention." *Journal of Construction Engineering and Management* 128 (4).

GreenDelta. 2020. " Basic Modelling in openLCA." In *OpenLCA Tutorial*.

Hong, Jingke, Geoffrey Shen, Yong Feng, William Lau, and Chao Mao. 2015. "Greenhouse gas emissions during the construction phase of a building a case study in China." *Journal of Cleaner Production* 103 (2).

ISO: International Organization for Standardization. 2006. Environmental Management: Life Cycle Assessment; Principles and Framework. ISO: Geneva, Switzerland.

Kazaz, A., S. Ulubeyli, B. Er, V. Arslan, A. Arslan, and M. Atici. 2015. "Fresh Ready-mixed Concrete Waste in Construction Projects: A Planning Approach." *Procedia Engineering* 123

Khoshnevis, Behrokh. 2004. "Automated construction by contour crafting—related robotics and information technologies." Automation in Construction. 13 (1): 5–19.

Kuzmenko, Kateryna, Nicolas Ducoulombier, Adelaïde Feraille, and Nicolas Roussel. 2022. "Environmental impact of extrusion-based additive manufacturing: genericmodel, power measurements and influence of printing resolution." *Cement and Concrete Research* 157.

Liu , Siyu, B ing Lu, Hongliang Li , Zehua Pan , Jingjing Jiang , and Shunzhi Qian. 2022. "A comparative study on environmental performance of 3D printing and conventional casting of concrete products with industrial wastes." *Cement and Concrete Research* 298 (134310).

Lyu, Fuyan, Dongliang Zhao, Xiaohui Hou, Li Sun, and Qiang Zhang. 2021. Overview of the Development of 3D-Printing Concrete: A Review. *Applied Sciences* 11 (21).

Mechtcherine, Viktor, Jasmin Grafe, Venkatesh N. Nerella, Erik Spaniol, Martin Hertel, and Uwe Füssel. 2018. "3D- printed steel reinforcement for digital concrete construction – Manufacture, mechanical properties and bond behavior." *Construction and Building Materials* 179:125-137.

Miryousefi Ata, Sara, Ali Kazemian, and Amirhosein Jafari. 2021. "Application of Concrete 3D Printing for Bridge Construction: Current Challenges and Future Directions." *American Society of Civil Engineers Construction Research Congress (CRC)*.

Mohammad, Malek, Eyad Masad, and Sami G. Al-Ghamdi. 2020. 3D Concrete Printing Sustainability: A Comparative LCA of Four Construction Method Scenarios. *Buildings* 10 (12).

Salet, A. M, Theo, Zeeshan Ahmed Y, Freek Bos P, and Hans Laagland L. M. 2018. "Design of a 3D printed concrete bridge by testing." *Taylor and Francis* 13 (3).

Scrivener, K., V. John, and E. Gartner. 2018. "Eco-efficient cements: Potential economically viable solutions for a low- CO2 cement-based materials industry"*Cement and Concrete Research* 114.

Tam, V., L. Shen, and C. Tam. 2007 "Assessing levels of material wastage affected by sub-contracting relationships and projects types with their correlations." *Building and Environment* 42 (3)

Tuan, D. Ngo, Kashani A lireza, Imbalzano Gabriele , T.Q. Nguyen Kate, and Hui David. 2018. "Additive manufacturing (3D printing): A review of materials, methods, applications and challenges." *Composites Part B: Engineering* 143.

Vantyghem, Gieljan, Wouter De Corte, Emad Shakour, and Oded Amir. 2020. 3D printing of a post-tensioned concrete girder designed by topology optimization. *Automation in Construction* 112.

Weng, Y., M. Li, S. Ruan, T. Wong, M. Tan, K. Yeong, and S. Qian. 2020. "Comparative economic, environmental and productivity assessment of a concrete bathroom unit fabricated through 3D printing and a precast approach." *Journal of Cleaner Production* 261.

Wolfs, R. J. M., and A. S. J. Suiker. 2019. "Structural failure during extrusion-based 3D printing processes." *The International Journal of Advanced Manufacturing Technology* 104 (1).

Xu, Weiguo, Yuan Gao, Chenwei Sun, Z. H. I. Wang, Jane Burry, Jenny Sabin, B. O. B. Sheil, and Marilena Skavara. 2020. "fabrication and application of 3d-printed concrete structural components in the Baoshan pedestrian bridge project." In *Fabricate 2020*, 140-147.

Yan, H., Q. Shen, L. Fan, Y. Wang, and L. Zhang. 2020. "Greenhouse gas emissions in building construction: A case study of One Peking in Hong Kong." *Building and Environment*, 45(4), April 2010, Pages 949-955.

Zeng, R. and A. Chini. 2017. "A review of research on embodied energy of buildings using bibliometric analysis." *Energy and Buildings*, Volume 155, 15 November 2017, Pages 172-184