Tran-SET

Transportation Consortium of South-Central States

Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation

Comparative Analysis of 3D Printed Bridge Construction in Louisiana

Project No. 21STLSU04

Lead University: Louisiana State University

Final Report

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Disclaimer

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16. Abstract

A construction 3D printing system could result in automated infrastructure development at reduced cost and time, significantly boosting overall productivity. Although there has been a growing interest in using construction 3D printing for projects such as house construction, implementing this innovative technology for infrastructure development, particularly bridge construction, has not been investigated as extensively. This study aims to compare the environmental impact of precast and 3D concrete printing (3DCP) techniques with a pedestrian bridge case study, located in Louisiana, where the bridge elements were 3D printed off-site and then transported and assembled on the bridge site. A detailed cradle-to-site life cycle assessment has been performed from the standpoint of material, construction, and installation stages, using an open-source software called OpenLCA. The results of this study showed that the mixtures commonly used in 3DCP have a higher negative environmental impact compared to the precast method due to the higher percentage of cement used in these materials. However, since 3DCP 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 use of 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.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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ACRONYMS, ABBREVIATIONS, AND SYMBOLS

3DCP: 3D Concrete Printing

3DP: 3D Printing

4DOF: 4 Degree of Freedom

AASHTO: American Association of State Highway and Transportation Officials

ACES: Automated Construction of Expeditionary Structures

AP: Acidification Potential

ASTM: American Society for Testing and Materials

CO_2: Carbon Dioxide

CO_2-eq: Carbon Dioxide Equivalent

DOF: Degree of Freedom

DOT: Departments of Transportation

EP: Eutrophication Potential

FFD: Fossil Fuel Depletion

GHG: Greenhouse Gas

GWP: Global Warming Potential

ISO: International Organization for Standardization

LCA: Life Cycle Assessment

RED: Reinforcement Entraining Device

TU/e: The Eindhoven University of Technology

SFP: Smog Formation Potential

EXECUTIVE SUMMARY

A construction 3D printing system could result in automated infrastructure development at reduced cost and time, leading to a significant boost in overall productivity. Although there has been a growing interest in using construction 3D printing for projects such as house construction, implementing this innovative technology for infrastructure development, particularly large-size bridges, has not been investigated as extensively. Bridges are complex structural systems subject to various static and dynamic loads, making automated bridge construction using construction 3D printing challenging.

Although there have been numerous studies on 3D concrete printing, the environmental impacts of this technology in construction have remained insufficiently explored. A few studies have investigated the environmental impacts of 3DCP technologies using different projects and LCA methods. 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.

This study aims to perform a comparative Life Cycle Assessment (LCA) to investigate the environmental impact of two construction methods, precast and 3DCP (the elements were 3D printed off-site and then transported to the site), 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 3D printed pedestrian bridge built in 2017 in the Netherlands. 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.

The cradle-to-site LCA results showed that Portland cement was responsible for 85% of the generated CO_2-eq by the material used in the 3D printed bridge. In addition, the concrete used in the 3DCP bridge had a higher GWP impact than the precast bridge due to the higher amount of cement typically used in printable concretes. However, since 3DCP 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, this study showed that 3DCP can reduce the GHG emission of constructing a small concrete bridge by 20% compared to 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 enabling optimized designs. 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 achieving a highly automated and sustainable bridge construction method in the near future.

1 INTRODUCTION

COVID-19 has become a global crisis, evolving at high speed and scale. No industry is immune to this crisis, and engineering and construction are no exception. Engineering and construction companies must preserve their operations' integrity and protect their workers. For constructing infrastructure such as bridge projects, adopting and implementing workplace safety orders and regulations issued by the state, local, and municipal governmental agencies in the workplace is challenging because of the nature of such projects and the number of workers needed to work closely at once. On the other hand, Departments of Transportation (DOTs) have experienced a relentless increase in the number of transportation infrastructure projects over the past several years. DOTs have hundreds of large and small projects underway with the common purpose of assuring that millions of individual travelers experience a smooth transportation network. Therefore, this crisis has pushed construction and engineering companies to a paradigm shift in many areas to do things differently than they did in the past, mainly to find safer and more efficient ways of building transportation infrastructures. In this environment, automation could serve a crucial role in mitigating the challenges that construction and engineering firms face, such as design problems, inefficiency, outdated techniques, and environmental challenges. In general, automated construction can provide large-scale remote collaboration with liquid architecture, virtual workplaces, and digital applications, which can minimize the spread of COVID-19 while ensuring that health and safety measures continue to be followed.

3D printing technology is an advanced manufacturing process that can automatically generate complex-shape geometries from a 3D computer-aided design model. Due to the significant advantages of efficiently and effectively creating functional parts, this process has been utilized in various industries, including aerospace, automobile, biomedical, and civil engineering (Xu et al. 2020). The prospect of reducing the need for human resources and large capital investments has prompted researchers to investigate its potential application in the building and construction industry. 3D printing continues to expand as new technologies, methods, and applications become available (Pan et al. 2021).

In recent years, 3D Concrete Printing (3DCP) technology has gained attention as an efficient, automated solution for dealing with tight schedules and fast production in construction projects (Li et al. 2022; Davtalab et al. 2022). 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” (Ngo et al. 2018). The 3DCP technology was 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, compared with traditional and prefabricated building methods (Yang, Zhu, and Zhang 2019). Today, automated construction using 3DCP can provide a safer, more productive, and more reliable workplace than conventional construction work (Hossain et al. 2020). 3DCP typically offers a more controlled working environment compared to traditional construction sites, with static workspaces and more structured supervision (Xu et al. 2022). It also aids in implementing safety processes and procedures, such as social distancing in a disease outbreak such as COVID-19. This automated construction technology requires minimal labor to be implemented compared to traditional construction procedures, which can help with issues around physical distancing while accelerating production (Perrot and Amziane 2019).

Although 3DCP technology has many advantages, it is still not commonly used worldwide because the promotion of 3DCP is not strong enough for people. Based on a survey conducted by Yang et al. (2019), 56% of people have never heard of 3DCP, 12% have heard of it but have no interest in 3DCP, 21% of people have heard of but have not used 3DCP products, and only 11% have used 3DCP products. Nowadays, there are already many 3DCP companies in the world and successfully printed buildings for people to live in. The 3DCP technology has become more mature and can provide sufficient protection for people who use 3D-printed buildings.

There are significant possibilities for the implementation of a 3DCP system for various applications such as low-income housing and emergency construction. Particularly in developing countries, where the housing problem arises because there is no economic wealth to develop the cities at the rate of our population growth, the shortened construction period of 3DCP technology can help increase the quality of life by providing low-income housing. Despite the contribution of this technology to emergency construction and affordable housing, utilizing 3DCP for infrastructure development also seems to hold great potential. This automated and accelerated process is also promising for civil structures, including buildings and bridges which typically require extensive labor to build. If successful, it is expected that 3D printing of structures can significantly reduce construction time and cost. However, the application of this innovative tool for infrastructure development, particularly bridge construction, has not been investigated as extensively. In the past few years, there has been a growing interest in bridge construction using 3DCP worldwide, leading to a few demonstration projects, such as 3D-printed bike and pedestrian bridges, mostly located in Europe and China. However, the application of 3DCP technologies for constructing new bridges in the United States is in the very early stages and has not been investigated thoroughly.

On the other hand, despite the numerous advantages of 3DCP, the sustainability performance and the environmental impact of this new technology have not been widely investigated, and there are doubts among researchers and practitioners if this technology is more environmentally friendly compared to traditional methods (Liu et al. 2022). The environmental impact of the construction and operation phases of buildings 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 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. 2022b). 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 these processes' low-tech and low-energy nature and the high reuse rate of casting equipment such as forms.

Despite the contributions of the previous 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.

2 OBJECTIVES

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 3D printed pedestrian bridge built in 2017 in the Netherlands. For the construction of this bridge, a novel method was used for integrating steel wire reinforcement into the 3D printed cementitious filaments. 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.

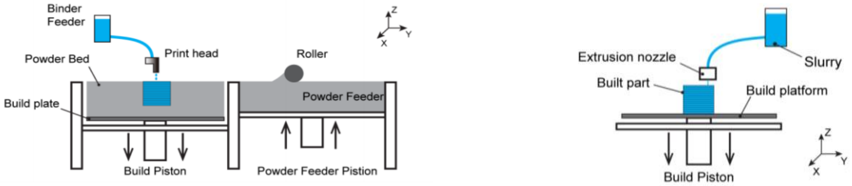
3 LITERATURE REVIEW

This study was focused on concrete 3D printing technology for bridge construction. Although concrete can take any shape, the current concrete construction is mainly limited to simple shapes with a constant cross-section because of the high cost of fabricating non-standard and customized formwork. 3DCP can overcome this limitation by reducing or eliminating the need for formwork. In general, the 3DCP technology for large-scale construction can be categorized into two groups powder-based and extrusion-based 3D printing.

3.1 3DCP Techniques and Robotic Systems

This study was focused on concrete 3D printing technology for bridge construction. Although concrete can take any shape, the current concrete construction is mainly limited to simple shapes with a constant cross-section because of the high cost of fabricating non-standard and customized formwork. 3DCP can overcome this limitation by reducing or eliminating the need for formwork. In general, the 3DCP technology for large-scale construction can be categorized into two groups powder-based and extrusion-based 3D printing.

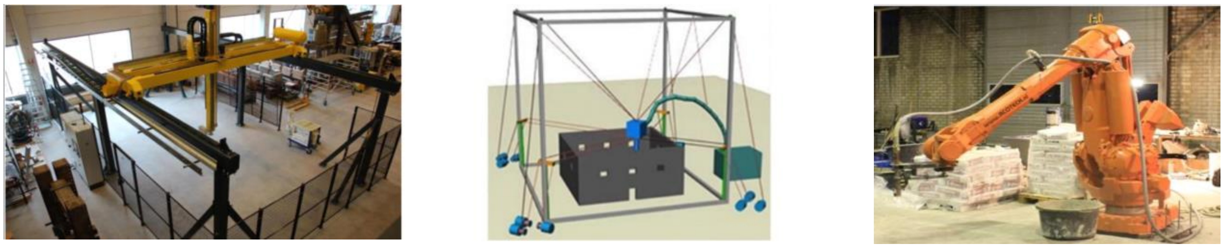
Powder-based 3D printing enables the production of free-form concrete elements without requiring a component-specific formwork or tool. In this technology, concrete components optimized for the flux of force or building physics requirements can be quickly produced. The printing process consists of two repetitive work steps in powder-based deposition: (1) application of a layer of dry particles and (2) selective deposition of a fluid phase onto the particle packing through a printer head or nozzle to bind the particles. The printer head is fitted with several spray nozzles that spray a binding liquid on predefined areas of the sand layer during the printing process. Finally, the non-bonded particles are removed in a de-powdering process. When the printing process is finished, the strength and durability of the product can be improved by infiltration or heat treatment (Lowke et al. 2018). Figure 1a shows a schematic view of the powder-based 3D printing technique. There are several advantages to the powder-based technique. First, there are no restrictions on the choice of form in this technique. Also, printed elements with this technique are mechanically stable with high production resolution. D-Shape printer is a powder-based 3D printer that has been used to print several large-scale structures. The main limitations of powder-based 3D printing include (i) a large amount of powder that needs to be recycled, (ii) usually extensive post-processing is needed, and (iii) it is not suitable for on-site construction. Extrusion-based 3D printing enables the production of large-scale components with different material preparation and delivery processes. It entails extruding layers of cement-based material to produce an element or structure based on a digital 3D model. Process planning and deposition speed selection are critical in this technique and must be consistent with the printing material's stiffening and hardening rate (Perrot, Rangeard, and Pierre 2016; Labonnote et al. 2016). In this technique, concrete material is forced through a nozzle to create an object layer by layer along a predetermined route. The basic configuration of an individual layer is generated by using robotic control to move the nozzle in the horizontal plane at a constant speed. When a layer is applied, the extrusion nozzle moves vertically over a gap equivalent to the layer height. The procedure is repeated by depositing a new layer on top of the previous layer, forming a "wall framework" (Wolfs and Suiker 2019). Figure 1b shows a schematic view of the extrusion-based 3D printing technique.



a. powder-based technique ***b. extrusion-based technique***

Figure 1 Schematic of 3D printing techniques (Sanjayan 2017)

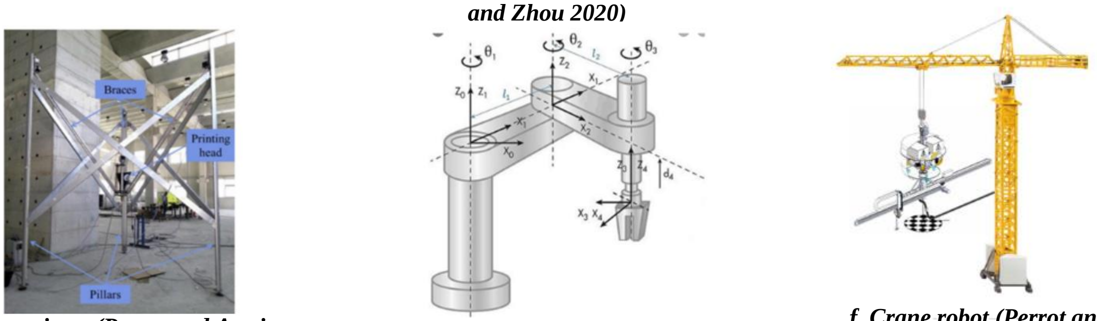
Depending on the size of the elements to be printed (elements of a building, small detached single-story homes, or multi-level buildings) and the 3D printing technique, different robotic systems can be used to move the nozzle for 3D printing (Buswell et al., 2018). Based on the literature, robotic systems to be used for concrete 3D printing are classified into six main categories of gantry 3D printers, cable-driven printers, robotic arm 3D Printers, delta printers, SCARA robots, and crane robots (see Figure 2).



a. Gantry Printer (Paul et al. 2018)

b. Cable driven (Khan, Sanchez, and Zhou 2020)

c. Robotic arm (Paul et al. 2018)



d. Delta printer (Perrot and Amziane 2019)

e. SCARA robot (Ko 2022)

f. Crane robot (Perrot and Amziane 2019)

Figure 2. Different robotic systems used in 3DCP

- Gantry robots are one of the most common technologies. The printer is typically composed of the following components: a gantry mobility system for x, y, and z positioning, a concrete deposition system, and a mixing and delivery system. Gantry printers range from small tabletop laboratory models to large-scale printers capable of printing full-size building components. Gantry printers are primarily limited to vertical extrusion. Thus, gantry-style printers produce 2.5D topologies rather than true 3D topologies. In addition, the gantry printer frame must be larger than the structure being constructed, which may necessitate a massive system and costly transportation, set-up, and teardown procedures. Gantry printers typically have low-cost and stability advantages, offering the ability to make larger prints and even print entire buildings at once. Gantry printers also allow for non-continuous printing, which is needed when printing entire buildings, are far easier to control, and do not require complex programming. Additionally, it can print complex architectural parts with a high degree of detail. The most noticeable and noteworthy gantry-based developments are D-Shape and Contour crafting.

- D-Shape is a factory powder-based 3D printer that can print architectural structures. It was created primarily to manufacture structural elements with complex geometries in a factory (off-site). However, using the technology to print on-site is currently being investigated, using on-site building materials such as sand and binder materials. D-Shape is criticized for being inefficient due to the difficulty of consistently hydrating cementitious powder; it is also inconvenient because the powder must ultimately be removed and the product cleaned, adding considerable time and effort to the process.

- Contour crafting is a specific in-situ method of the extrusion-based technique introduced by Khoshnevis for printing cement-based materials in 1997, making it the first in-situ method in the field of 3DCP (Khoshnevis 1997). The primary advantages of the contour crafting technology are the superior surface finish and the significantly enhanced fabrication speed. In addition, contour crafting can facilitate the integration of other robotics methods for installing internal components such as pipes, electrical conductors, and reinforcement modules to enhance the mechanical properties (Khoshnevis et al. 2001).
- A cable-driven system is designed to clip between several fixed points making the system lightweight and transportable compared to a gantry-based system. The cable-driven system secures the nozzle assembly with a set of fixed points and cables so that the nozzle can be in three dimensions. As a result, the device can be scaled up without dramatically raising the cost. This design, however, shares some of the drawbacks of the gantry system, such as the three-axis restriction, which restricts the system’s ability to execute complicated movements or several procedures. Furthermore, while these devices do not need a huge direct footprint for the equipment, they require a wide area for the equipment to be adequately isolated so that the cables do not overlap with the written structure.
- The robotic arm can provide a six-axis movement, allowing more freedom of movement and enhancing the geometric sophistication achievable. By altering the procedure, the arm can deposit concrete and embedded components and perform post-processing on the structure. Compared to gantry systems, the compact size of robotic arms allows transportation to remote areas, and their decreased assembly requirements can result in a shorter deployment period compared to cable-driven systems. However, the primary drawback of robotic arms is their scale - they have a limited scope and must be transported to print structures greater than their reach.
- Delta printing technology is a set of printing arms that moves up and down in a trigonometric manner. The delta robot enables the printer head or nozzle to be quickly taken into place. In other words, the robot travels the shortest distance possible to position

a sheet. Therefore, fabricating and lifting printed items is a reasonably straightforward method. It is suggested that the stiffening and structural build-up rates of the cement content be proportional to the load associated with the weight of the printed structure. The printer has a top speed of 40 cm/s, which is faster than other printers, but the printing rate is determined by the volume of content within the extruder. The extruder can accommodate huge volumes of material (up to 200 kg), but the weight is limited to 40–50 kg to reduce the impact of mechanical movements during deposition (Valente, Sibai, and Sambucci 2019).

- SCARA robots usually have a cylindrical work envelope with differences in the diameter and width of the cylinder, providing excellent freedom of movement. The degree of freedom of a robot is determined by the number of joints, joint position, and the axis each joint control. SCARAs are four-axis robots with X-Y-Z motion and rotating around the Z-axis. Since a SCARA robot lacks the shift and rotational movement of a six-axis arm robot, some mechanisms can be added to accomplish additional axis motion if the SCARA can meet payload requirements. When selecting a robot, speed is a significant consideration, and SCARAs are usually among the fastest on the market. They have fewer rotating joints and four axes. SCARA robots can be used when cycle time is crucial.
- Customized crane robots have also been used as construction 3D printers. These robots offer better mobility compared to gantry robots, which also makes it possible to frequently move the robot and 3D print a multi-unit or multi-story structure on the job site. On the other hand, these systems are not as stable and rigid as gantry robots and usually have a smaller build volume.

3.2 3DCP in Bridge Construction: Current Practices and Challenges

Considering the recent emergence of 3DCP technology as well as the limited number of (demonstration) projects using 3DCP for segmental bridge construction, there is minimal experimental and field data on this topic. The main challenges of using 3DCP technology in civil infrastructure such as bridges are as follow (Khoshnevis 2004; Buswell et al. 2018; Yossef and Chen 2015):

- Automated fabrication is often not suitable for large-scale conventional designs;

- The smaller ratio of automated products in comparison with other industries;
- Only limited materials can be used by automated machines;
- Expensive automated machines tend to be unfeasible economically; and
- Increasing pressure towards environmental issues of construction materials.

Although there are several applications of 3D printing technology in building construction, the use of this technology in civil structures is still at a primitive stage (Yossef and Chen 2015). Bridge construction is widely accepted to fall behind the aerospace and automotive industries in terms of technological adoption, creativity, and efficiency. 3DCP technology has been used for bridge construction in a few demonstration projects in different countries. To the best of the authors' knowledge, all the completed 3D-printed concrete bridges are listed in this article, as summarized in Table 1. These are relatively small pedestrian and bicycle bridges. However, these demonstration projects highlight the massive potential of 3DCP technology for accelerated bridge construction on different scales. These 3D-constructed bridges are shown in Figure 3.

Table 1. A summary of 3D Printed Bridges

No	Year	Location	3DCP Technology	Robotic Printer	Bridge Length (m)	Bridge Width (m)	Printing Location
1	2016	Spain	powder-based	Gantry Printer (D-shape)	8 m	1.75 m	Off-Site
2	2017	Netherland	Extrusion-based	Gantry Printer (Counter Crafting)	8 m	3.5 m	Off-Site
3	2020	Japan	Extrusion-based	Gantry Printer (Counter Crafting)	6 m	1.2 m	Off-Site
4	2019	United States	Extrusion-based	Gantry Printer (Counter Crafting)	10 m	0.9 m	On-Site
5	2017	China	Extrusion-based	Robotic Arm (Six Axis)	26.3 m	3.6 m	Off-Site
6	2020	Israel	Extrusion-based	Robotic Arm (Six Axis)	27 m	3 m	Off-Site

(Buchanan and Gardner 2019) (Salet, Ahmed, et al. 2018) (Wolfs and Suiker 2019)

(Buswell et al. 2018) (Xu et al. 2020) (Vantyghem et al. 2020)

Figure 3. Application of 3DCP in pedestrian bridge construction

The 3D-printed pedestrian bridge in *<u>Spain</u>* was completed in 2016 with a length of 8 meters and a width of 1.75 meters. The bridge was constructed using D-Shape printing technology, fused concrete powder, and polypropylene reinforcement in eight sections, each with a maximum horizontal dimension of 2.2 meters. Raw materials that were not used during the construction process were recycled. In addition, the amount of waste produced by 3D printing technology is minimized by recycling the raw material during printing (Mechtcherine et al. 2018). The 3D-printed pedestrian bridge in the *<u>Netherlands</u>* was constructed in 2017 using gantry printing technology. It used a novel method of integrating cable reinforcement into the print filament. The 3D printer is unique in that it incorporates a steel wire into the nozzle when printing. It used less concrete and resulted in a shorter duration compared to the conventional method (Wolfs and Suiker 2019). The 3D-printed pedestrian bridge in *<u>Japan</u>* was constructed in 2020 using the Gantry Printer system. The bridge has a length of 6 meters and a width of 1.2 meters, and it is made of 44 3D printed components with pre-stressed steel that were assembled by placing pre-stressed concrete steel into the concrete parts generated by the 3D printer. This method decreased the weight of the 3D-printed bridge by approximately 75% without sacrificing strength characteristics. The 3D-printed pedestrian bridge in the *<u>United States</u>* was constructed in 2018 with a length of 10 meters and a width of 3 meters in Los Angeles, CA. A gantry-based printer, Automated Construction of Expeditionary Structures (ACES) technology, was used to print this bridge. This project resulted in reducing construction duration time from five days to one day, reducing the number of required workers from eight to three workers, reducing the amount of material transported from 5 tons to less than 2.5 tons, and improving energy quality due to higher insulation R-values (Buswell et al. 2018). The 3D-printed pedestrian bridge in *China* is the world's longest arc shape pedestrian 3D Printed concrete bridge, constructed in 2017 with 176 concrete units produced by a 3D printing system with two six-axis robotic arms. The length of the bridge is 26.3 meters, with 3.6 meters in width. Fiber-reinforced concrete was used for this bridge. Compared to a conventionally designed concrete bridge of equal dimensions, the cost of this 3D-printed bridge was just two-thirds that of a conventionally built one; this distinction can be due to the fact that no designs or reinforcement bars were used during the printing and building of this bridge, resulting in considerable cost savings (Xu et al. 2020). The 3D-printed pedestrian bridge in *Israel* was built in 2020 for research purposes at the Israel Institute of Technology with a length of 27 meters and a width of 3 meters. This experimental bridge is made of concrete material. The printer used was a six-axis robotic arm with a length of 3.2 meters and a weight of 125 kg, as well as 6 degrees of freedom, enabling printing in moving almost any direction and tool alignment. The actual printing took three working days and allowed at least three operators to operate concurrently (Vantyghem et al. 2020)

There are a few major technical issues with regard to automated bridge construction using 3DCP. Widespread implementation of 3D-printed bridges will not be possible unless these technical challenges are resolved. "Concrete reinforcement" and "process reliability" are among these main issues which will be discussed in this section.

- In conventional concrete construction, rebar reinforcement is commonly used to satisfy structural requirements under different loading conditions, including dynamic earthquake loads. However, the automation of rebar reinforcement is a complex task that has not been accomplished yet. Therefore, manual rebar reinforcement and a few alternative techniques have been used in conjunction with 3DCP (Classen, Ungermann, and Sharma 2020). The alternative reinforcement techniques include inline reinforcement integration through the placement of steel wires or cables within concrete layers (Bos et al. 2018) and pre- or post-tensioned tendons to realize pre-stressed 3D printed concrete behavior (Bos et al. 2019; Asprone et al. 2018). All these reinforcement techniques are either manual or have not been evaluated thoroughly yet, to be considered as an acceptable reinforcement method to replace steel rebars. Using a manual reinforcement technique indeed negates the main advantages of 3DCP, which are reduced construction time and cost and mainly achieved through automation. Therefore, an automated reinforcement technique is an essential part of automated bridge construction technology, which needs to be verified by extensive testing at different scales before it can be used in real-life bridge construction projects.

- Process reliability could be considered another major existing challenge for the widespread use of 3DCP for bridge construction. Failure or malfunction of the system components, variations in the printing materials, and the impact of ambient conditions are the most common issues which are observed in different large-scale 3D printing systems. Process failure due to material preparation and delivery equipment malfunction has been frequently reported, mainly because the existing commercial equipment is not designed explicitly for the 3DCP application. In addition, the use of conventional mixers and pumps imposes strict requirements with regard to the ingredients and proportions of the concrete materials (rheology, maximum particle size, fibers, etc.). Moreover, some degree of variations is commonly observed in the fresh properties of Portland cement-based mixtures. While these variations are not concerning in conventional construction, in 3DCP, they could lead to extensive deformations and progressive collapse of a freshly printed structure or element (Kazemian et al. 2019). In 3DCP, thin layers of 2.5-5 cm dimensions are continuously extruded for many hours, and the process could be adversely affected by slight variations in the printing mixture. In fact, during the printing process, the stability of the incomplete structure depends on two factors: the increasing strength and stiffness caused by thixotropic build-up and setting of the printing mixture versus the gradually increasing load as more layers are deposited on top of each other (Wolfs, Bos, and Salet 2018). An imbalance between the loading conditions and the stiffness of layers, or extrusion of layers with unacceptable properties, could lead to extensive deformations and progressive collapse of a freshly printed structure. Therefore, automated real-time quality monitoring systems must be specifically developed for construction 3D printers. Kazemian et al. (2019) have proposed an automated extrusion quality monitoring and control system based on computer vision to improve the geometrical accuracy and consistency of the 3D printed layers during 3DCP. In another study (Davtalab et al. 2022), an automated layer defect detection system was designed for automated inspection during 3DCP. This software system was trained and tested using 1M images and includes a convolutional neural network (for semantic pixel-wise segmentation) and a layer defect detection module. Further research and extensive evaluation and testing are needed to advance and validate different real-time automated quality control techniques before implementing them in commercial 3DCP systems.

Finally, while most academic and commercial efforts are focused on the prefabrication of 3D printed elements and sub-structures, there are new possibilities for on-site bridge construction using 3DCP. One construction 3D printer would be able to fabricate a large number of bridge elements with different geometries and internal features on the construction site. This construction paradigm will eliminate the high transportation costs associated with the shipping of large and heavy precast concrete elements commonly used in bridge construction. In addition, a considerable portion of construction costs is related to the formwork which is fabricated and used for each type of bridge element, and the time-consuming process of setting up these formworks and removing them after the concrete hardens. Therefore, significant time and cost savings could be realized by eliminating the formwork from the bridge construction process through 3DCP. A higher level of construction automation improves construction productivity and could play an important role in expediting the replacement of deteriorating infrastructure in the United States.

3.3 Environmental Impacts of 3DCP on Construction Projects

3DCP has emerged as a viable alternative to traditional concrete construction primarily due to its possible benefits of enhancing productivity and decreasing construction time and cost. With all the potential uses of 3DCP, limited research has been carried out to quantify the environmental impacts of this innovative technology.

To quantify the environmental impacts in detail, all stages of the construction process must be considered for evaluation, beginning with earlier construction stages (e.g., raw material preparation), and continuing through the demolition of the structure. Life cycle assessment (LCA) is a technique to calculate and analyze the environmental impact of a product over its lifetime. In construction, it is the tool to calculate the environmental impact of the entire construction process and has been widely investigated in previous studies (Abu-Ennab et al. 2022; Häfliger et al. 2017; Nwodo and Anumba 2019; Saade, Guest, and Amor 2020).

Several studies investigated the sustainability of 3DCP over conventional construction using LCA tools, and most of the outcomes agreed that 3DCP offers environmental benefits (Cerdas et al. 2017; Kreiger and Pearce 2013; Kohtala and Hyysalo 2015). One of the most recent studies conducted a comparative LCA study between 3D printable concrete materials using industrial wastes compared with conventional ones (Liu et al. 2022). This study not only focused on the material differences between cement-based or geopolymer concrete, but also quantified the environmental performance of various construction methods in different applications. The results in the material level indicated that although geopolymer concrete is a greener alternative to cement base concrete, with around 20% of industrial waste, it does not surpass Portland cement concrete when applied in 3D printing. It is because geopolymer concrete has a higher activator content to achieve the desired printability. In the component-level analysis, the results showed that the potential environmental benefit of 3DCP increases with building complexity (Liu et al. 2022).

Another recent study (Mohammad, Masad, and Al-Ghamdi 2020) demonstrated the environmental benefits of 3DCP over conventional construction by applying a cradle-to-gate LCA of four wall section case scenarios. The considered elements included a 3D-printed wall section with and without reinforcement, a conventional concrete wall section, and a lightweight 3D-printed concrete wall section without reinforcement. This study conducted a comprehensive cradle-to-gate LCA for all wall cases. Several environmental impact indicators were quantified in this study, including global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), smog formation potential (SFP), and fossil fuel depletion (FFD). The results demonstrated that 3DCP significantly reduces environmental impacts compared to the traditional method. However, these environmental enhancements diminished when 3DCP was combined with reinforcement elements. In addition, using an alternative concrete mixture like lightweight 3D-printed concrete showed the potential environmental impact reduction in all five indicators compared to other scenarios. Eventually, the findings of this study supported the advantages of 3DCP technology and recommended developing sustainable printable concrete materials and novel reinforcement techniques for 3DCP. The outcomes of the study revealed that future research studies should focus on developing innovative reinforcement methods suitable for 3DCP rather than adopting conventional reinforcement techniques (Mohammad, Masad, and Al-Ghamdi 2020).

In another study, Wang et al. (2020) performed a comparative LCA between a 3D-printed vs. precast bathroom unit (with a unit size of 1.6 m length, 1.5 m width, and 2.8 m height) using the International Organization for Standardization (ISO) 14040: “Environmental management — Life cycle assessment — Principles and framework.” The scope considered in this study covered material and electricity consumption, installation process, cost, and productivity, and Mid-point and end-point values are considered to quantify to substitute most environmental impact indicators.

The results revealed that 3D-printed bathroom units attained a total 25.4% cost reduction, an 85.9% reduction in CO_2 production, and an 87.1% decrease in energy utilization compared to precast ones (Weng et al. 2020). With further sensitivity analysis of both case studies, it was discovered that the formwork and reinforcement presence in the precast method was responsible for higher environmental contamination (Weng et al. 2020).

In another study, Alhumayani et al. (2020) explored the sustainability performance of additive construction technology compared to conventional construction. The standard cradle-to-site LCA method was applied to evaluate the environmental damages of a unit of a load-bearing wall by utilizing two types of construction material: concrete-based and cob-based material, constructed using 3DCP and precast techniques. As expected, the cob-based 3D-printed concrete performs better than concrete-based 3D printing material regarding global warming performance. In addition, the results of this study showed that 3D-printed walls have better sustainability performance than the conventional approach. The absence of formwork or reinforced steel in 3D-printed walls significantly decreased environmental impacts. However, 3DCP required more fly ash and a high amount of cement to be extrudable, which increased the contribution of 3DCP to global warming by about 70 % (Yao et al. 2020). As the Portland cement content of the printing material has a high ecological footprint in the LCA studies, recent studies have highlighted the importance of designing high-quality environmentally friendly cement-based materials for 3DCP (Alhumayani et al. 2020).

In another study, Kuzmenko et al. (2022) focused on embodied and operational energy and environmental impacts of 3DCP, using a cradle-to-gate methodology. This study used a concrete cell as a   functional unit and evaluated the environmental impacts using the volume of materials and embodied required for 3D printing using a robotic arm. The results of this study suggested the printing process's contribution to climate change depends primarily on its spatial resolution. (Kuzmenko et al. 2022b). In another study, Abu-Ennab et al. (2022) quantified and compared the ecological footprint of additive construction technology and conventional construction techniques to calculate the possible environmental impacts of 3DCP. The functional unit for a cradle-to-gate LCA in this study was a 3D-printed wall (with an innovative concrete mix containing calcium sufflaminate) compared to a conventional wall. The results of this study indicated that the 3DCP technique lowered the total environmental impacts compared to the conventional techniques in three environmental impact indicators of EE (by 12%), GWP (by 55%), and EP (by 4%) (Abu-Ennab et al. 2022).

Yao et al. (2020) performed a comparative LCA between two case scenarios of ordinary concrete panels and 3D printing geopolymer concrete panels, the ex—ante LCA method. The data needed to model the LCA have been collected from the manufacturer to distinguish the trouble spots for environmental enhancement. The result showed that geopolymer concrete is the better choice as it reduces the carbon footprint of concrete materials. At the same time, it still has the worse impact on the environmental impact indicators, such as depletion of abiotic resources and stratospheric ozone depletion. In addition, the outcomes reveal that 3DCP can reduce the amount of waste. This investigation also suggested that decreasing the amount of silicate in the geopolymer concretes is the most effective solution to reduce the ecological impacts. However, this kind of technological solution is challenging to be applied by the industry (Yao et al. 2020).

In addition, Gislason et al. (2022) conducted a comparative LCA study to investigate the potential environmental improvement for the load-bearing beam structure, comparing 3DCP and conventional beam construction using a cradle-to-grave LCA methodology. The results indicated that the conventional cast method have a lower environmental impact than 3DCP beams (Gislason et al. 2022). They suggested that low-clinker cement could be an alternative material to reduce the environmental impacts of 3D-printed structures.

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.

4 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 (Zeng and Chini 2017). The present research methodology is based on the environmental LCA method framed by the international standards ISO 14040 (Standardization 2006). Following the LCA methodology presented by Yan et al. (2010), A cradle-to-site LCA was performed that included raw material extraction, construction (precast vs. 3DCP), and installation for the studied bridges (Yan et al. 2010). 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). The construction sector is the second largest CO_2 emitter, accounting for roughly 36% of final energy use and 39% of energy and process-related carbon dioxide emissions, 11% of which resulted from manufacturing building materials and products such as steel and cement (IEA 2019). In this study, a carbon dioxide equivalent (CO_2-eq) metric is used to compare the emissions from various GHG based on their GWP.

In this study, a three-step approach is used to measure the environmental impacts of 3DCP vs. precast bridge construction, as it is shown in Figure 4. In the first step, an already constructed 3DCP bridge is used as a case study. Next, a similar bridge is designed based on the precast technique to perform a comparative LCA. In the second step, the LCA system boundaries and functional units are defined based on the studied and designed cases. Finally, in the third step, the studied and designed bridges, as well as the system boundary, quantities, and functional units, are modeled in an LCA software for further analysis.

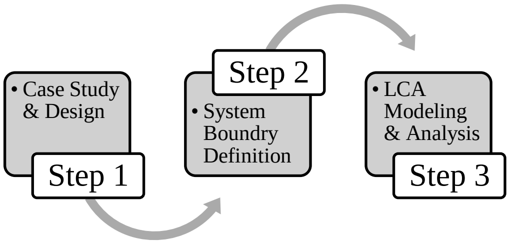


Figure 4. The designed research methodology

4.1 Case Study & Design

Section 4.1 covers the proposed "Task 2: Case Study" in the proposal. The scope of the proposed activity was to study a segmental concrete bridge as a benchmark. The proposed bridge was the Red River bridge in Boyce, Louisiana. We collected all the information regarding the design and construction of this segmental concrete bridge from the Louisiana Department of Transportation and Development (LaDOTD) to be used in this project. However, after reviewing the documents, the project team realized that the documents were too old to provide a reliable benchmark for this study. Therefore, the project team decided not to use this bridge as a case study. However, after performing the literature review on current 3DCP practice in bridge construction, the project team decided to change the case study to a smaller concrete pedestrian bridge that was built in the Netherlands in 2017. All the information about the new case study is provided here. We contacted the stakeholders of the newly selected bridge and collected all the required information in a timely manner. It resulted in not changing the scope of the project but changing the case study.

A small 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 and pumped through 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 (Bos et al. 2017b). This technique allowed a fully automated process that does not limit the geometrical possibilities offered by the 3DCP technology (Bos et al. 2017b). The printing process, final slabs, and final bridge are shown in Figure 5.

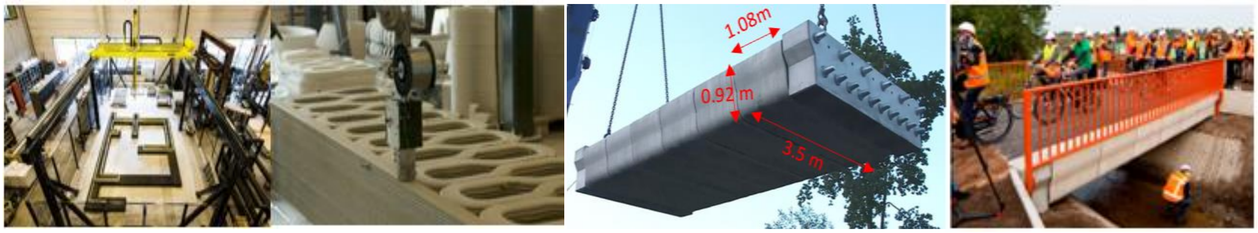
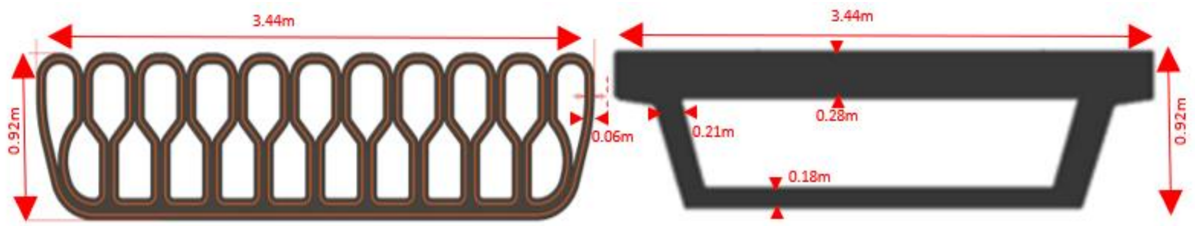


Figure 5. The case study bridge and printing process at TU/e (Bos et al. 2017b)

To compare the 3DCP 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 3DCP 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 3DCP bridge are shown in Figure 6.



a. 3DCP bridge slab (Salet, Ahmed, et al. 2018) ***b. Box grinder precast bridge slab (Zhou et al. 2017)***

Figure 6. The designed slab for the box grinder precast and 3DCP bridge slab

4.1.1 Estimates of construction materials and waste quantities

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

3DCP 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 3DCP and precast bridges, respectively. It illustrates that the concrete needed for the 3DCP bridge is around 74% of the precast bridge.

4.1.2 Concrete Properties

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. 2022a). 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 mixtures 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*

4.1.3 Reinforcement Method

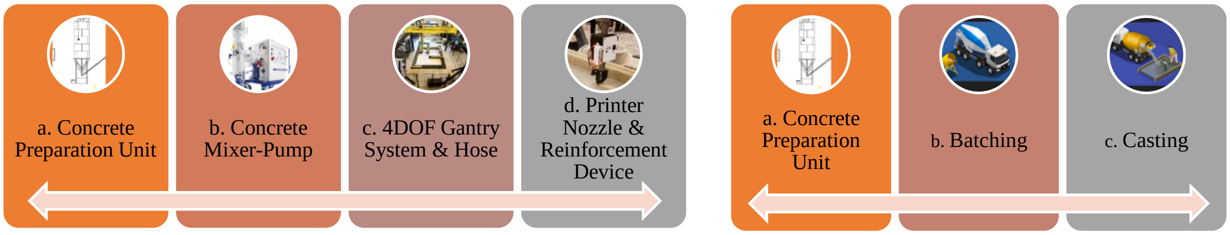
In addition to the type and amount of concrete, the type and method of reinforcement could be different in the 3DCP and precast bridges. For the 3DCP bridge, high-strength steel Bekaert Syncrocord wires were used for reinforcement. Compared to ordinary reinforcement steel, the ductility of steel wires is limited. Wires with a diameter of 0.97 mm were considered for the 3DCP bridge (Bos et al. 2017b). 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, Ahmed Y, et al. 2018) is assumed for both bridges.

4.1.4 Quantity of formwork

As discussed earlier, formwork is only required for the precast technique. The amount of formwork equal to the dimension of one section of the bridge is assumed for this study. Based on previous research, aluminum formwork can be one of the options for precast bridge construction. The typical aluminum type for formwork is Grade 6082 and 6005A Aluminum Alloys, which provide durability and strength. For our study, we assumed one piece of formwork for all bridge sections, and based on the dimension of our precast bridge case study, the weight of the formwork is calculated (Administration 2016). To calculate the amount of formwork and the weight of the aluminum used in this bridge, we have used the thickness, specific weight, and several aluminum sheets. Considering 5 Kg assumed amount for connectors, bolts, and nuts as well as 1kg of epoxy glue to cover the possible coatings and the weight of the consumed aluminum sheet, we have estimated a total weight of 164.9 kg for the formwork required for the designed bridge case.

4.1.5 Embodied energy during construction

Within extrusion-based 3DCP, different technological set-ups exist, differentiated by the type of printing device, material formulation, fabrication environment, and, consequently, the size and type of object they can produce. The present work considers a generic approach to the entire printing unit based on the sub-processes shown in Figure 7.



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

Figure 7. The subprocesses for the construction of the bridge using different methods

Concrete batching includes the primary mixing of most of the concrete ingredients. This phase is almost the same in both 3DCP and precast methods, where the concrete is produced. We have assumed a subprocess for "standard" concretes and "standard" mixing devices. Specific water-to-cement ratio concretes may, for instance, require more prolonged and more energy-intensive mixing. The embodied energy data for the concrete batching stage is driven from the blow equation, as suggested by (Utomo Dwi Hatmoko et al. 2020):

$$Energy\ Consumption\ \left(\frac{Mj}{km}\right) = Fuel\ Consumption\ \left(\frac{litr}{km}\right) * Caloric\ Value\,\frac{Mj}{Litre}$$

The concrete mixer pump unit for 3DCP bridge construction consists of an M-Tec Duomix 2000 mixer pump with a linear displacement pump feeding concrete by a Ø 25 mm hose to a gantry robot (Bos et al. 2017a). These are expected to run through the entire printing duration and aim at continuously feeding the mobile printing device. For one hour of pumping, the machine power is 10.15 kW per hour, so based on the formula kW x time = kWh for 48 hours of printing, there will be an energy consumption of 487.2 kWh for printing 11.7 m^3 of a 3D-printed concrete bridge in our case study. In addition, the Gantry printer includes a mobile tool for positioning the printhead, a command system, and the printhead itself, along with a 'reinforcement entraining device' (RED) that enables the introduction of a reinforcement medium to the concrete filament (Bos et al. 2017a). This mobile tool is a motion-controlled 4-degree-of-freedom (DOF) gantry robot serving a print area of 9 × 4.5 × 2.8 m. We have assumed a default linear print speed of 100 mm/s (0.1 m/s) and a pump pressure of 1–3 MPa (10–30 bar). The energy consumption here is calculated based on the technical specifications power of the printer and the speed of the gantry printer at Eindhoven university. 4DOF gantry consumes 7kw per hour, so for 48h of printing, there will be 336 kWh of electricity consumption for 11.7m^3 concrete printing (Kuzmenko 2021).

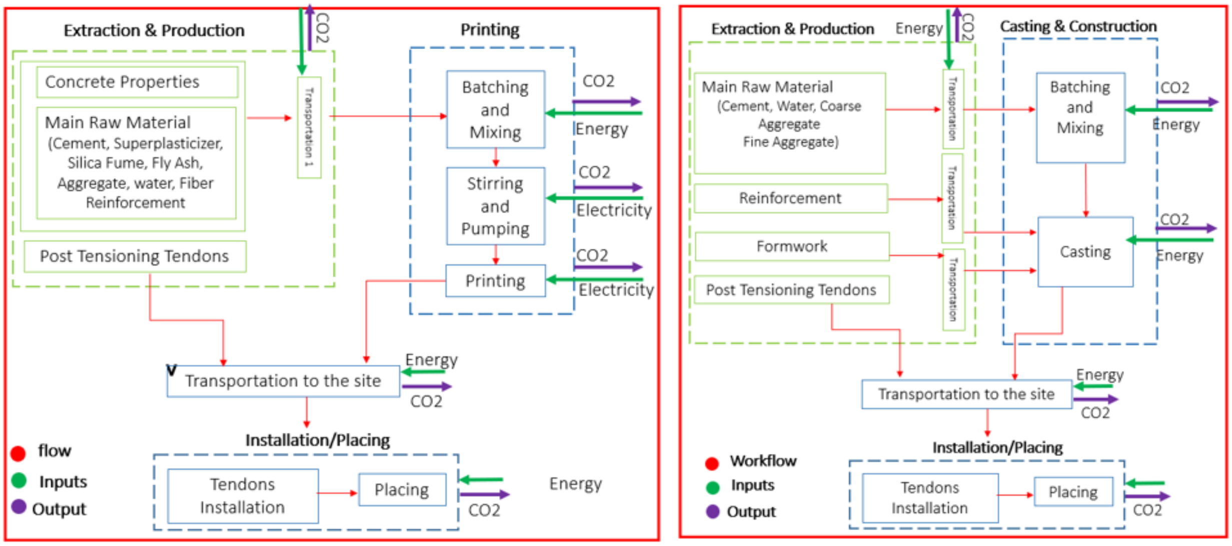
Table 3. Estimated embodied energy consumption for case scenarios

Energy Consumption	Precast Bridge	3DCP Bridge
Printer	-	336 KWh
Casting	596 MJ	-
Stirring & Pumping	-	487 KWh
Batching	352 MJ	269 MJ
Transportation	1300 MJ	900 MJ
Placing and Installation	153 MJ	117 MJ

4.2 System Boundary Definition

Section 4.2 covers the proposed "Task 3: Conceptual Process Design" in the proposal. Since we changed our case study in this project, we needed to adjust the conceptual process design. Originally, the case study that we proposed to consider was a traditionally built precast concrete bridge. However, the newly selected project was a precast bridge built based on the 3D concrete printing technique post-tension method. Therefore, instead of benchmarking a traditional bridge and designing a similar 3DCP bridge in the project, we decided to use this 3DCP bridge and design a traditional construction method to build a similar bridge in Baton Rouge, Louisiana. Also, since the bridge was already 3D printed, we decided not to create a small plastic version as proposed in the proposal. As we proposed, we defined the project location in the state of Louisiana to ensure no change in the scope of this project. The developed conceptual process design is shown as a part of our system boundary definition.

For each designed bridge, a separate system boundary was defined in this study (see Figure 8). 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.



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

Figure 8. The designed system boundaries for the construction of the case study bridges

Two function units are considered for LCA in this study (1) a unit of concrete used in each case scenario (1 m^3 of concrete), and (2) the whole bridge constructed in each case scenario. These function units allow us to compare the two case scenarios and their environmental impacts based on the concrete, total materials, construction, and total impacts.

4.3 LCA Modeling and Analysis

In this study, OpenLCA software is utilized for the life cycle assessment. OpenLCA is an open-source software for LCA and sustainability assessment (GreenDelta 2020a). The open-source nature of this software makes it very suitable for use with sensitive data. (Noi, Ciroth, and Srocka 2017). The system boundaries of the study are set from cradle to gate (A1–A3 according to EN 15804), as the question addressed here relates to the construction phase only. 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 2020b). 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.

The model inputs are raw material extraction, mixed fresh concrete material for 3DCP and precast concrete, reinforcement and formwork used in precast, transportation and fuel consumption for both bridge scenarios, and concrete waste (Kuzmenko 2021). The elements needed for modeling the system boundary in OpenLCA are flows and processes. Flows are all product, material, or energy inputs and outputs of processes in the product system under study. A flow is defined by the name, flow type, and reference flow property. OpenLCA distinguishes three flow types:

1. elementary flows: material or energy of the environment entering or directly leaving the product system under study;
2. product flows: material or energy exchanged between the processes of the product system under study;
3. waste flows: material or energy leaving the product system.

Each flow must be defined by a reference flow property such as mass, volume, area, etc. Processes are sets of interacting activities that transform inputs into outputs. Every process is defined by an output flow as a quantitative reference with the flow type product flow, either selected or created when modeling the case scenarios in the OpenLCA.

5 ANALYSIS AND FINDINGS

Section 5 covers the proposed "Task 4: Comparative Analysis" in the proposal. Since we changed our case study in this project, we needed to adjust the comparative analysis. The newly selected project was a smaller pedestrian bridge, and therefore, only a few construction workers were used for 3D printing the bridge elements. In addition, we could not find any managerial information about this project as it was printed in a university in the Netherlands as a showcase. It resulted in not being able to have enough information for logistic project management analysis. In addition, since the project was originally built out of the US, we could not find accurate information about the cost of construction in US Dollars, disabling us from performing an economic impact analysis. Therefore, we decided to focus mainly on the Environmental impact analysis, as proposed in the proposal. On the other hand, we added additional elements to the scope of the project for a more comprehensive environmental impact assessment, including assessing several impact factors, assessing the environmental impact of concrete materials designed/used, the environmental impact of different concrete reinforcement strategies, and assessing the environmental impact of different construction stages in addition to the life-cycle assessment of the case study. The results of this comprehensive environmental impact analysis are provided in this section.

5.1 Comparing the Environmental Impacts of Concrete Mixtures

First, the GPW impact analysis was performed using generated CO_2-eq amount based on the concrete mixture design in each scenario: 3DCP and precast. The results showed that the extraction of the materials needed for 1 m3 of concrete would result in generating 499 kg and 367 kg of CO_2-eq for 3DCP and precast bridges, respectively. Figure 9 shows the LCA result regarding the GWP impact assessment for 1 m3 of concrete used in the case study. With respect to the GWP impact of 1 m3 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 Portland cement used in the 3DCP concrete mixture (almost 35% more Portland cement compared to the precast concrete mixture). Because of the significant impact of Portland cement production on generated GHG, it can be concluded that printable concrete with a high amount of Portland cement would not be environmentally sustainable.

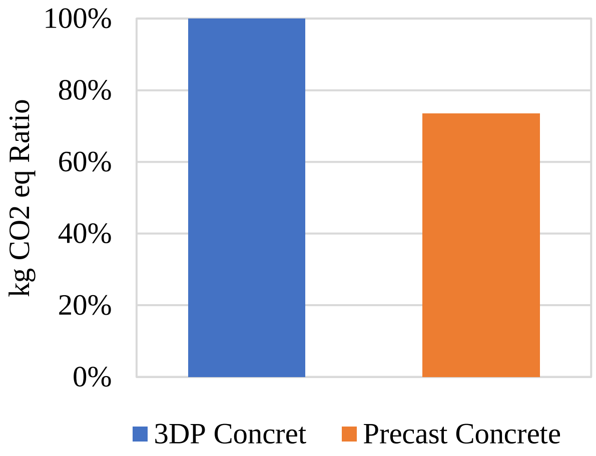
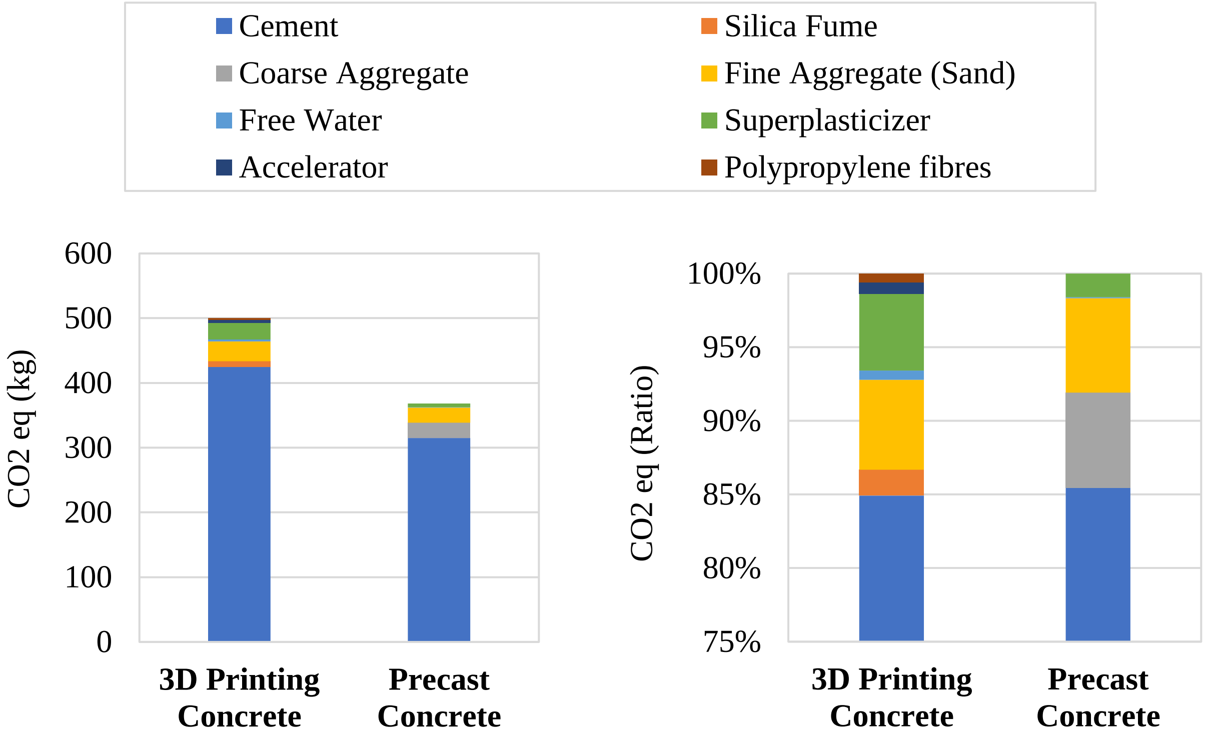


Figure 9. The GWP impact assessment of the concrete unit for both scenarios

Figure 10 illustrates the contribution of each component of concrete mixtures to the overall GWP using generated CO_2-eq amount for each scenario. For 1 m3 of concrete, the production of Portland cement is the most significant contributor to global warming in both case scenarios: 315 out of 367 kg CO_2-eq for precast concrete and 425 out of 499 kg CO_2-eq for 3DCP concrete.



a. The total CO_2-eq for 1 m^3 of concrete *b. The ratio of CO_2-eq for 1 m^3 of concrete*

Figure 10. The GWP impact assessment of the concrete mixture for both scenarios

As the results show, in both scenarios, the contribution of Portland cement to GWP impact is around 85%, which is in line with previous studies (Salas et al. 2018; Turner and Collins 2013).

In addition to GWP, the contribution of Portland cement in other environmental impact categories is analyzed for 3DCP concrete. The results are shown in Figure 11. As the results show, except for the categories of ‘land use’ and ‘water consumption,’ Portland cement (and its production) is the main contributor to other environmental impact categories in the 3D printing concrete. It can be concluded that to improve the environmental impact of constructing infrastructure using 3DCP, more research is required to enhance the printable concretes by minimizing the Portland cement content by using more sustainable alternatives.

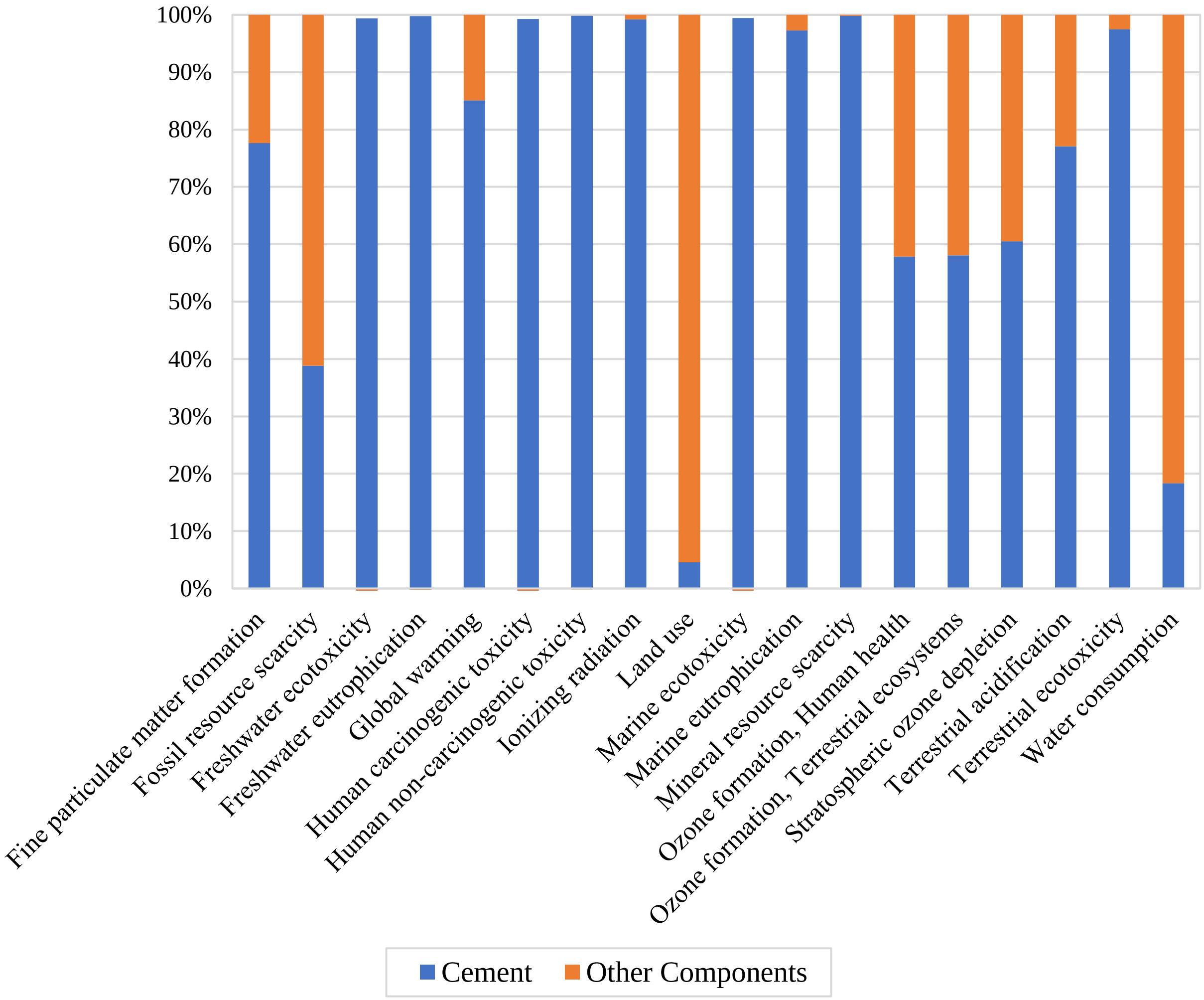


Figure 11. The environmental impact assessment of the 3DP concrete mixture

5.2 Comparing the Environmental Impacts of the Total Concrete

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 3DCP technique could reduce the concrete needed for the same bridge by 35% compared to the precast method in this case study. On the other hand, 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 due to the higher amount of Portland cement used in the 3DCP concrete mixture. Therefore, as Figure 12 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 Portland cement used for construction.

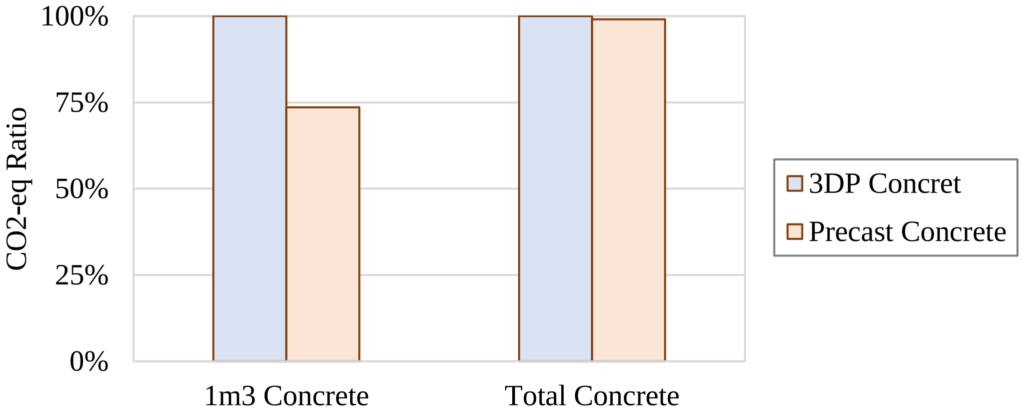


Figure 12. The GWP impact assessment of the total concrete used in the case study

Figure 13 illustrates the contribution of each component of concrete mixtures to the overall GWP using generated CO_2-eq amount for total concrete in each scenario. For the total required concrete, the production of Portland cement is the most significant contributor to global warming in both case scenarios – as it is stated, it contributes to 85% of total CO_2-eq in both scenarios. For the remaining components, the fine aggregate is the second contributor to GWP in both scenarios, followed by superplasticizer in 3DP concrete and course aggregate in precast concrete.

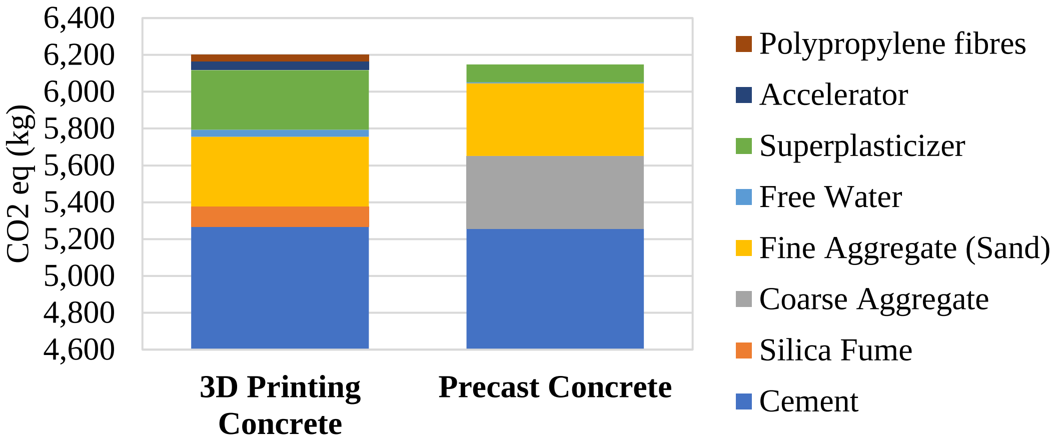


Figure 13. The GWP impact assessment of the concrete mixture for total concrete

In addition to GWP, the impact of the total required concrete on other environmental impact categories is analyzed for both 3DCP and precast bridges. The results are shown in Figure 14. As the results show, except for the categories of 'fossil resource scarcity' and 'water consumption,' there are no significant differences between the impact of the total concrete required for both bridges. In these two categories, the 3DCP bridge performs better because of the reduction in the use of coarse aggregate in the concrete mixture. Although coarse aggregates are necessary in terms of the strength and economic feasibility of producing concrete, most 3D printers are not capable of printing concrete mixtures containing coarse aggregate.

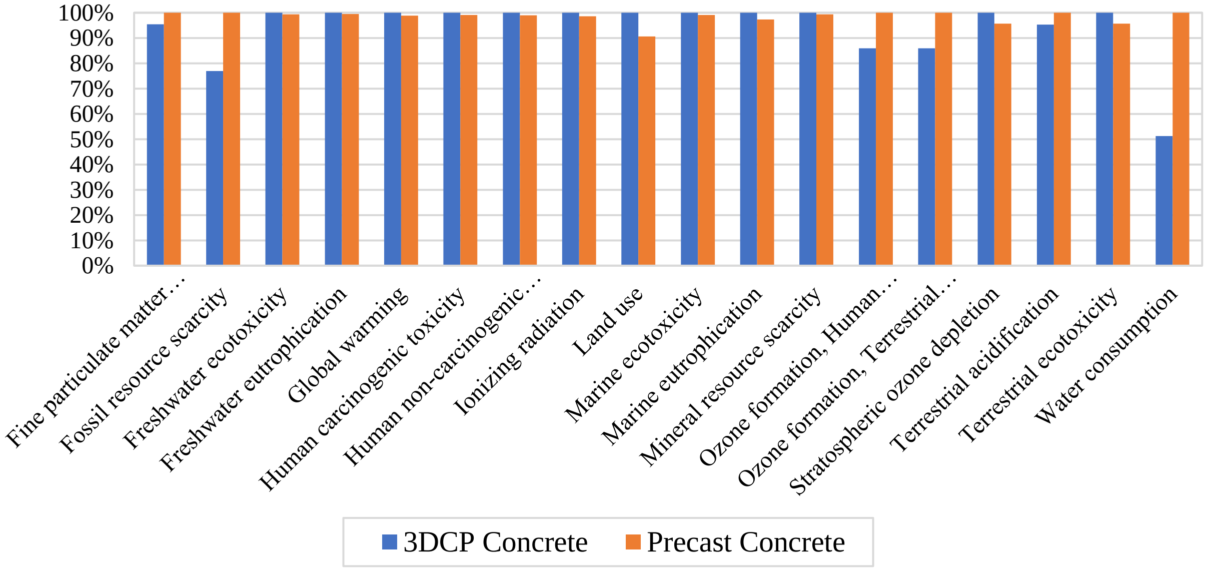


Figure 14. The comparative ratio of environmental impact assessment for total concrete

5.3 Comparing the Environmental Impacts of Bridge Construction

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. Figure 15 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. It highlights that to reduce the environmental impact of infrastructure, specifically the GWP, most of the attention should be given to materials. Reducing the materials (like what 3DCP can offer) or replacing the unsustainable materials with more environmentally-friendly substitutes can significantly reduce the environmental impacts in infrastructure development.

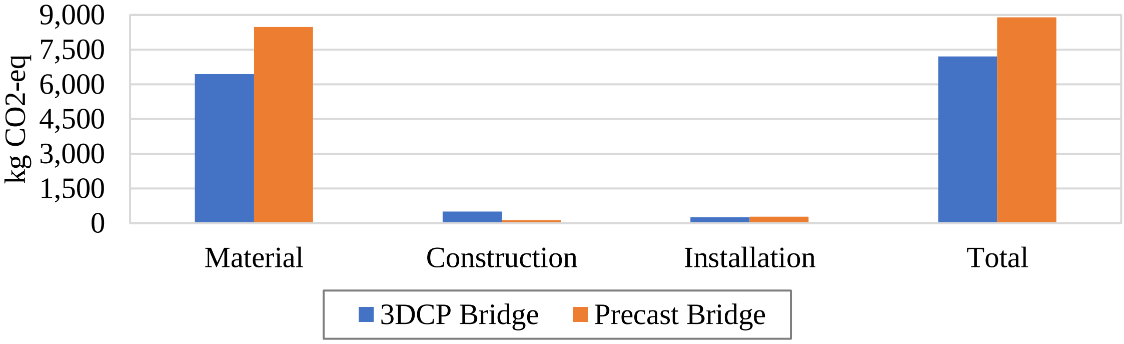


Figure 15. The GWP impact of each stage in bridge construction in terms of total CO_2 Eq

In addition, Figure 16 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. Besides, 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 shown in Figure 5.b are 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.

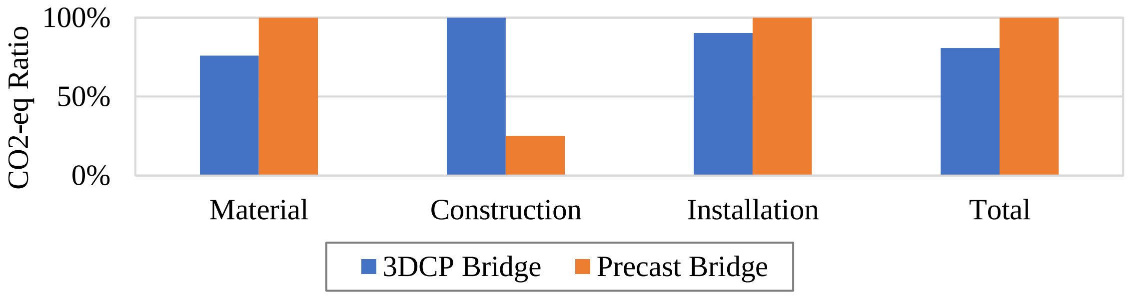


Figure 16. The GWP impact of each stage in bridge construction in terms of CO_2 Eq ratio

Figure 17 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 limiting the use of coarse aggregates) 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 Portland cement in the concrete mixture.

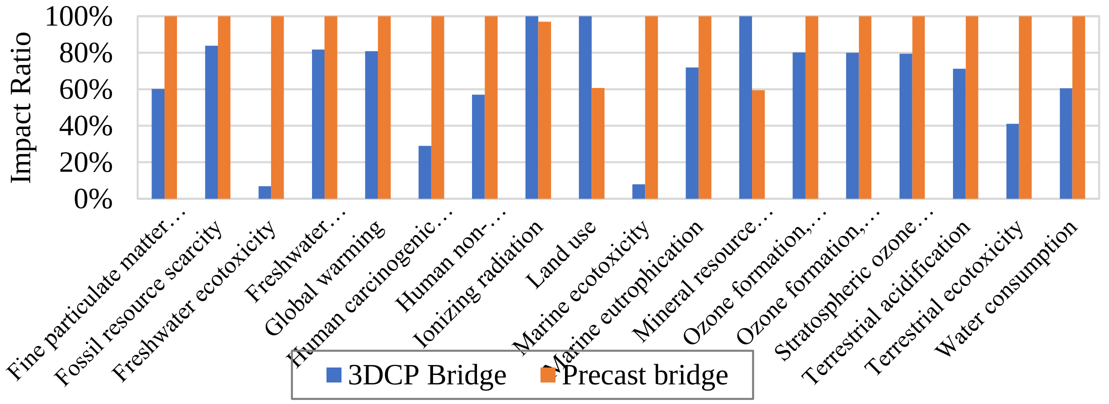


Figure 17. The comparative ratio of environmental impact assessment in bridge construction

6 CONCLUSIONS

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. The bridge elements were 3D printed off-site and then transported and assembled on the bridge site. 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 Portland cement was responsible for 85% of the generated CO_2-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 Portland 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 the use of 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, this study showed that 3DCP can reduce the GHG emission of constructing a small concrete bridge by 20% compared to 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 commonly used printable concretes require a higher amount of Portland cement, resulting in higher environmental impacts, 3DCP can significantly reduce the need for materials by topology optimization. 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.

Finally, it should be mentioned that there are alternative new approaches for implementation of 3DCP for bridge construction, which were not explored in this study. For instance, 3DCP robots can be used on the construction sites to fabricate the bridge elements to further increase the bridge construction speed, and eliminate the need for transportation of heavy concrete elements. Such paradigm shift in bridge construction will have significant implications on the sustainability of the overall process which needs to be studied in the future upon availability of field data on 3D printed bridges.

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