A Digital Workflow for the Design and Manufacturing of 3D Printed Concrete Bridges in a Circular Economy:

A Parametric Approach to Integrated Design and Fabrication

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Matthew Ferguson

A thesis submitted in partial fulfillment of the requirements for the degree of **Engineering Doctorate**.

The design described in this thesis has been carried out in accordance with the TU/e Code of Scientific Conduct.

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0. Public Summary

Low productivity, material depletion, waste, and emissions are widespread in the construction industry. On top of this, many bridges reaching the end of their service life need repair or replacement.

This design project investigates how digitisation and integrated design and manufacturing processes can aid in addressing sustainability and productivity issues. This project develops a digital workflow for bridge design and manufacturing using 3D printed concrete in combination with circular economy design concepts of disassembly and material reduction.

Design Criteria

For the development of the project, design criteria were established. This process initially looked at two previously printed bridges in the Netherlands. From this, design criteria for both the design tool and the resulting bridge designs were established. These criteria include:

- Use concrete 3D printing and work with relevant printing systems.
- Use structural analysis to guide user decisions.
- Use prestressed tendons and modularise for simple assembly and disassembly.
- Implement principles of the circular economy.

Design Tool

The project developed a parametric design tool for creating bridges using 3D-printed concrete. Five 'blocks' manage distinct design elements in the design tool.

1. Alignment allows the user to match the bridge to an existing location or shape a new bridge through length, span and shape.
2. Cross-sections along the curve allow the user to shape the bridge. Size and thickness control linked to a structural check enables efficient material distribution.
3. 3D Form interpolates the cross-sections into a 3D shape. Here the user can see how the beam will look.
4. Segments are created in the beam to engage with material, manufacturing and transport constraints.
5. Code Generation block generates code suitable for standard printing systems.

The user can make changes and modifications at any stage in the process. The manufacturing constraints are embedded into the design process, helping to ensure that what is designed can be produced.

Design Concepts

Two bridge concepts were created to demonstrate the tool's flexibility in different scenarios. One design uses a freeform cross-section type to create a pedestrian bridge over a river. The other is a more straightforward highway bridge using a modular cross-section type and reuses existing supports.

Public Dissemination

One of the ambitions is to share results and knowledge generated throughout the project. This knowledge dissemination is demonstrated by three public presentations reaching an industry, academic and general public audience.

Conclusions and Recommendations

The tool created helps demonstrate how integrated approaches to design and fabrication can help with the challenges presented in sustainability and productivity but simultaneously with the ambition that what we produce is attractive and appropriate to its location.

1. Opposite, test elements being printed.

1. Introduction

The construction industry needs to change: low productivity, skilled labour shortages, huge environmental impact through resource depletion and large amounts of waste and emissions generated [1]. Projects are often delayed and over budget, with quality also suffering [2] [3]. This industry has challenges and also a responsibility. This industry affects how people live, their surroundings, and their quality of life. Much of the construction industry still operates in a very traditional manner, with projects undertaken through large amounts of labour and hand processes [4]. With labour shortages continuing and the effects of climate change worsening, we must use the available technology to address these problems. With the global population expected to reach 10 billion people by 2050 [5] and the effects of climate change already visible, the standard working methods need to be reassessed in every industry.

These challenges present us with a need to reconsider and re-evaluate the way this industry operates. An excellent opportunity for change comes through digitisation, with the construction industry currently among the least digitised [6]. How can digitisation help us with productivity, creating a safe and efficient working environment? How can it help us with sustainability and climate change? How can we achieve this while responding sensitively to each site's needs? These questions are asked and challenged throughout this project.

Integrated digital design and manufacturing strategies offer one solution for tackling the environmental and productivity challenges we face in the construction industry. Digital design integrated with automated fabrication processes can reduce labour demand, increase the efficiency of materials, and reduce waste [7]. A parametric design approach allows a single design to have multiple outputs, offering customisation within a defined range. This approach again feeds into the advantages of digital fabrication processes where economies of scale are less rigid than traditional processes. Applications requiring multiple customisable design versions are well suited to this approach.

The Dutch government, along with many others, faces the challenge that many bridges are reaching the end of their service life, being built after WWII, and thus, must be repaired, wholly renewed, or replaced [8]. This project aims at providing a tool to assist in this challenge, connected to the digital manufacturing process of 3D concrete printing, building on existing research and projects by Eindhoven University of Technology (TU/e) [9].

The project, commissioned by Rijkswaterstaat (The Dutch Directorate-General for Public Works and Water Management), took place from October 2020 to October 2022, using the TU/e 3D printing and structural testing facilities, along with discussions with the 3DCP group to aid the development. The project consists of two areas of investigation, culminating in two reports: Structural Design Considerations for Pre-Stressed Beams and Dry Connections by Rong Yu and the report presented here, A Parametric Approach to Integrated Design and Fabrication.

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2. Concrete construction waste.
Image credit RMIT.

Project Scope and Objectives

This project addresses the issues described above by investigating how we design and manufacture objects for the built environment, how we use materials and how objects can be disassembled to be reused or recycled.

Sustainability

The project addresses the goal of sustainability by integrating the principles of a circular economy. The European Commission has identified a circular economy as a critical strategy for reducing the number of raw materials used and the associated environmental effects [10] [5]. Objects should be designed to reduce, reuse, and recycle their materials.

This strategy is implemented in this project by designing bridge structures to be dismantlable and avoid permanent fixings. Another strategy is to reduce the amount of material used through structural optimisation. Using 3D printing technology, material use can be minimised by placing it in the positions it needs to be structurally. This process contrasts with conventional methods of casting concrete using formwork, where solid forms are often created due to simplicity and cost constraints.

Productivity

The project creates a digital design and manufacturing workflow to produce bridge elements using concrete 3D printing in an integrated digital design and fabrication process. This holistic approach contrasts with current conventional design and fabrication methods, which are segmented, where changes are slow and expensive. The design phase using the new tool is more efficient as the tool can produce numerous high-quality designs quickly and easily. The fabrication process improves as manufacturing constraints are incorporated into the design process.

This project aims to be applicable to the current state of the art of 3DCP; therefore, material research and new reinforcement methods did not form part of this project's scope. As sustainability is a crucial requirement for this project, it should be noted that current material compositions used for concrete 3D printing still need to be improved to make it a truly sustainable option. This concerns both the relatively high cement content and the absence of large aggregates in typical printable mixtures [11]. This project assumes that a sustainable 3D printing concrete mixture will be available soon. At that point, the digital tool can be adjusted to consider the properties of that material composition.

Deliverables

In this project, these are the outcomes:

1. **A Parametric Design Tool** capable of designing and fabricating 3D concrete printed bridges incorporating structural, manufacturing and sustainability constraints.
2. **Disseminating knowledge** about the potential of parametric design tools and integrated design and fabrication using 3D printed concrete within the context of the built environment and the current climate crisis.

Methodology

Design Tool

To develop the design tool, design criteria had to be established; this is provided in chapter 2, where precedents are detailed, lessons learned from them are specified, and the tool's criteria are then defined. The iterative development of the design tool, of which all steps were validated using experimental manufacturing and structural tests, is described in chapter 3. Two design concepts created using the design tool are developed to indicate the tool's possibilities and are presented in chapter 4.

Disseminating knowledge

By exhibiting results and sharing findings with peers, academia, industry and the general public, the knowledge generated from the project was disseminated. This has taken place at three international events and is described in chapter 5.

Conclusions and recommendations are given in chapter 6.

2. Design Criteria

This project aims to create a workflow capable of designing and constructing multiple 3D-printed concrete bridges while addressing issues of sustainability and productivity. The goal is not to design and build a single bridge.

Precedents

This project expands on work undertaken at TU/e during the design and construction of two bridge projects in the Netherlands. It incorporates some of the lessons learned from those projects into the workflow development.

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Gemert Bridge

The first bridge is located in the village of Gemert and spans 6.5m with a width of 3.5m. The pedestrian bridge is the first to be made from 3D-printed concrete and therefore faced challenges as there were no precedents, guidelines or testing regulations [12]. To reduce the risk of failure, the bridge was designed to be very simple in form. The bridge is split into identical segments along the span, with each segment printed with the layers horizontally and then rotated 90 degrees before being assembled with post-tensioned prestressing tendons.

Instead of using solid concrete for the bridge, the design used advantages available by the manufacturing process to incorporate an infill pattern, reducing the amount of material used. The pattern was designed to ensure that the segments had enough material to withstand bending and shear forces. Using traditional formwork and reinforcement methods, two solid cast concrete bulkheads were added at either end to introduce the prestress forces evenly. A 1:2 scale model of the bridge was created and tested to failure to test the design and manufacturing process. The final full-scale bridge was tested in situ up to the design load.

The segment sizes were limited by the laboratory facility lifting equipment (5 tons), which resulted in a height of approximately 1m per segment. Each segment was glued together with high-strength concrete adhesive before prestressing. The bridge was craned into position after being assembled near the final location.

5

Nijmegen Bridge

The second 3D-printed concrete bridge built with TU/e involvement crosses a river in Nijmegen. Rijkswaterstaat was involved with developing this bridge with the ambition to introduce more design freedom and create a larger structure than the Gemert bridge to explore further the possibilities of 3D printing technology for bridge applications. This pedestrian bridge used a similar prestressed segment strategy but consisted of five individually prestressed unique elements spanning 29 metres, each supported by columns [13] [14].

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Michiel van der Kley designed the bridge shape, paying particular attention to creating a form that would be difficult to produce using traditional formwork techniques. Summum Engineering created a parametric model for this project that began with the designer's intent and progressed by embedding manufacturing and structural constraints. TU/e built an element for testing, and Saint-Gobain Weber Beamix fabricated the entire bridge [15]. This bridge used a similar 'bottle' shape infill geometry and glued segments like the Gemert bridge. This bridge's design included a printed parapet and 3D-printed concrete formwork for the bulkheads.

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Lessons Learned

- The bridge's spans are printed in multiple segments constrained by lifting weight.
- Printing segments rotated 90 degrees from the orientation of use.
- Incorporating unbounded prestressed tendons for reinforcement that passes through the voids of the infill pattern.
- Both bridges were printed offsite, transported to their sites, and assembled on location. Therefore the logistics need to be considered in the design process.
- Bridges were tested destructively and non-destructively to assess their performance.
- From the Nijmegen bridge, 3D printing the geometry for the bulkheads and using the printed elements as lost formwork.
- Designers worked with a parametric design tool for the Nijmegen bridge. This approach aims to create a closer relationship between what is designed and produced.

While these bridges have made significant advances in innovation, there is still room for improvement. Improvements can be accomplished by implementing the circular economy principles of material optimisation, design for disassembly, and reuse.

While the Nijmegen bridge was initiated with a specific form and location in mind, the design tool presented in this document puts the manufacturing equipment's capabilities at the forefront, driving the process.

3. Previous. Beam designs created as part of the project and printed at Vertico, Eindhoven. Image credit Kees Leemeijer, Vertico.
4. Gemert Bridge opening day. Image credit TU/e.
5. Gemert Bridge 'Bottle' shape print path. Image credit TU/e.
6. Nijmegen Bridge in situ. Image credit Municipality of Nijmegen.
7. Nijmegen Bridge during assembly. Image credit Municipality of Nijmegen.

Criteria

Based on the above precedents, lessons learned and design for circularity, a workflow to design and produce bridges has been created. The workflow includes Design, Fabrication, Assembly, Bridge Use, and Disassembly, with disassembly linking back to assembly.

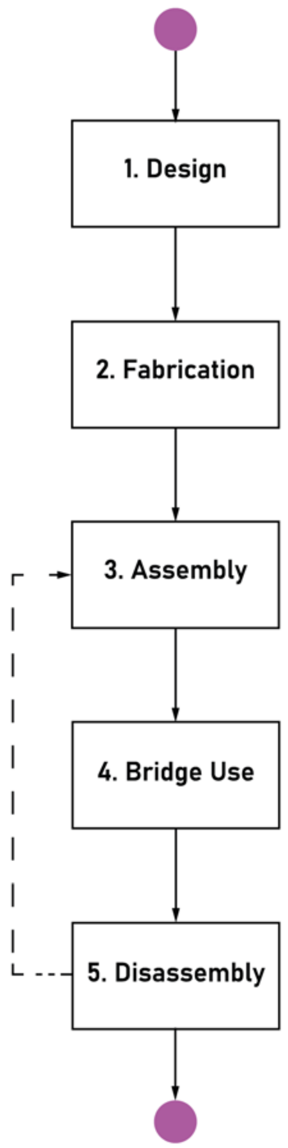
For the design element of the workflow, a parametric design tool is created that considers the following steps in the workflow: Fabrication, Assembly, Bridge Use and Disassembly.

The design tool should:

- Allow the use of a wide range of geometry to create bridge designs that are both elegant and suitable for their environment.
- Integrate structural analysis and provide relevant information to the user to make informed decisions.
- Be adjustable for modifications at any point during the design process.
- Generate fabrication information suitable for standard large-scale 3D printing systems.
- Be expandable in the future as new techniques, materials, analyses, and reinforcement strategies become available.

The bridge designs should:

- Work with 3D-printed concrete.
- Use prestressing tendons as reinforcement.
- Match existing and new infrastructure, such as supports and abutments.
- Implement a form of modularisation that allows for easy assembly, installation, and disassembly.
- Incorporate the principles of a circular economy: reduce, reuse, recycle.



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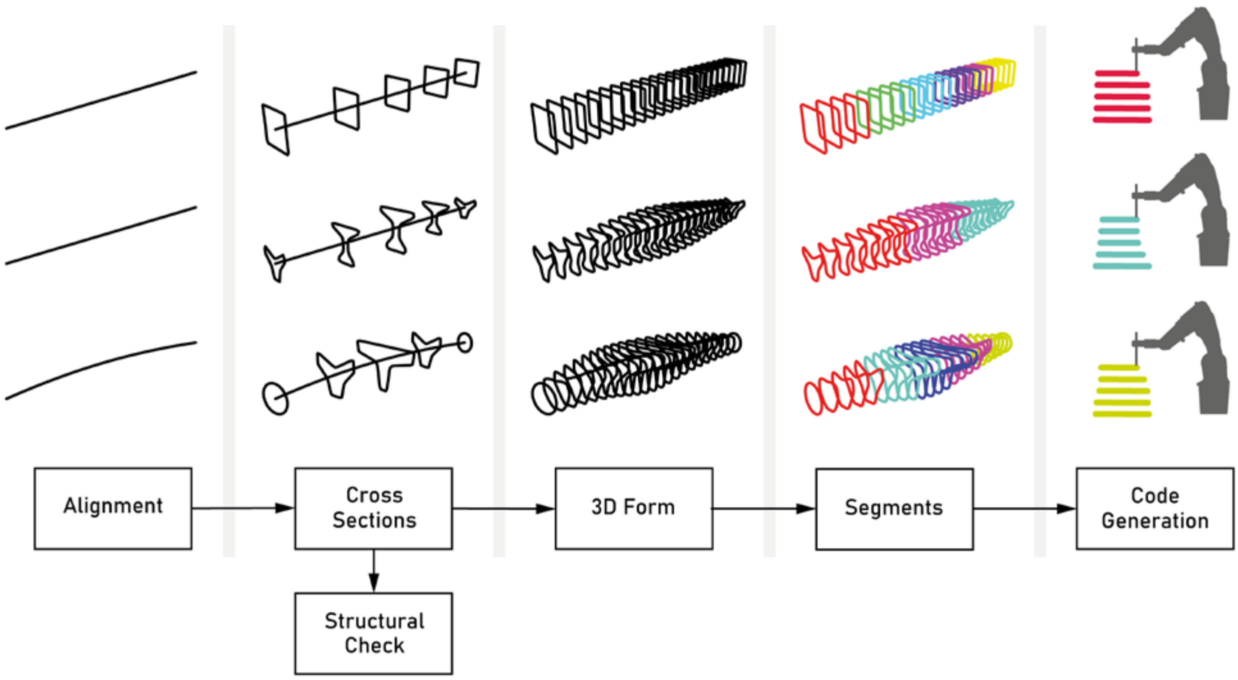
8. Workflow diagram created for the bridge design, production and use life cycle.
9. Opposite, print test looking at nozzle shape and corner radius.



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3. Design Tool

The development of a parametric design tool that allows users to create bridge designs suitable for 3D concrete printing and generate code for their fabrication is described in this chapter. The tool, which provides a single environment for users to move from design to fabrication, was developed iteratively in the Rhino/Grasshopper [16] [17] environment based on both design criteria and experimental results of manufacturability and structural testing.

Combining design and fabrication into a single environment emphasises the benefits of thinking and working with design and fabrication cohesively. The tool comprises a series of "blocks" forming a single workflow with data flowing from one to the next. The image above depicts this process. This chapter examines these blocks, including their inputs, options, and reasons for making the design decisions that form them. The process is written and described sequentially; however, it is essential to note that the user can make changes and adjustments at any point during the design process.

A Structural Check block is included to incorporate structural analysis into the tool and ensure that the design is structurally sound and materially efficient. This development of this block forms the basis of Rong Yu's EngD investigation and is outside the scope of the report presented here.

10. Diagram showing the 'blocks' of the design tool moving from Alignment through to Code Generation. The images above the text show three different bridge beams being designed and their state at that point in each block. The Structural Check block is the work of Rong Yu.
11. Elements of the MAI 2PUMP PICTOR-3D which forms part of the small-scale print setup.
12. Test print using the small-scale print setup.

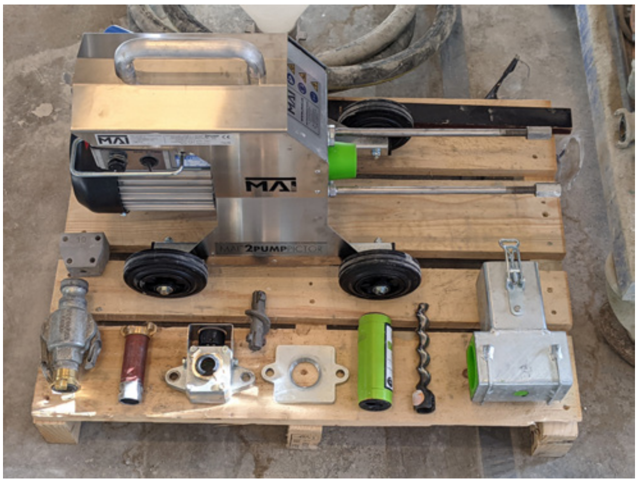
Manufacturability

To develop the parametric design tool with embedded manufacturing constraints, it was necessary to design, test and redesign iteratively throughout the process. The ambition is to build a strong relationship between what is designed and what can be produced.

A large-scale gantry printing system is available and is being developed by the 3DCP group at TU/e. The setup is described by Bos [18]. However, to test ideas quickly on a smaller scale using less material and to test designs on the two most common systems, Gantry and 6-axis robots, a small-scale system using a 6-axis robot was developed.

The setup consists of an MAI 2PUMP PICTOR-3D, a 5 meter hose, a circular 15.5mm nozzle and a 6-axis ABB IRB 1200 robot. This setup allows small amounts of material to be used and created in batches.

Each of the 'blocks' presented in this chapter was tested using this setup and again at intervals on the larger gantry system. These concepts were tested to ensure the ideas work in industry by outsourcing production to Vertico, a 3DCP company based in Eindhoven [29].



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Alignment

```
; ------------------------------
; DATA INPUT
; Point A, Point B, Point C
; ------------------------------
; DATA OUTPUT
; Alignment Curve
; ------------------------------
```

The Alignment is used to determine the bridge's position, length and span shape. The Alignment is a curve which spans from one point to another, providing the base for the tool to operate. A straight Alignment can be used to cross a passage directly. A curved Alignment allows for more flexibility in designing bridge spans from one location to another, perhaps linking with existing infrastructure or avoiding obstacles such as trees.

This block draws a line connecting the input values of A and B. The user has the option of making this line straight or curved. A third input, point C, is necessary for a curved line. Users can also stream geometry from other software applications by adding the speckle plugin [19]. This plugin increases the ability to work in a collaborative environment.

As this alignment curve is altered, revised, or updated, the following blocks are updated correspondingly. The advantages of quickly adjusting this curve mean the whole design process is flexible should a change in the bridge length, shape or location be required.

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13. A straight alignment curve from point A to B.
14. The Alignment curve as a curved line following three points, A, B and C.
15. The numbered cross-sections correspond to positions along the alignment curve.
16. The second and second-to-last alignment planes (shown as 1 and 5) can be adjusted along the length of the alignment curve.
17. Monolithic, Modular, Freeform. Examples of the three cross-section types in the form of a front-view cross-section. An image of a car is included to help identify the bridge deck and suggest scale.

Cross Sections

```
; ------------------------------
; DATA INPUT
; Alignment Curve
; ------------------------------
; DATA OUTPUT
; Scaled Cross-Sections
; ------------------------------
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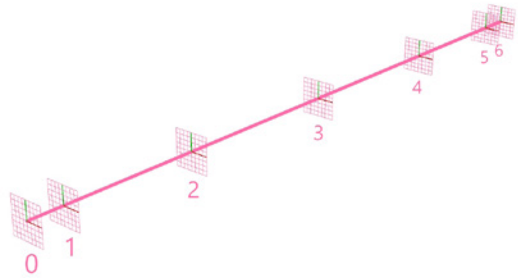

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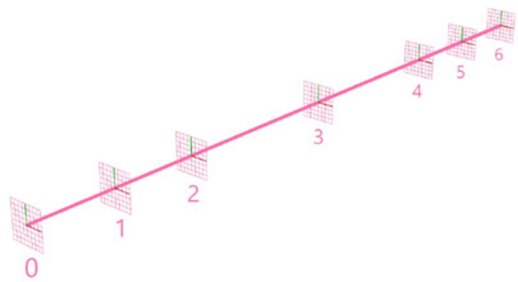
Alignment Planes

The alignment curve from the previous block is brought forward, and an n number of planes are constructed along its length. These planes are numbered and serve as positions for the cross-sections.

The alignment curve is divided into parts of equal length, with planes created at these divisions. Two extra planes are added in the second and second-to-last positions; these planes can move, within a range, along the length of the alignment curve to provide increased control in the following 3D Form block. The ability to manipulate these two planes assists in controlling the overall shape of the beam, especially at the ends where contact with other parts may be necessary. The other planes are fixed to ensure smooth transitions when creating the form of the beam.



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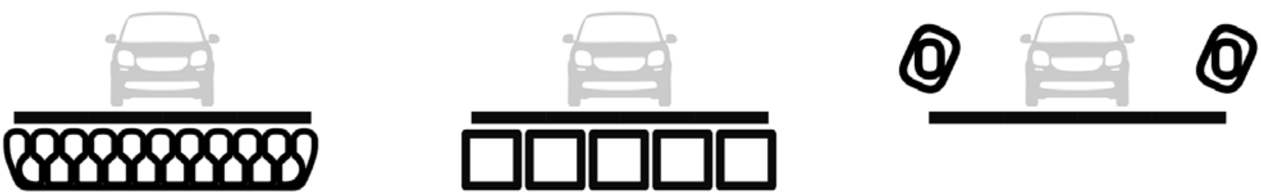

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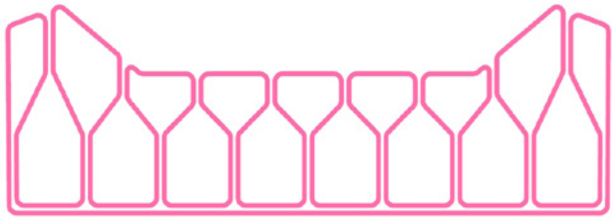
Cross-Section Type

The tool has three cross-section types, which are explained below. The choice to give three cross-section types was made to make it suitable for various settings. Depending on the user's primary requirements, any of the three types may be the best fit.

Monolithic

The monolithic type is directly inspired by the 3D-printed bridges described in chapter 2. The user provides an outer shape from which 'bottle' shaped infill geometry is created. Monolithic refers to a continuous print path consisting of the external shape and infill geometry and the fact that the cross-section consists of one single element.

Benefits of this type include reducing the amount of material used for the infill compared to solid cross-sections used in conventional construction methods. Another advantage is that voids in the infill provide suitable locations for the prestressing tendons. However, one of the drawbacks of using a monolithic type is that it has reduced capacity for addressing the circularity criteria of reusability, as it is not flexible to be adjusted in the future. This type may be desirable where one is confident that the dimensions of the bridge will not need to change in the future. For example, where long service life is planned or at locations where changing the dimensions of a bridge would not be possible.



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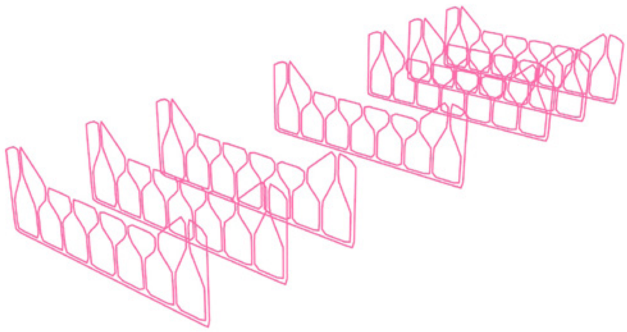

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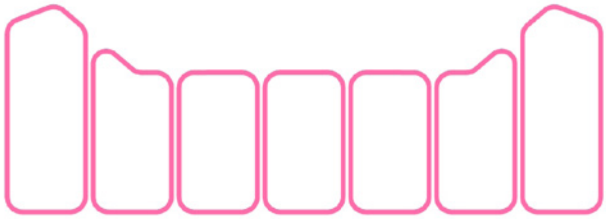
18. Example of a monolithic-type cross-section. The user provides the outer geometry with a 'bottle' shape infill generated by the tool. The dimensions of the infill can also be controlled.
19. 3D view showing the monolithic bridge-type cross-sections arranged on the alignment planes.

Modular

The Modular cross-section type employs the same outline geometry as the monolithic type described above; however, the modular type addresses the circularity criteria for reusability. Instead of creating infill geometry, this type is divided into discrete components across the bridge's width.

This division allows for the production of separate elements, allowing the possibility to broaden or narrow the bridge or reuse individual pieces elsewhere. This modularisation improves the bridge's potential to meet its design life and avoid redundancy by adapting to changes in needs, thus avoiding unnecessary waste.

Structural calculations are more straightforward using hollow elements. Production failures can be contained to single elements rather than the whole bridge section, reducing waste and increasing productivity.



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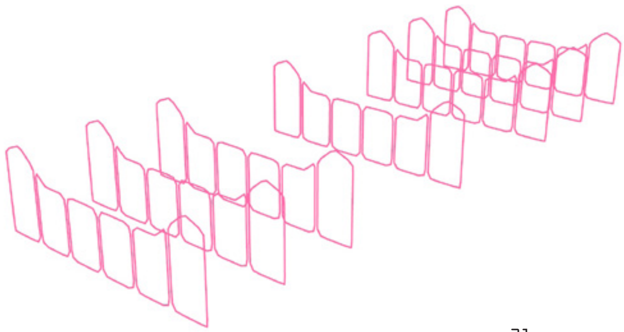

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20. A Modular cross-section created using the same outer geometry as the monolithic shown above, this time divided into separate elements.
21. Modular cross-section type on planes.

Freeform

In the third cross-section type, Freeform, the user provides the cross-section geometry to generate hollow beams. This option is given to maximise the potential of the 3D printing process by allowing for a wide range of geometry and increased shape optimisation capabilities.

The beams are relocated to the bridge's sides, allowing for more design freedom. As the bridge beams and deck are designed independently, the deck may be constructed using materials other than concrete, such as biobased materials where appropriate, improving the sustainability performance.

Another benefit of separating the deck and beams is that the beams no longer require a flat region to act as a deck surface. This separation provides design flexibility and increased opportunities for shape optimisation, concrete in bridge designs can be placed where it is most beneficial, tying back to the circularity design goal of reducing material. This option may provide increased design sensitivity, allowing for the creation of slenderer structures and more organic shapes that represent the design possibilities of 3D-printed concrete.

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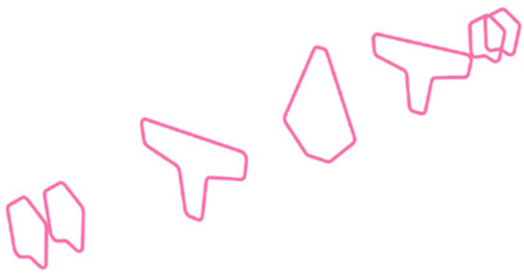

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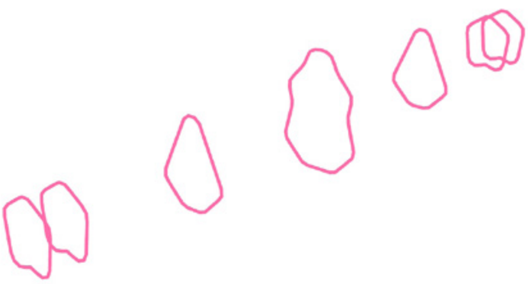

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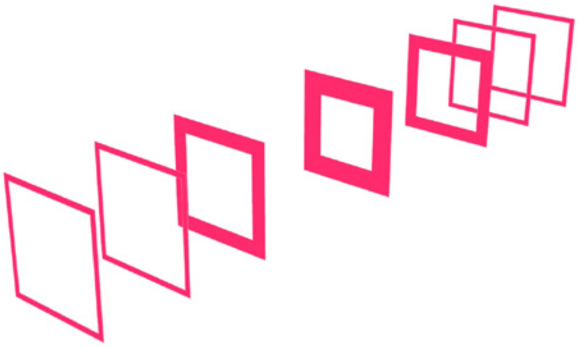
22. Example of the 'freeform' type input. The use can create a shape which is then mirrored.
23. 3D view of different cross-section shapes on planes.
24. As above with different cross-section shapes.
25. Print test of square cross-sections with changing print width.
26. Square cross-section with changing print width.
27. Square cross-sections with changing dimensions.

Cross-Section Manufacturing Constraints

Addressing material consumption as outlined in the design criteria is a critical project consideration. The tool offers two methods for optimising material use. The first is to scale the cross-section dimensions larger or smaller; there are constraints on this size, both minimum and maximum, depending on the printing system used, available print bed, nozzle size, and logistics.

The second method of optimising the material use of the cross-section is controlling the printed layer's width, known as ´print width´. In terms of material optimisation, scaling the entire geometry provides more significant benefits; however, adjusting the print width without affecting the outer dimensions may be helpful in situations where a fixed external geometry is required.

The varying print width can be created during printing by controlling the speed the machine is moving or the flow rate of the pumped concrete. There are manufacturing constraints on the achievable width specific to the system, with greater control of this width when using a round nozzle than a rectangular one. This process of scaling cross-sections and print-width was tested for manufacturability at the TU/e and Vertico. Using the TU/e setup, varying the print speed from 47 to 110 mm/s with a 15.5mm internal diameter round nozzle, a print width range of 16-35mm was achieved. A simple test can determine the print width range for tool users with different printing systems and materials. The print width range can be measured by moving in lines at specified speeds, and this range can be entered as constraints into the tool.



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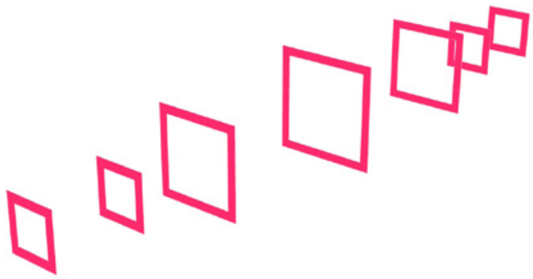

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Beams were created using the tool to test the scaling printing types, constant cross-section, changing cross-section and changing print width. For the cross-section scaling, the user can choose between the centre or top position to scale from. Scaling from the centre is more suited to the freeform type, whereas scaling from the top is advantageous if the top of the beam will be utilised to construct a bridge deck with a level surface to traverse over.

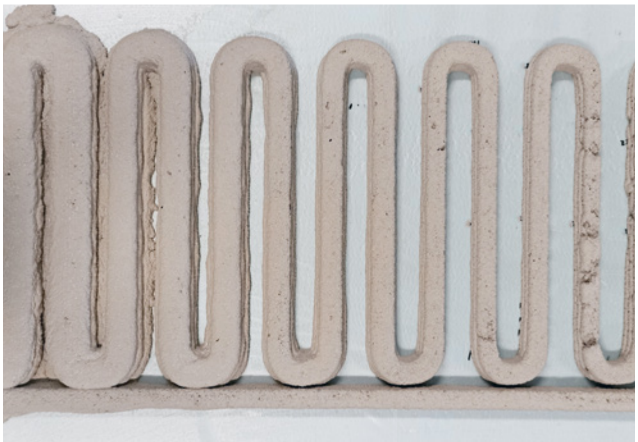
Along with the size, there are also manufacturing constraints on the possible shape of the cross-sections. Print tests were conducted to explore these and implement the results into the tool.

Due to the way the material is extruded, 3DCP technologies cannot generate sharp corners. Consequently, sharp cross-sectional corners are filleted at this point in the design tool, which helps bridge the gap between what is envisioned and what can be produced. The user can control the minimum radius of the cross-section corners depending on the intended printing system, with a default of half the print width.

Structural Analysis

With the tool, it is possible to generate a wide variety of forms with different shapes and sizes of cross-sections. However, it is essential to check if the design is structurally sound and materially efficient.

Controlling the cross-section height and print width at certain positions allows the user to specify values for each cross-section. These values are then transferred to the 'structural check' block, which performs structural analysis of bending and shear, allowing the user to make informed decisions about the material use of the beam designs. Rong Yu has developed this structural check block, with more details in their EngD report.



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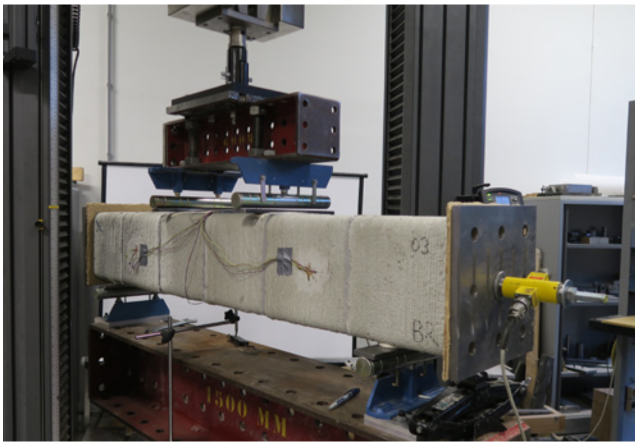

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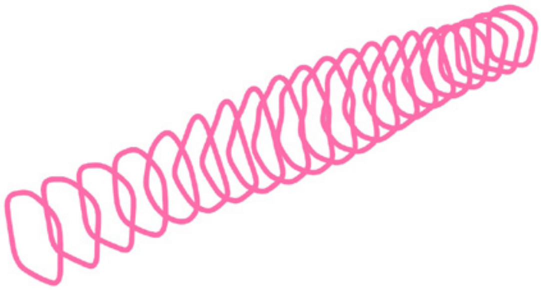
28. Print test of changing print speeds to identify print width.
29. Bending tests occurred on the three different beam types.
30. Printed and assembled beam using square cross-sections with changing size.
31. Cross-section shape print test.
32. The three printing strategies were also tested on three beams produced by vertico. Image credit Kees Leemeijer, Vertico.

3D Form

```
; ------------------------------
; DATA INPUT
; Cross-Sections
; Layer Height
; ------------------------------
; DATA OUTPUT
; 3D Form
; ------------------------------
```

In 3DCP, computer-controlled equipment moves a nozzle extruding wet concrete or mortar in a predefined shape. This nozzle then moves upwards and continues depositing material on top of the material previously deposited beneath, forming layers of material. The distance between layers is an integral part of the setup and is influenced by the pump flow rate, the speed with which the robotic arm moves the nozzle, and the desired appearance of the final object.

Layers take a central role in the tool as they form a core part of the 3DCP manufacturing process. Instead of creating a solid model and then slicing it into layers, this step is skipped by generating the curves guiding the nozzle directly from the previous block's cross-sections. The length of the alignment curve is divided by the input layer height to create the number of layers required. The cross-sections are interpolated along the alignment curve's length, resulting in a '3D Form'.



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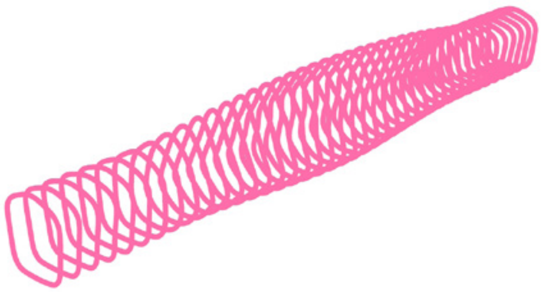

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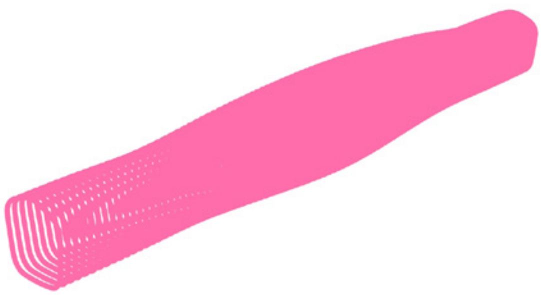

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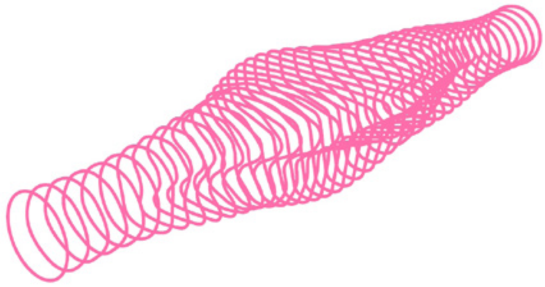
33. 3D form created by interpolating the previously created cross-section along the alignment curve. The number of layers corresponds to the desired layer height of the printed element.
34. Same as above, however, with a smaller distance between layers
35. Even smaller distance between layers.
36. Form created with changing shape
37. Square cross-sections with scaling applied to the centre.
38. Multiple different shapes on a curved alignment.
39. Square cross-sections without scaling.
40. Various shapes with scaling
41. Square cross-sections with scaling applied to the outer sections. The cross-sections are aligned at the top.



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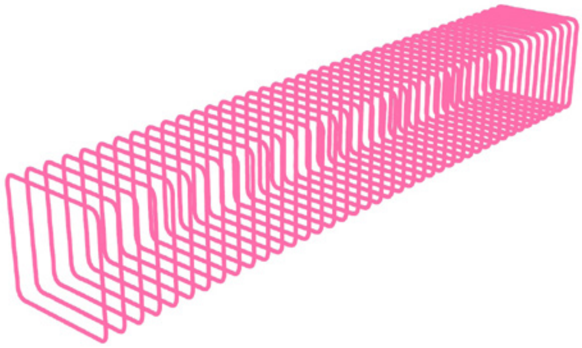

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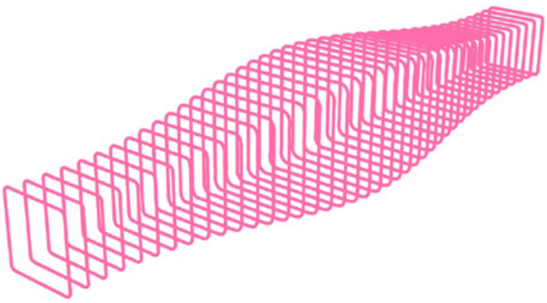

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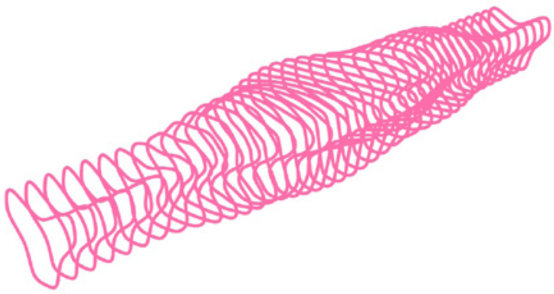

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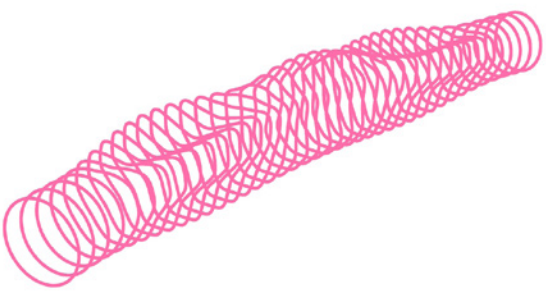

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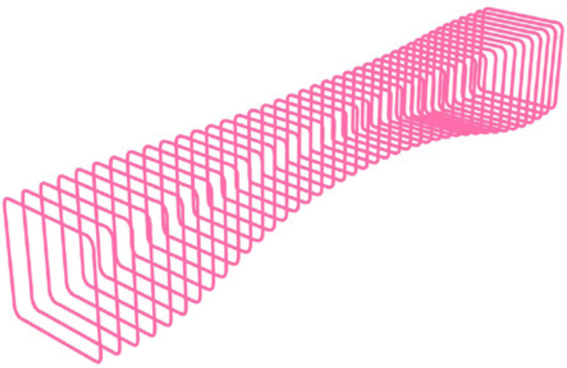

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Segments

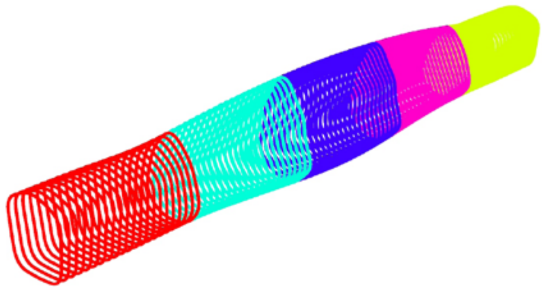
```
; ------------------------------
; DATA INPUT
; 3D Form
; No. Segments
; ------------------------------
; DATA OUTPUT
; Segments
; ------------------------------
```

Most 3DCP systems print layer by layer, moving upwards in the vertical direction. The layers in the bridge beams created in this design tool are perpendicular to the bridge span direction. Therefore, the bridge designs require a 90-degree rotation into the upright position before printing. The constraints of this printing process, material buildability, and logistics must be considered as part of the design process.

The Segments block divides the layers created in the 3D Form block into segments. The user may define the number of segments into which the beam should be split based on the previously introduced criteria.

Buildability refers to the capacity of an extruded layer to retain its uniform shape under self-weight imposed by sequentially deposited layers. Buildability failure may be caused by plastic collapse, elastic buckling, or a combination of the two [20].

Logistics relates to what can be transported or handled. This tool is designed for off-site 3DCP manufacturing operations in a factory setting before being delivered to the site. Therefore, handling, transporting, and assembly operations should be considered when designing the bridges. Machine limits relate to the available space for the printing equipment to utilise; there will also be a maximum height or reach of the equipment to consider.



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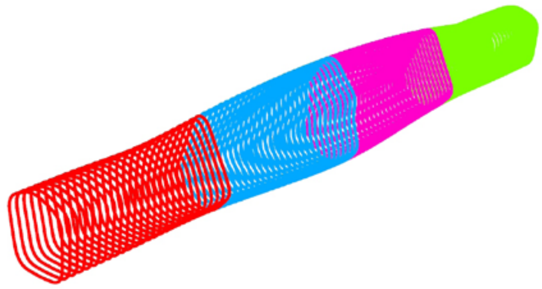

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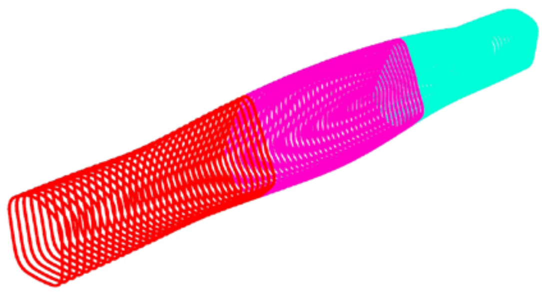

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42. Beam divided into four equal segments. Each colour shown represents a segment to be printed individually
43. A beam split into four segments.
44. A beam split into three segments.

Prestressing

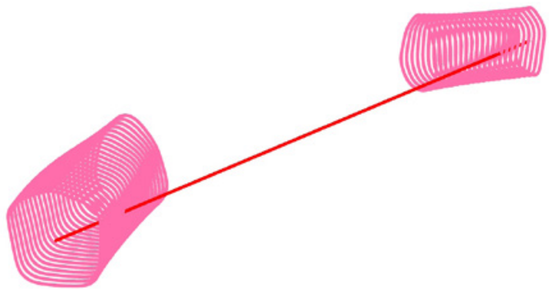
The tool created bridge designs which use unbonded post-tensioned steel prestressing tendons. This system necessitates sufficient space in a straight line from one end of the beam to the other. The tool includes a check to show the user whether their beam design meets this requirement. This check can be especially critical, and thus included in the tool, for bridges with strongly varying cross-sections or curved Alignment.

Bulkheads

Bulkheads are required to introduce the prestress force evenly into the beams. These are solid cast concrete elements on both ends of the beam to prevent splitting tensile forces caused by the prestressing tendons.

The user can divide all segments equally, including the bulkheads, or provide a custom value for the bulkheads. The custom dimension input is provided to minimise the bulkhead's material use.

In addition, the user can generate infill geometry for the bulkheads. This infill shape produces a void for the prestressing tendon to pass through. The surrounding region may be filled with concrete, called lost formwork.



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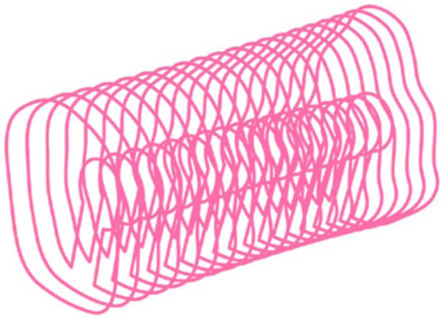

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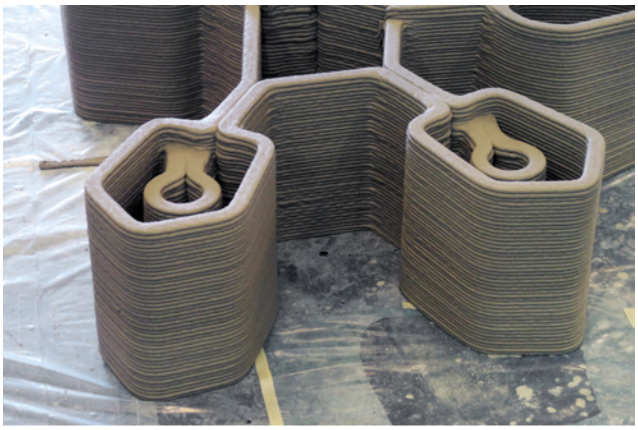

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45. Prestressing line, shown in red, runs from one beam's end to another. This beam design uses a sharply curved alignment curve resulting in a clash.
46. 3D view of a Bulkhead with infill geometry.
47. Side view showing the optional infill geometry. The centre of the circular shape can be used for the prestressing tendon.
48. Print test of bulkheads with infill geometry.

Connections

The bridges described in chapter 2 consist of multiple segments joined using a high-strength concrete adhesive (Sikadur CF31). The user can match this approach with the design tool, which provides flat interfaces between the segments suitable for glueing.

However, as stated in the design criteria, design for disassembly and reuse are essential requirements. Therefore, glueless or 'dry' connections were investigated to meet these specifications, resulting in an interlocking shape between segments provided in the tool. These interlocking shapes aim to offer a glueless connection with sufficient shear capacity. Rong Yu, as previously mentioned, is responsible for the structural calculations used to generate these shapes. Tests of the interlocking shapes were performed to ensure manufacturability.

The previously created layers that comprise the 3D Form must be adjusted to produce the interlocking shape. Multiple interlocking forms can be used; currently, the tool provides an interlocking shape based on a sine wave that the user can customise by adjusting the amplitude and frequency values. This sine wave is then extruded, producing a surface at the segment interface connection points

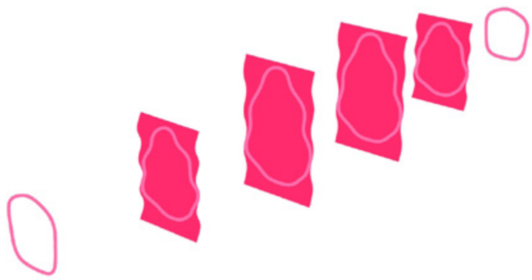
The curves initially created at the segment connection points are pulled to match the shape of the previously described surface. The flat-end curves are added to the interlocking curves and interpolated along the alignment curve. The reason for generating the interlocking using this method is to achieve a smooth transition from flat ends to interlocking connections along the bridge span while ensuring the desired interlocking values are present at the segment connection points.

Working with interlocking segments aids the assembly process and opens the possibility of working with glueless connections.

The interlocking shape can be controlled at each connection providing the user greater control. This shaping also affects the appearance of the beams and highlights the layered manufacturing process.

Planar printing is printing with the nozzle perpendicular to the printbed at all times. Non-planar printing means that the nozzle remains perpendicular to the print layer. If the layer curves, the orientation of the nozzle will follow that shape.

The best results for interlocking segments come from non-planar printing with 6-axis robots. Therefore, tool users should consider the printing system's capabilities while designing the connection shape.



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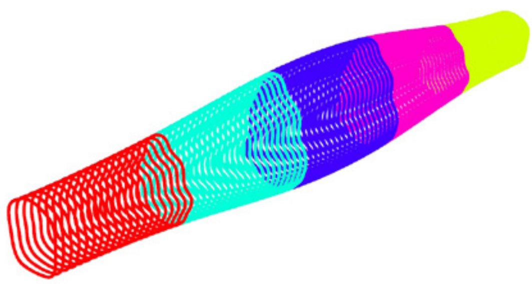

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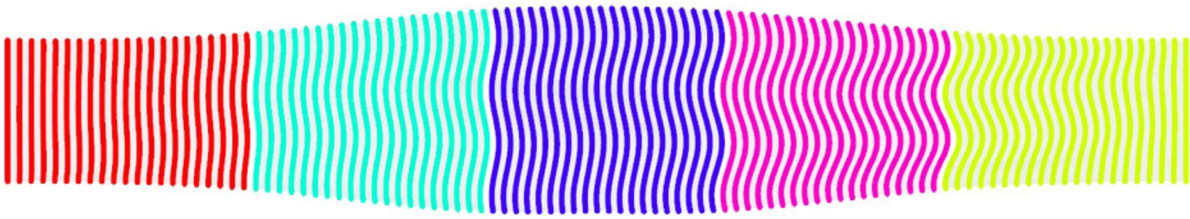
49. 3D view shows the surfaces that create the interlocking shape and the resulting contours. The outer curves remain flat.
50. The curves are again interpolated and segmented.



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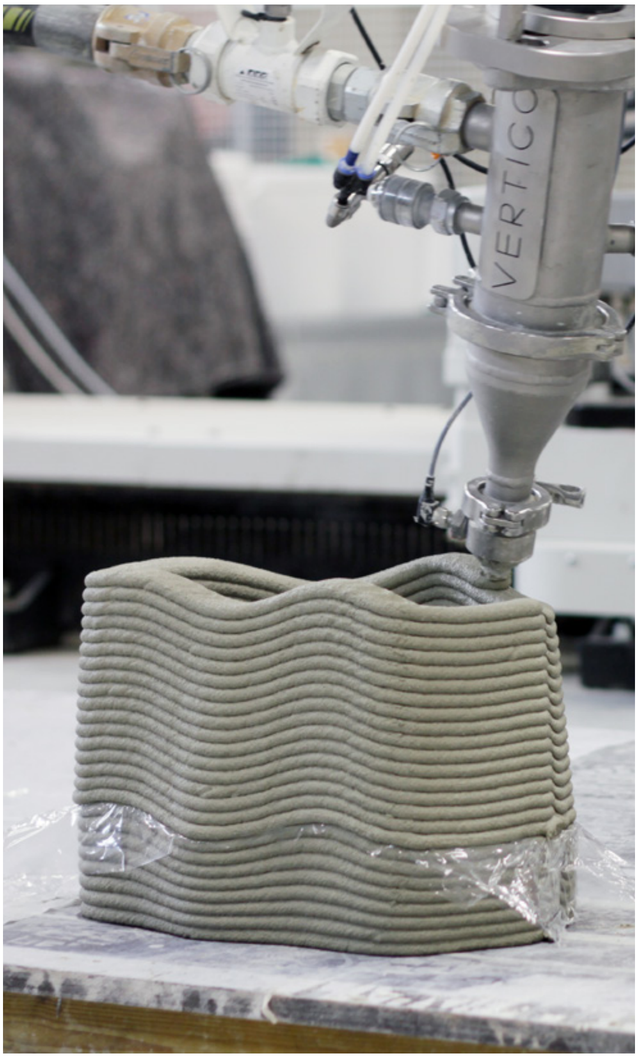

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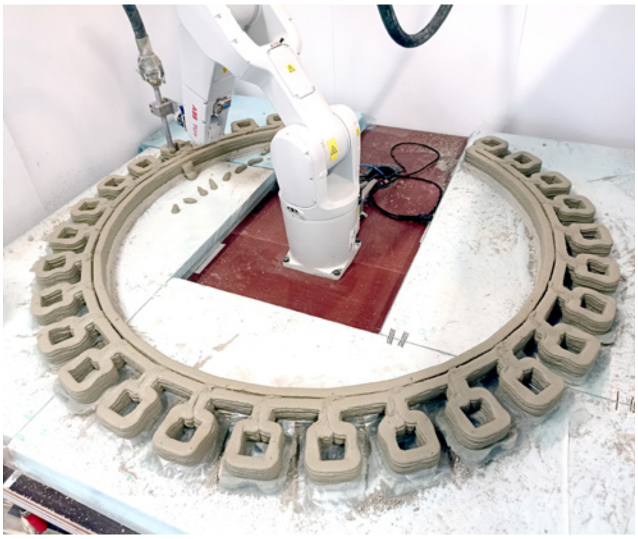

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51. Side view of a segmented beam
    with different interlocking
    values at each interface.
52. Non-planar print test at Vertico.
53. Print test of interlocking segments.

54

Support Material

As the print bed of 3DCP systems is usually flat, support material is necessary to create segments with non-planar curves on both sides. The support material is generated by projecting the bottom layer of the segment down onto a plane. The projected and bottom segment curves are interpolated at the desired layer height using the method described in the 3D Form block.

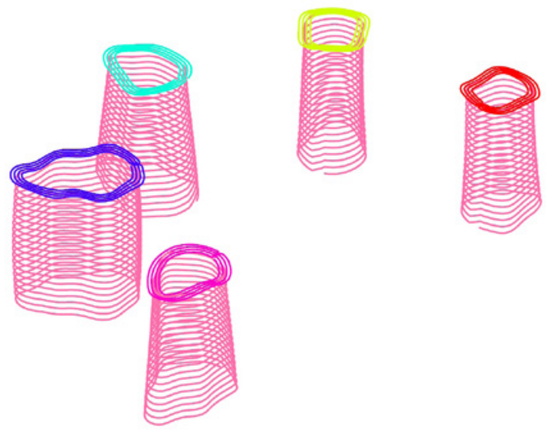
For the support material to work effectively, it needs to be sufficiently strong enough to hold the weight of the segment which will be printed on it. During fabrication tests, concrete was used as the support material, reaching this strength after several hours. The duration of the support material reaching this strength depends on the material and could be decreased if accelerators were used.

Before printing the segments on the support material, a plastic sheet is added to reduce possible adhesion. The same concrete material was utilised in the testing for both the support material and the printed parts. To minimise waste, utilising concrete as a support material and discarding it is not optimal. It could be possible to print the support material using a recycled, more ecologically friendly material using the same workflow.

Milling

Experiments milling green-state concrete were performed to identify if the tolerances of the interlocking segment connections could be improved. Initial tests were performed using the side edge of a milling tool with successful results. However, one major drawback was the robot's reach, making it difficult to mill the entire surface of a beam segment.

The suitable material age of the green-state concrete was explored to identify any manufacturing constraints. With the material used, rotating the milling tool at a high RPM and moving the tool over the material slowly (25mm/s) with a material age of approximately 1.5 to 2.5 hours achieved results with a high-quality top surface. There is a trade-off as moving the tool slowly over the material means the whole operation takes longer, meaning that the age of the first segment is different from that of the last segment. Research in this area is also taking place a Loughborough University [21] [22].



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54. Side view of support material, shown in blue, with segment on top.
55. 3D view of segments with milling toolpath created on the top layer.

To reduce the reach issue, milling from the top was investigated using the end of the milling tool. Initially, the interlocking shape formation took an approach where the segment's top layer was selected and divided into points. Alternating points move in opposite directions of the same distance, forming a sine wave along the contour. These points were then offset inwards towards the shape's centre and an equal distance away from the centre. The offset points were connected to form a 'zig-zag' style toolpath.

In fabrication tests, this approach seemed to generate satisfactory results. However, geometrical inaccuracies could be seen when working with tight corners.

As a result, the interlocking shape formation was changed to the surface-based approach described in the previous section. The milling toolpath generations strategy was also changed to use the same surface to ensure geometric accuracy, improving the tolerances between the segments.

The milling toolpath is created by taking the top layer of the segment or support material and projecting this curve onto a flat plane. The offset is then performed using either a 'zig-zag' or 'spiral' option. This new curve is then projected onto the surface created to use the interlocking shape. This method ensures that the form of the milling toolpath directly compares with the intended geometry of the interlocking shape. Using a surface approach, a 'normal' value can be extracted, giving extra control over the orientation of the milling tool. For both the 'zig-zag' and 'spiral' approaches, the offset value is adjusted to the print width, ensuring the entire segment's top surface is milled.

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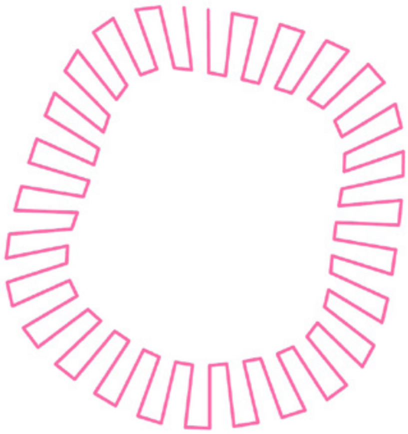

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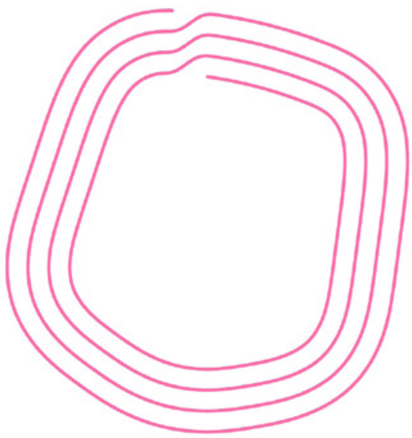

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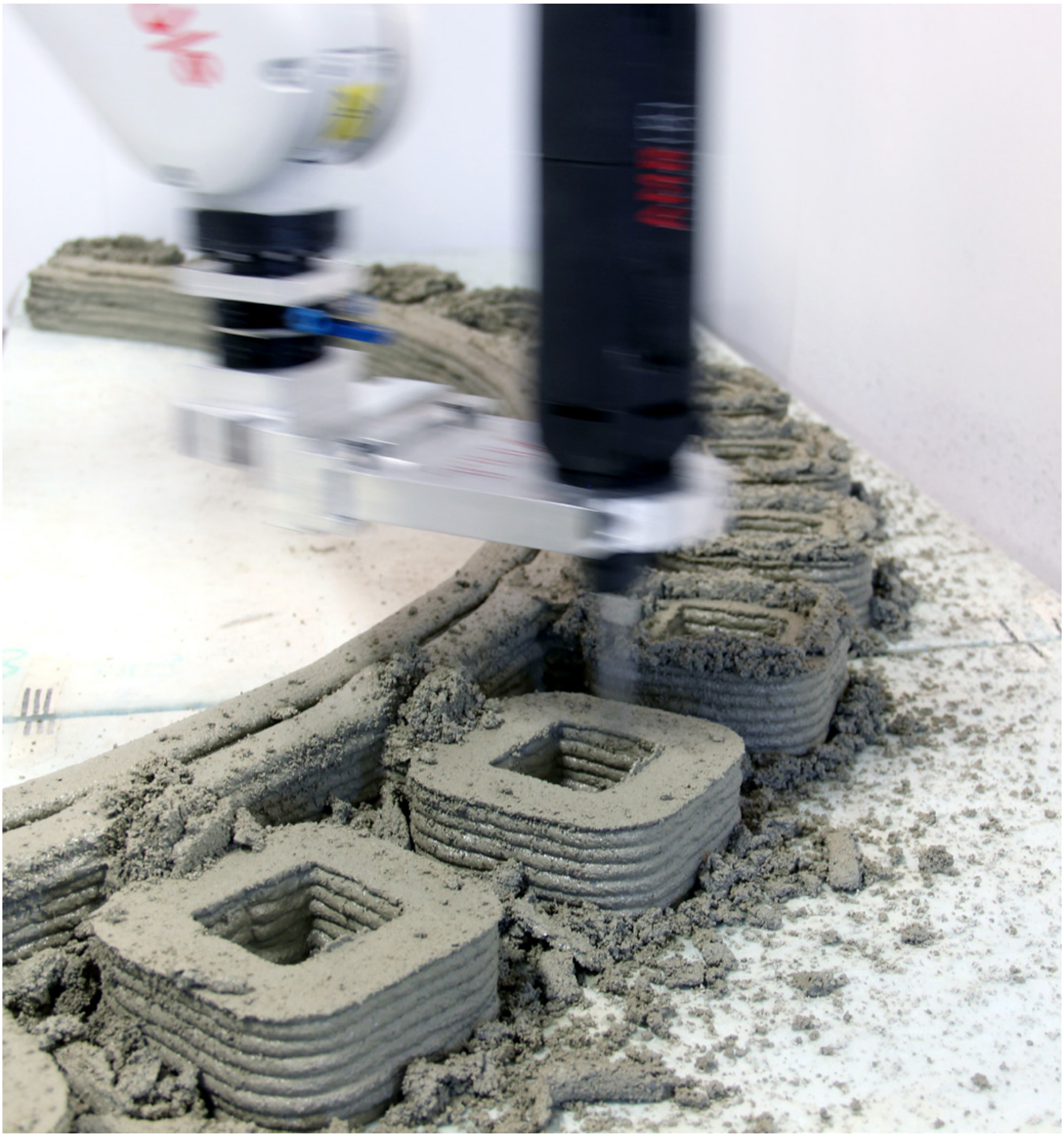
56. Milling test on interlocking segments.
57. Top view of the 'zig-zag' milling toolpath.
58. Top view of the 'spiral' milling toolpath.



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59. Milling test on flat segment.
60. Hardened interlocking segments milled during their green-state.
61. Printed and milled interlocking test segments. The segments shown use a cork interlayer material.

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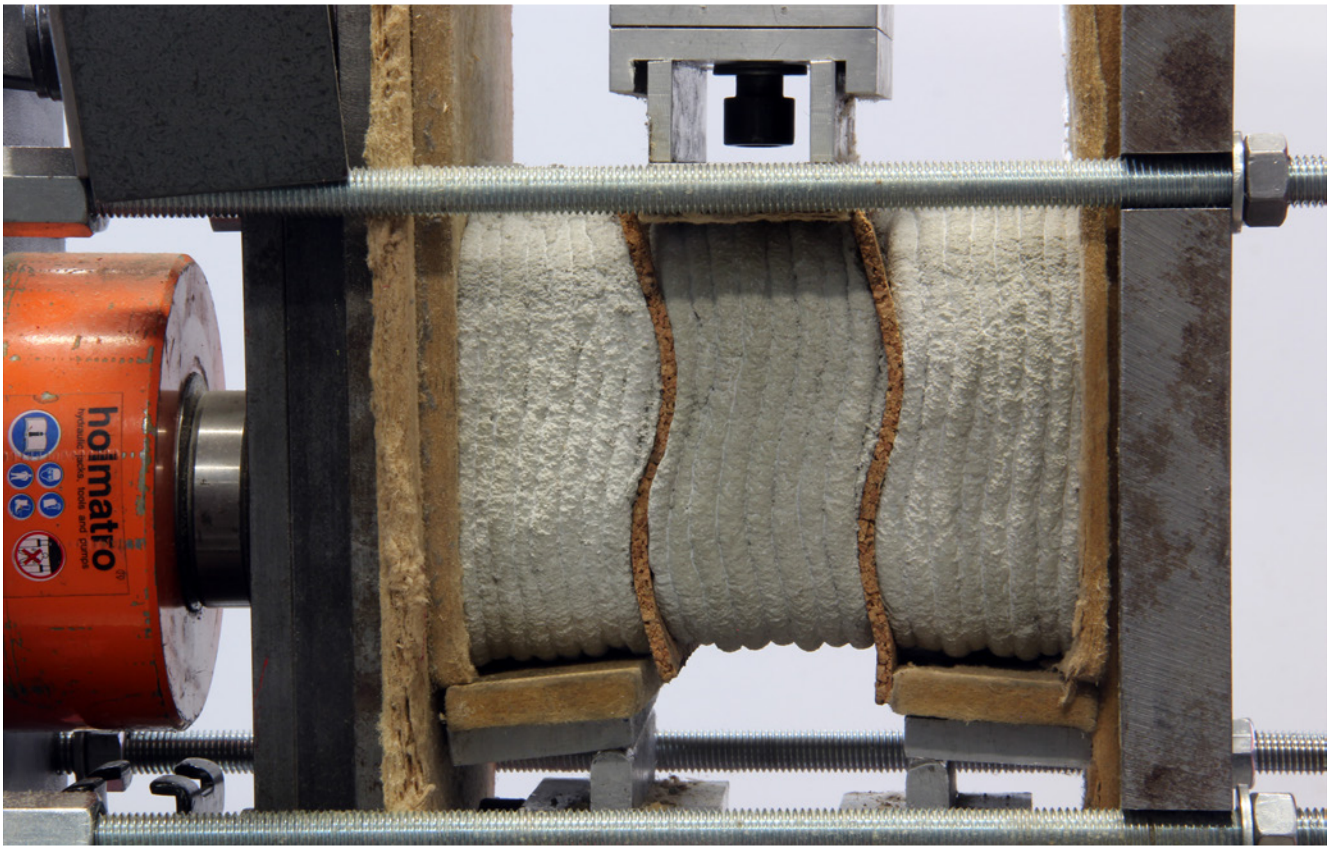

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Code Generation

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; ------------------------------
; DATA INPUT
; Print Geometry
; ------------------------------
; DATA OUTPUT
; Production Code
; ------------------------------
```

This block looks at how and what is required to generate the code for production.

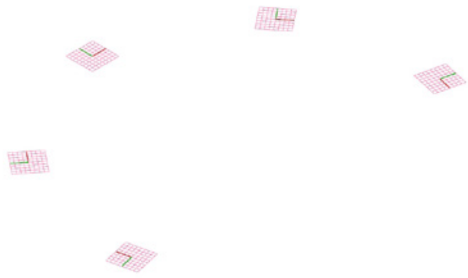
Print Preparation

The bridge beams are designed along the alignment curve, with the layers created perpendicular to this. The first part of the Code Generation block is to orient the segments in line with the print bed, a horizontal plane in the XY direction. Printing objects in a bottom-heavy orientation is beneficial to ensure stability and reduce print failure. If necessary, the tool then rotates the segments so that the larger parts of the geometry are at the bottom.

It is possible to select which segments to print, duplicate specific segments or leave some out. This approach adds flexibility to the printing process, including the option to create multiple versions of selected segments. Once the desired segments are chosen, they are oriented onto a 'work object.' The work object is an arrangement of planes the segments take during printing. Arrangement options of a circle or a grid formation are available. The circular formation work object was created with industrial robots in mind, where the robot arm's reach imposes constraints on the print area. Having the robot in the circle's centre makes the reach even to each segment. The user can select a different arrangement for a gantry or a robot on a track.

Two different printing strategies are offered. The first and most common is to print the segments as separate objects, one at a time, called 'Individual segments'.

The second option is referred to as 'connected segments'. This strategy combines the layers of each segment at the same height into one continuous layer. This approach is helpful for testing geometry and when the buildability of the material is not suitable for the desired geometry. This method extends the layer print



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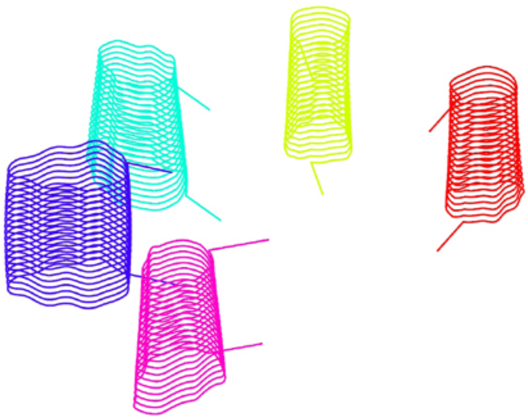

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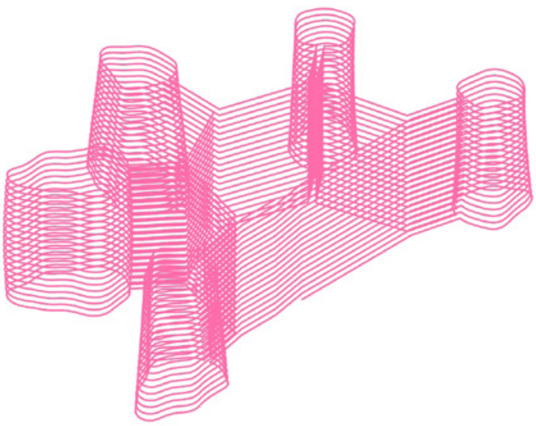

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time meaning that the material has longer to harden before the next layer is added, resulting in the ability to print taller objects. The disadvantage of this method is the increased manual labour and waste material generated, going against the design criteria. The connection pieces need to be cut and removed after printing. Therefore, this strategy is not recommended for bridge production. However, it can be beneficial for smaller-scale geometry and material testing.

The groups of individual layers are then combined into continuous curves. This part employs the SaladSlicer plugin developed with the 3DCP group at TU/e [23].

Code Export

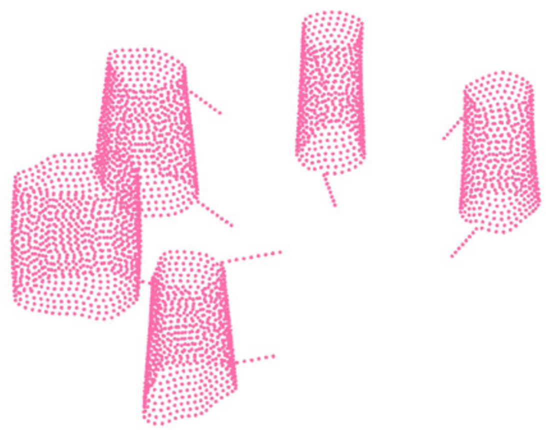
As described in the design criteria, the design tool should be capable of producing code suitable for commonly used 3D printing systems. The two most common system types used in research and industry are gantry systems and industrial robots. Both share fundamental logic and are controlled by moving through coordinates in 3-dimensional space.

Gantry systems generally use three axes moving in x, y, and z; and are often used for creating large-scale objects. Industrial robots, most well known for their use on automotive assembly lines, can move with six degrees of freedom but are restricted in the printable area. The design tool produces relevant code for both systems.

Gantry System

Geometry from the print preparation is moved to the final position on the print bed. An extra lead in and out is added, along with a bucket position. The bucket position is a location to start the print from where a bucket is placed underneath the nozzle. Material flows through the system, and the print can begin when the material is at the correct consistency.

The geometry is divided into points acting as X, Y, and Z absolute coordinates. These points, along with a header and federate controlling the speed, create the G-code. This code is then saved onto a USB stick and uploaded onto the controller. From here, the file can be loaded and run by the operator. This G-code export makes use of the SaladSlicer plugin [23].



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62. Planes are created to provide a location for the segments on the print bed. The user can control the layout, shape and size. This example shows a circular formation.
63. 3D view of the 'Individual Segments' print strategy arranged on the work object. Each colour represents a segment.
64. Connected segments strategy creates a continuous print path between all the segments. This strategy creates a longer print time per layer, allowing for increased buildability.
65. The path is divided into points to generate G-code, with each point creating an absolute coordinate.

Industrial Robots

Unlike G-Code, which is standardised across multiple CNC manufacturers, industrial robot manufacturers employ a specific language for their robots. RAPID Code for ABB robots was selected to incorporate into the tool to test the tool process of working with 6-axis robots. The method of code export for ABB RAPID Code has many similarities with G-code. The print geometry is divided into planes instead of points. The use of planes is due to the additional axis available to robotic arms. Instead of a point in space, there is a direction to that point. This direction provides extra opportunities for working with non-planar printing and milling.

The connection between the grasshopper environment and ABB robots uses the Robot Components plugin to generate the RAPID Code [24].

Printing at a controlled speed is essential for achieving a high-quality printed object. During fabrication tests, it was discovered that rotating the targets towards the centre of the robot improved the consistency or the print speed. Therefore, this rotation is included in the design tool.

Within the code export for industrial robots, specific tools are available depending on whether printing or milling. Each tool has a programmed tool centre point (TCP) which moves to match positions in the targets described previously at a predefined speed.

Run Code

The code can now be used to control the movement of the robotic equipment.

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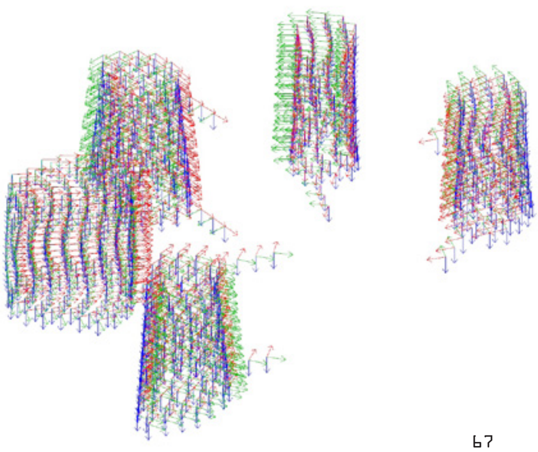

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66. Print path divided into targets for RAPID Code.
67. Print test using a gantry printing system and the 'connected segments' printing strategy.
68. Opposite, Printed test segments.

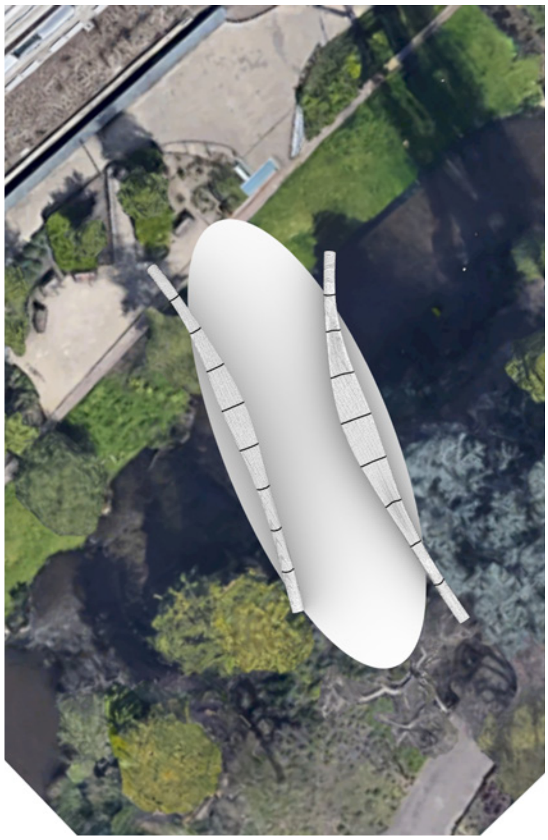
4. Design Concepts

This chapter presents two concepts of how the design tool could be used. This chapter aims to demonstrate the flexibility of working with integrated digital design and fabrication.

Design 1 – Freeform

This concept creates a bridge crossing a small river, with each bank at different heights. The ambition is to expand the public space and connect the seating areas on both sides of the river. The Freeform type was chosen for this concept, with two curved beams spanning the river with a timber deck hanging below. The deck form is created from an ellipse, curving opposite to the bridge beams. One beam is higher than the other to allow for different views from the bridge.

This bridge concept employs dry interlocking connections to improve the potential for reusability. The surface texture of the bridge has also been incorporated into the design, highlighting the interlocking shape. Steel cables hang from the beams holding the deck.



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69. Aerial view of bridge concept crossing river.
70. Close-up of interlocking beams and connections.
71. Opposite, 3D view.
72. Overleaf, View from on the bridge deck.

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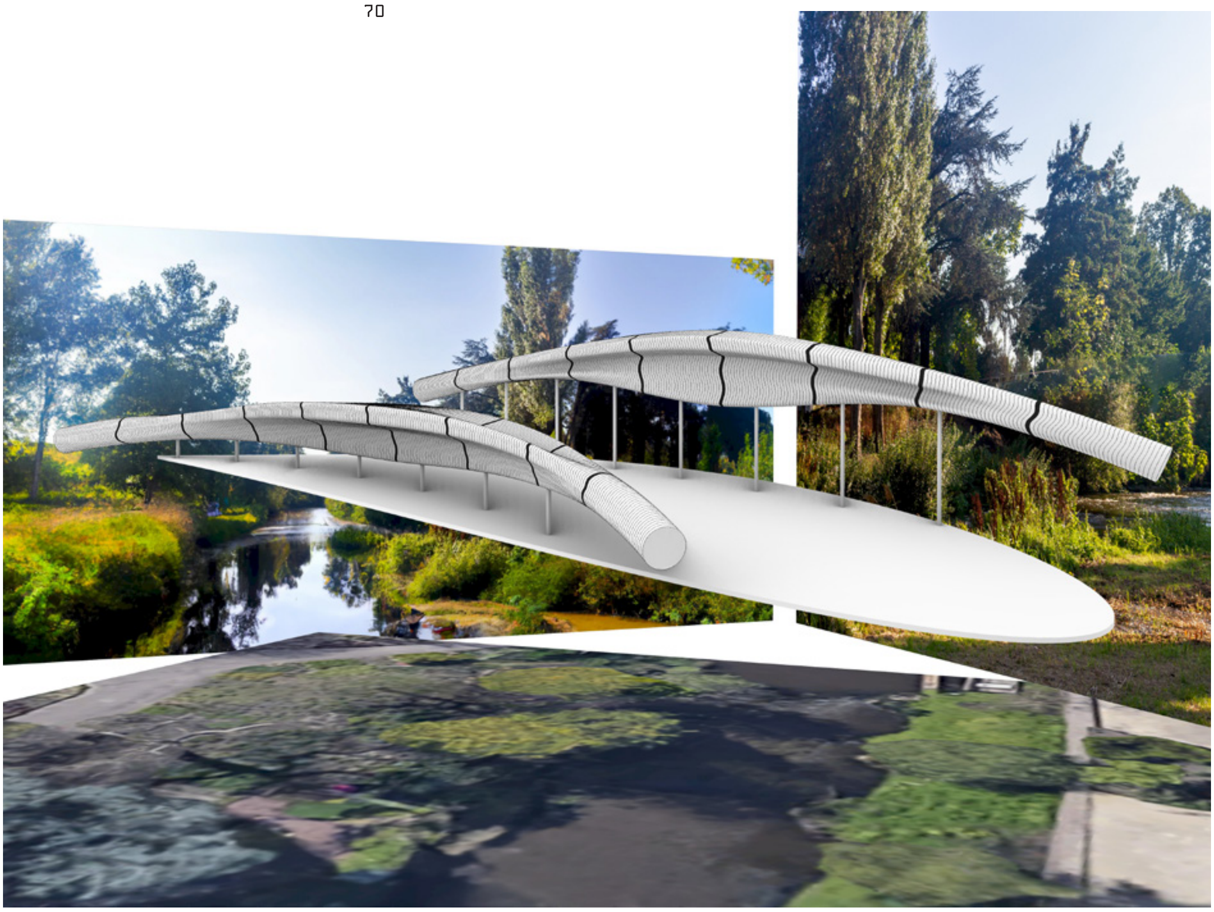

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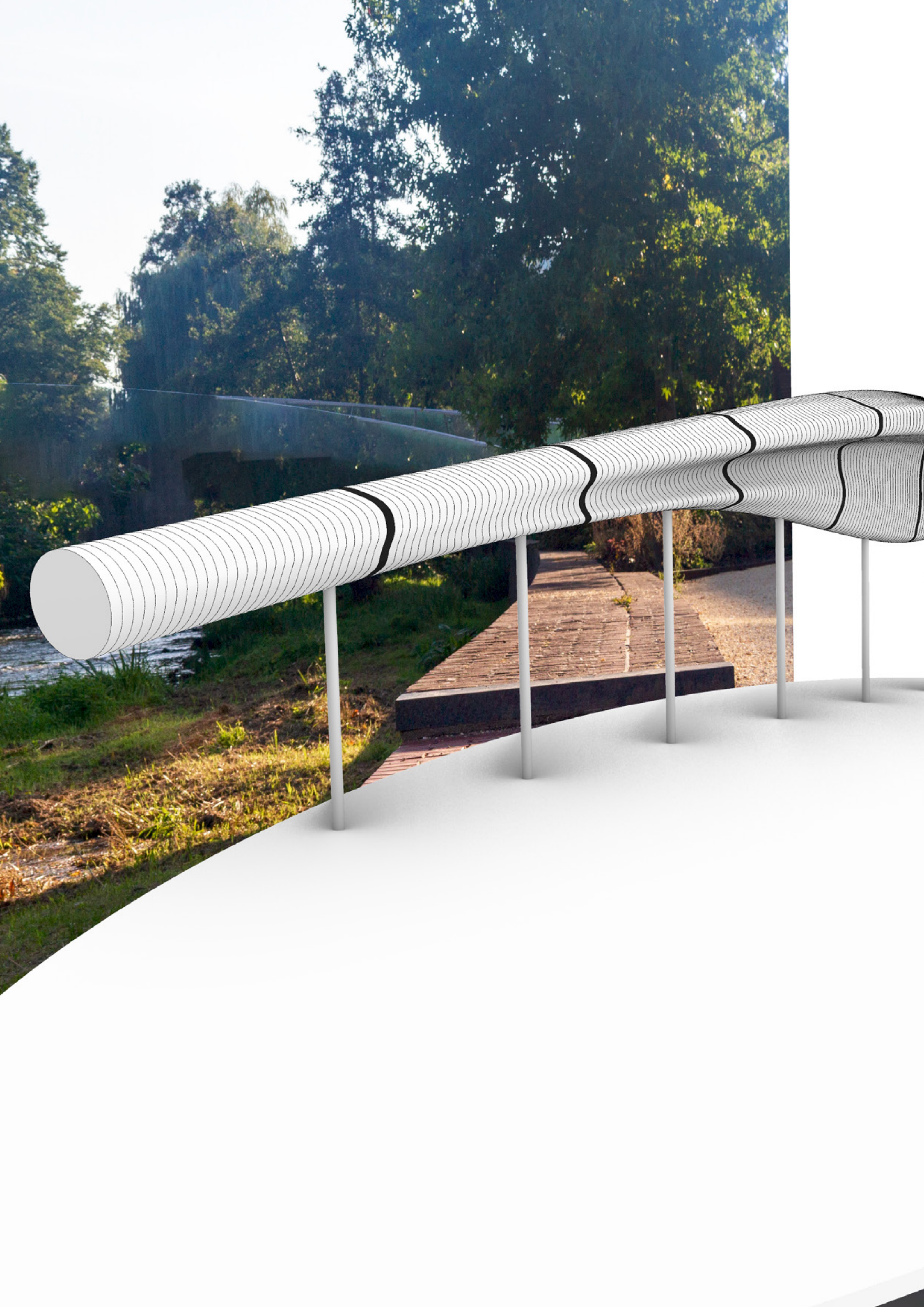
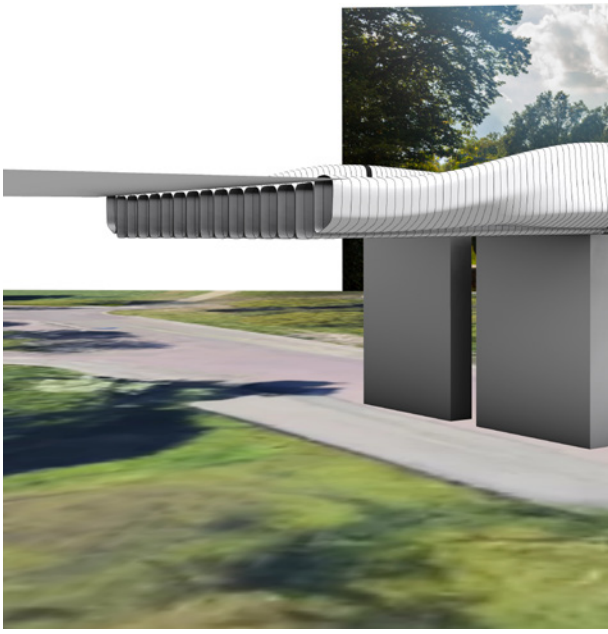
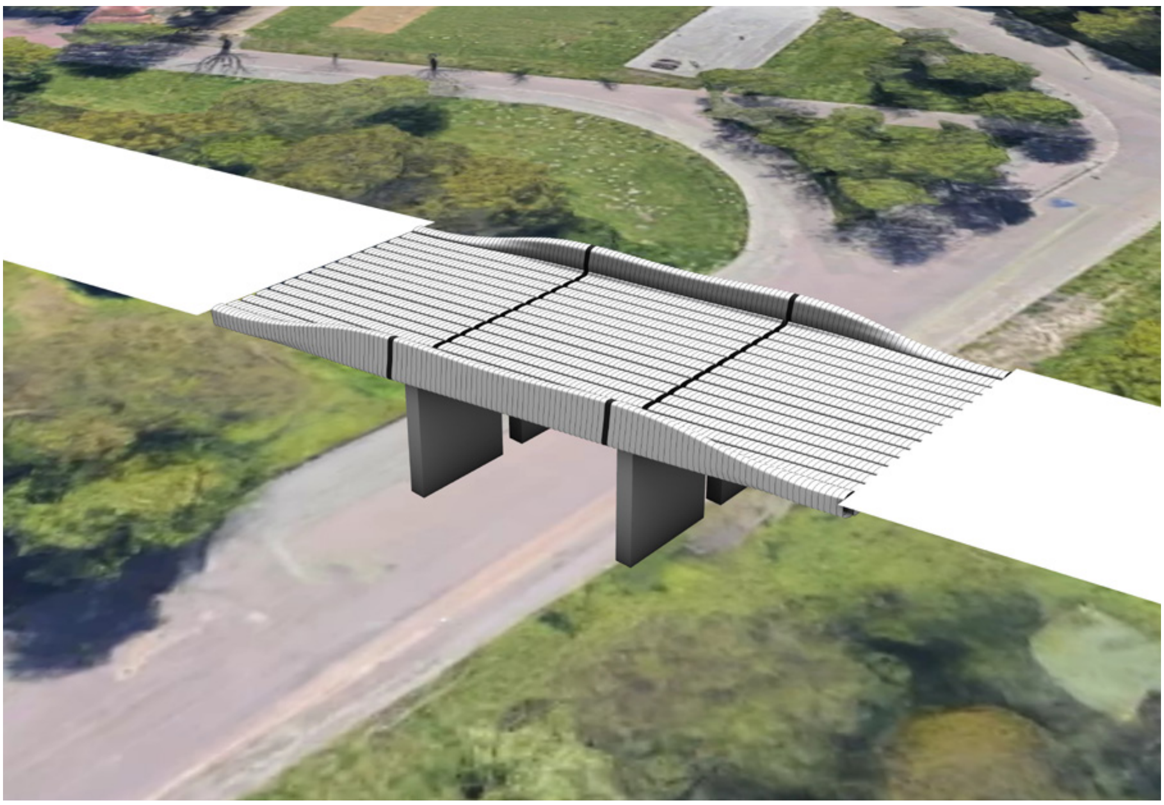


Design 2 - Modular

This bridge design reuses existing supports created in the 1960s. The bridge supports car traffic and crosses over a cycle path. For this design, a modular bridge type was chosen to accommodate the deck structure as part of the design. The modular approach divides the bridge across the width aiding ease of manufacturing and transport compared to producing a single element. The design follows a simple form, with the bridge split into individual prestressed elements at the existing support points. The sides of the bridge have been raised, hiding the traffic and reducing the noise from the pedestrians below. Lighting has been integrated into the elements to provide visibility under the bridge in low light.

Map data was imported into the design tool to create the alignment curve. Multiple options could then be explored before deciding on the design. The modular beam elements use the changing wall thickness option to reduce the material used. If necessary, this design can be widened or narrowed in the future.





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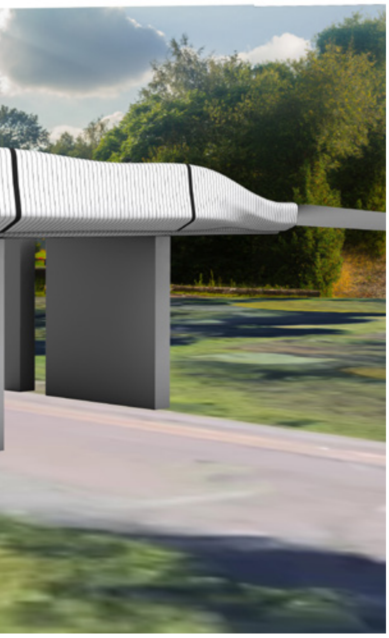
73. Highway bridge concept crossing cycle path.
74. Bridge concept being held by existing supports.
75. View of the bridge concept showing the 'modular' cross-section type. Each piece is a separate element to aid reusability.
76. Overleaf, highway bridge concept visualisation.



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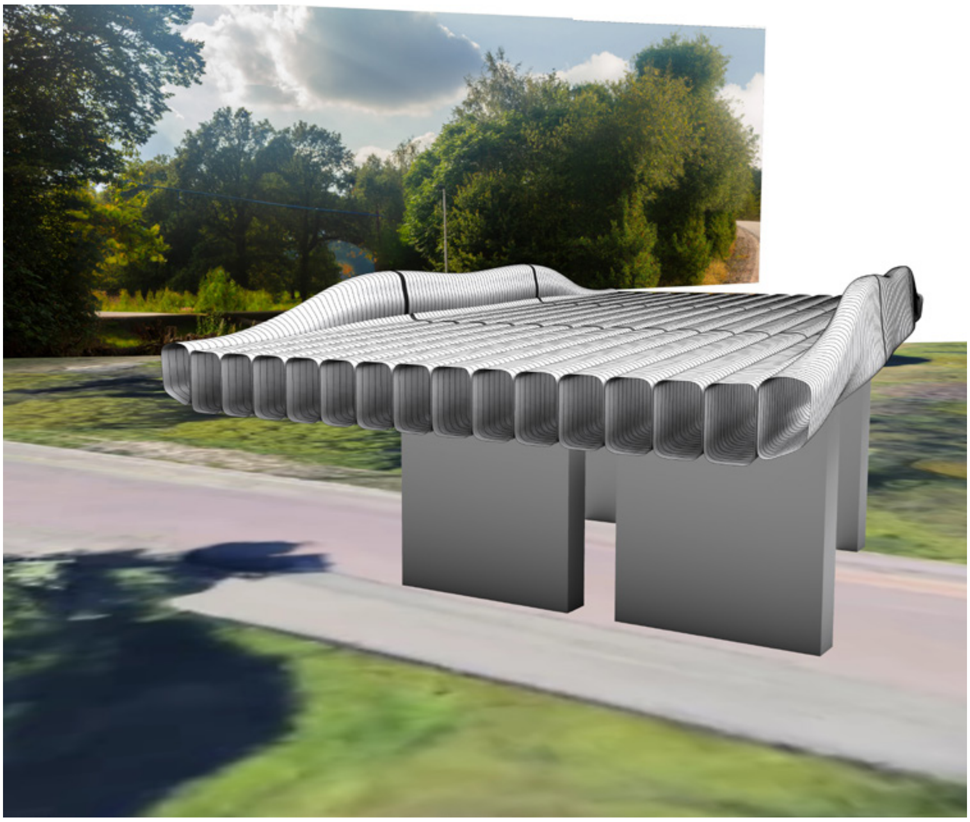

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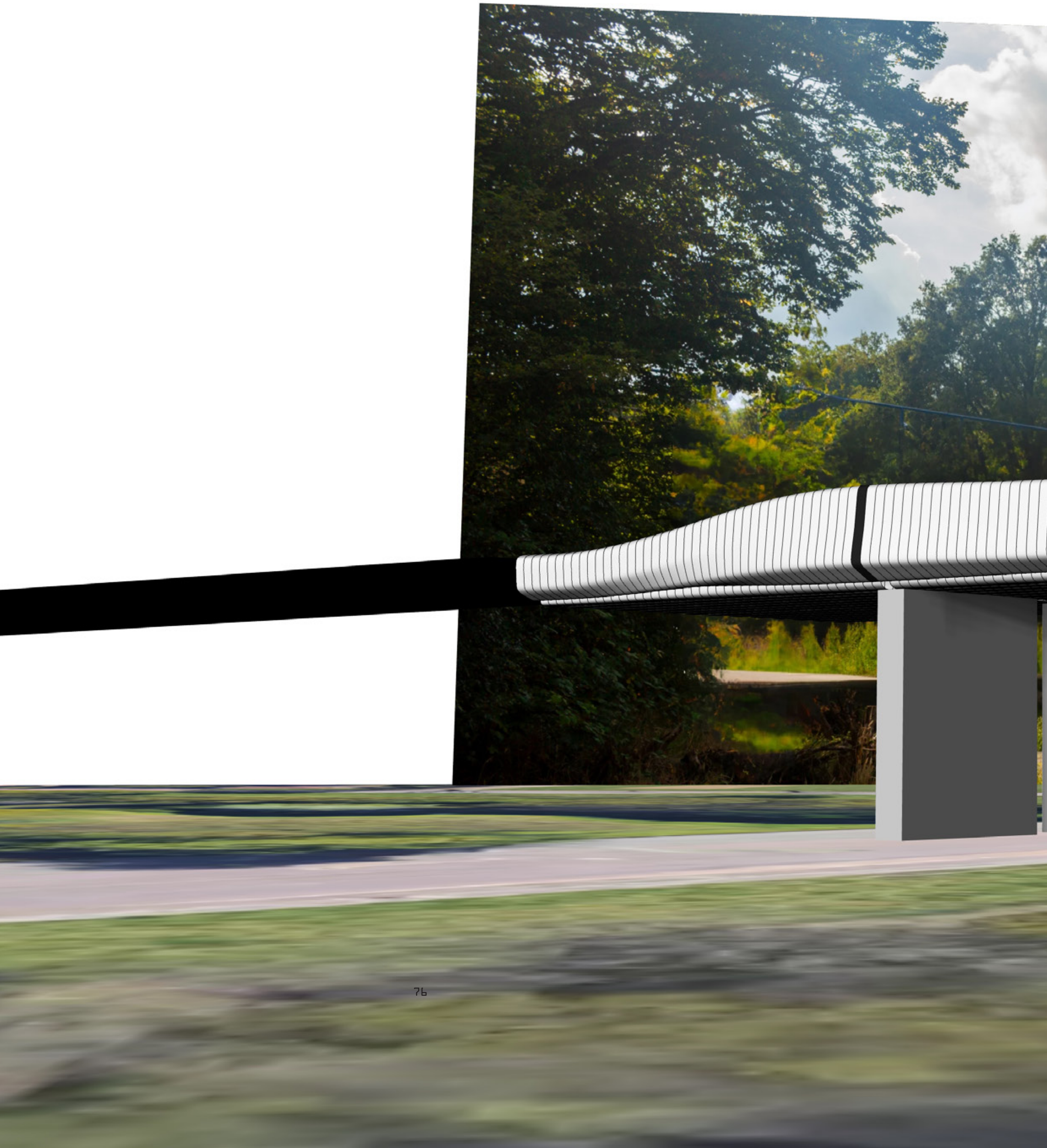

5. Public Dissemination

Public dissemination occurred through international presentations with industry, academia, and the general public. The ambition was to share knowledge and receive feedback, helping shape the project. An additional aim was to increase awareness of the potential of parametric design tools and integrated design and fabrication using 3D-printed concrete within the context of the built environment and the current climate

BE-AM

As a part of the Formnext trade fair, the Built Environment Additive Manufacturing (BE-AM) is an annual exhibition and symposium [25] in Frankfurt, Germany. This exhibition caters to an industry audience and set the project within the context of innovative fabrication methods for the built environment. For the 2021 edition, a 1.5m length scale concrete printed beam consisting of six segments was designed and fabricated using the design tool. This beam was assembled with dry connections using a threaded rod to introduce the prestress force. Rectangular cross-sections changing in scale were used, with the centre cross-section rotated to create a gently curving beam. The project was included in Formnext TV as an example of innovative applications of additive manufacturing in the construction industry, during which segmentation and reinforcement strategies were discussed.

This event took place around the midpoint of the project and prior to the development of the interlocking connections. The beam created used flat connection pieces, and due to the changing shape, the beam assembly required a supporting structure. The assembly of this beam would have been easier with the use of interlocking connections.

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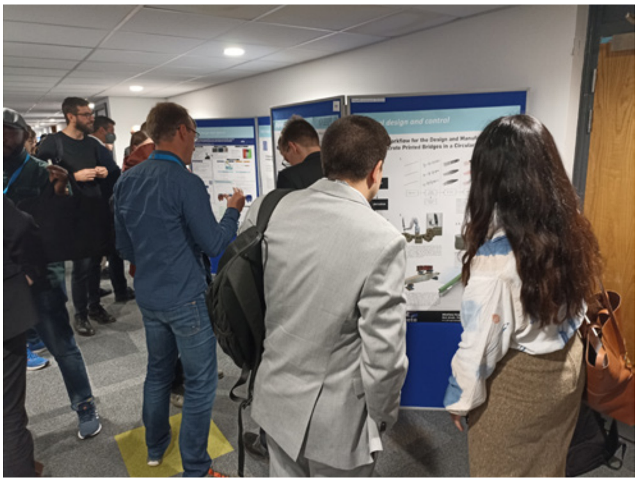
77. Visitors attending the BE-AM exhibition.
78. Concepts of the project being discussed on Formnext TV at the BE-AM exhibition.
79. Part of the jig used to assemble the beam.

Digital Concrete Conference

Digital Concrete (DC22) is an academic conference that presents leading research on cement and concrete in conjunction with digital technology [26]. For DC22, a poster outlining the digital workflow was created, adding to discussions at the conference on appropriate applications for 3DCP and how sustainability issues can be addressed. The poster received a Project Influencer Award at the conference.

The conference confirmed that the project's topic is relevant as part of the development of 3DCP applications. 3DCP is at a crossroads in its evolution, with the danger of losing industry acceptance if the advantages of productivity and sustainability are not realised. Several pilot projects exist [27], however, few currently are used as competitive alternatives to conventional practice. Tools such as this one can aid with this adoption by industry.



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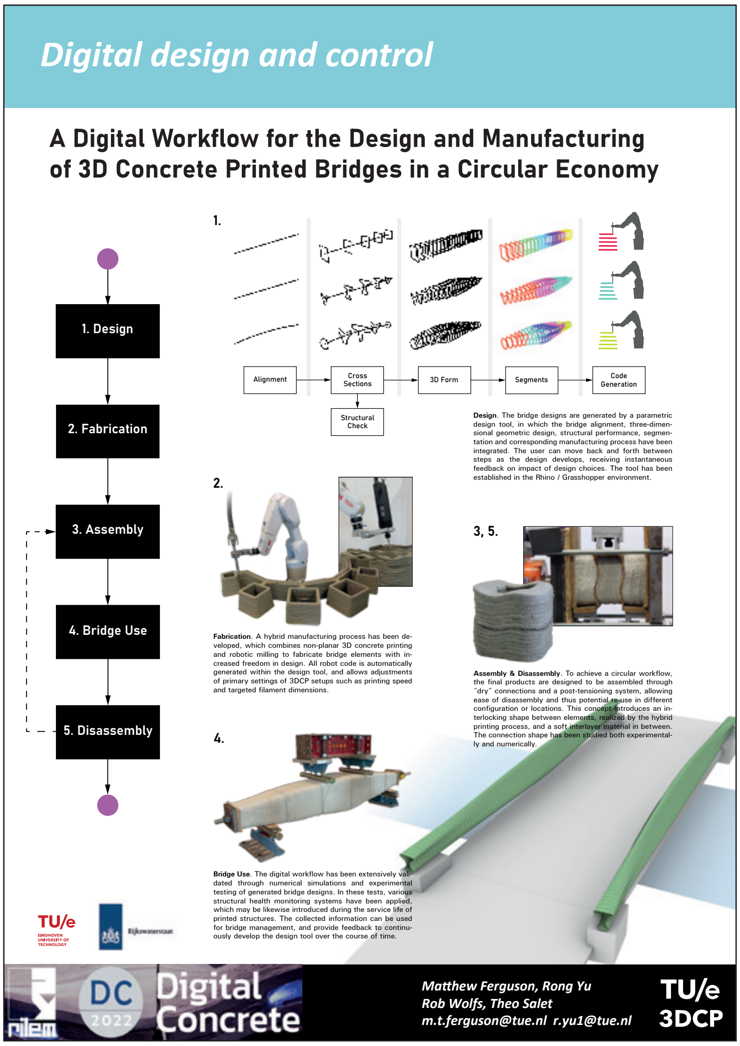

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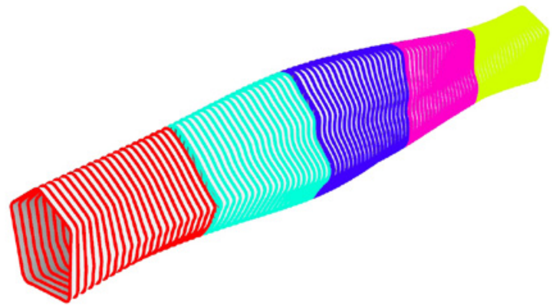
80. Digital Concrete Conference delegates discussing the contents of the poster.
81. Poster presented as part of the Digital Concrete conference.

Dutch Design Week

The Dutch Design Week is Europe's most prominent design exhibition, attracting around 70,000 visitors [28]. Held every year in October, the exhibition coincides with the end of the project. Ideas of integrated digital design and manufacturing tools, material optimisation and principles of circularity are presented to a general public audience to encourage thought surrounding the role and responsibility of design in the built environment.

For the 2022 exhibition, A two-meter 3D-printed concrete beam comprising five segments was created. The segments employ an interlocking shape, as described in chapter 3, with a different amplitude at each connection to show the versatility and customizability of the tool and manufacturing process. The cross-sections of the beam are also rotated to highlight the freeform capabilities of the 3DCP manufacturing process.

Geometry with interlocking segments created in the design tool was used to print the beam, which was produced by Vertico using non-planar printing with a robotic arm. This result again confirms the applicability of the design tool to state-of-the-art 3DCP systems.



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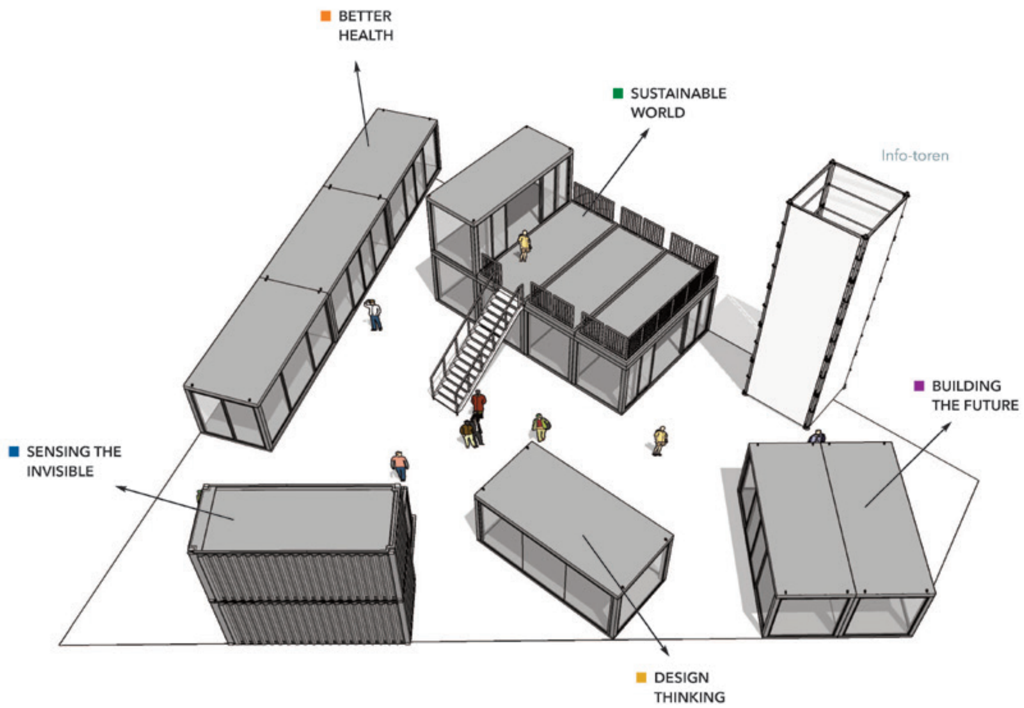

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82. Beam design with interlocking segments.
83. Site plan for the 'Drivers of Change' section of DDW. Image credit Volle-Kracht.
84. Opposite, beam during production at Vertico.


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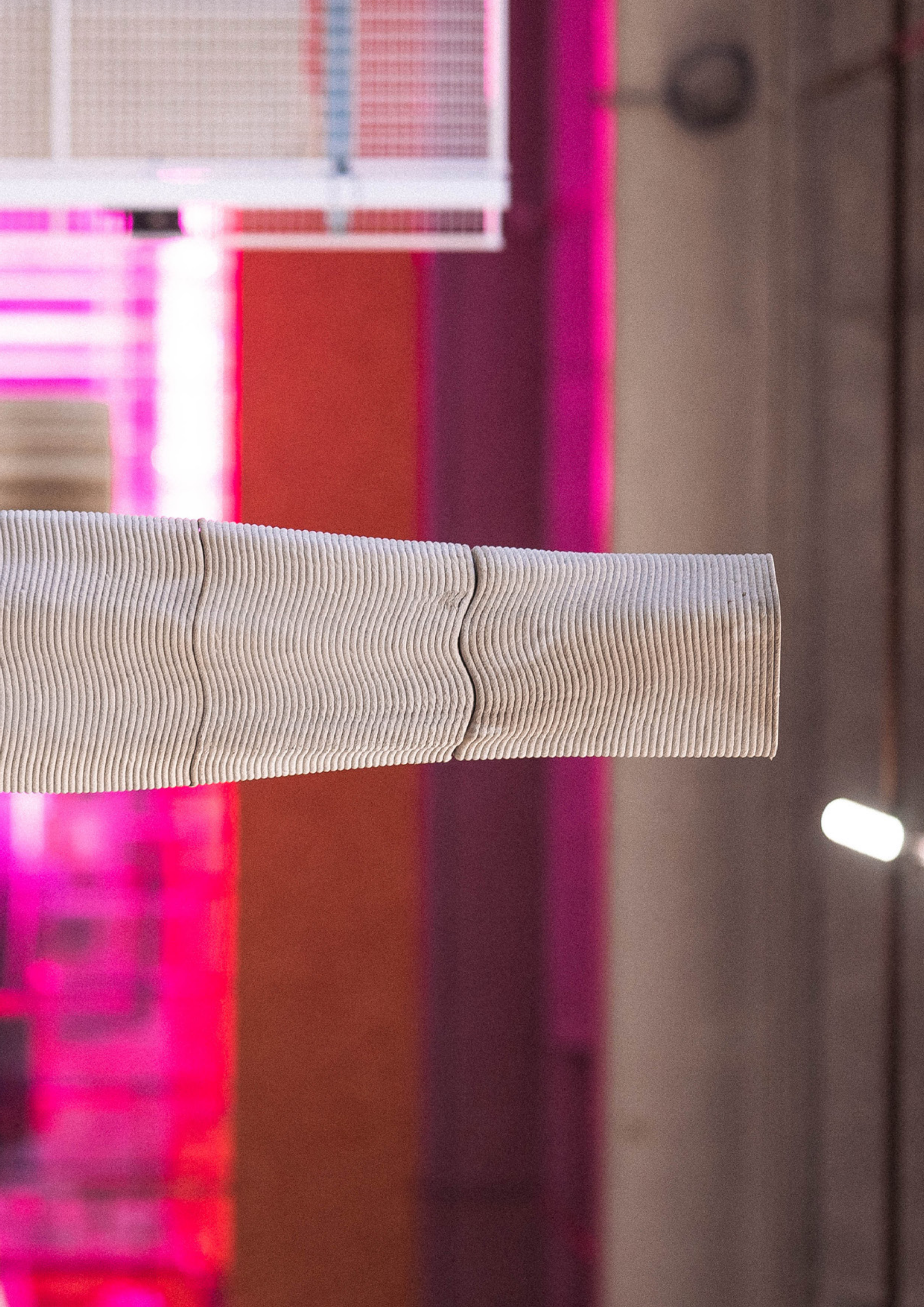

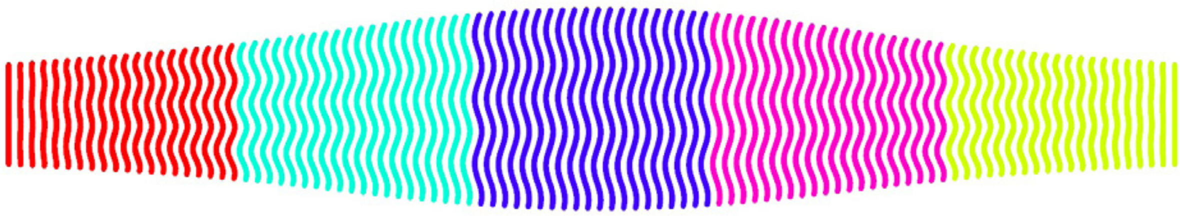

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6. Conclusions and Recommendations

The project's goal was to develop a digital workflow for designing and manufacturing 3D-printed concrete bridges using circular economy principles, aiming to aid with the challenges faced by Rijkswaterstaat in replacing numerous bridges in the coming years. A design, fabrication, assembly, bridge use, and disassembly workflow was established. In order to realise this workflow, a parametric design tool considering each of these steps was created.

Challenges

The material reduction ambitions introduced in the circular economy goals were addressed in two ways:

1. By implementing design for disassembly strategies, enabling the bridge elements to be used and reused.
2. Shape optimisation strategies allow material to be used in locations where it is most effective, reducing its overall consumption.

As described, the problem of low productivity and labour shortages exists within the construction industry. This problem was addressed by using digital manufacturing processes capable of reducing labour and directly connecting the design process to manufacturing equipment, improving efficiency moving from design to fabrication.

The tool aids Rijkswaterstaat with the task of replacing bridges by offering a strategy to identify the feasibility of working with 3D-printed concrete in this context, allowing them to work with designers to create materially efficient bridges suitable for their context.

Deliverables

Two key deliverables were identified as part of the project:

1. A Parametric Design Tool capable of designing and fabricating 3D concrete printed bridges incorporating structural and manufacturing constraints.
2. Disseminating knowledge about the potential of parametric design tools and integrated design and fabrication using 3D printed concrete within the context of the built environment and the current climate crisis. This knowledge is shared through outward-facing channels such as exhibitions, conferences, and discussions.

85. Previous, Beam design printed at Vertico for the Dutch Design week. Image credit Kees Leemeijer, Vertico.
86. Interlocking segmented beam design.

Design Tool Considerations

A set of design criteria were established to create the design tool by investigating precedents such as existing 3D-printed concrete bridges and applying circular economy principles.

The design tool is currently capable of moving from an alignment curve, inputting cross-sections, generating a 3D form, dividing into segments, adjusting the geometry for printing then generating production code.

Rhino and Grasshopper were used as a base for the tool to integrate design and manufacturing into a single environment. The tool is created in a series of blocks, each performing a specific function. Others can adjust and expand these blocks to further research as new materials and processes are developed.

There is room to expand and build on each of the blocks:

Alignment

The alignment can be controlled by inputting points or connecting with other software using the plugin Speckle. This block could be further expanded by incorporating geographic map data and connecting with existing bridge databases. This could benefit Rijkswaterstaat to help facilitate choices based on specific locations of bridges in their portfolio.

Cross-Sections

Users can input arbitrary cross-section geometry and receive feedback to make informed decisions on their beam design. This block could be expanded by including a cross-section library of recommended forms. Topology optimisation algorithms could be included to reduce material use further. Varying print width is currently available in the tool to reduce material. This could be further expanded by exploring printing multiple adjacent layers and infill patterns. Any new printing strategies added to the tool should be tested for manufacturability.

3D Form

The 3D Form block creates print layers by interpolating the cross-section curves. This block could be expanded to include surface finish and texture options for the printed objects, adding extra aesthetic control to the design process.

Segments

The tool currently divides the beam layers into equally sized segments. This segmentation strategy could be improved by integrating other criteria, such as material buildability and the weight of the segments. Models analysing the buildability of printed structures exist, and the tool would offer increased benefits by incorporating them. Additionally, these models could be automated.

The tool can generate interlocking shapes between segments currently using a sine wave. The tool could be expanded to include other shapes. Additionally, the tool could suggest the interlocking amount at each connection point based on structural requirements.

Support material, which enables the fabrication of non-planar segments, was tested using concrete. Concrete is not ideal for this application as this support material is designed to be disposable and does not meet the sustainability goals of reducing waste. Further investigation into environmentally friendly materials for this application would be of benefit.

The tool can generate toolpaths for milling to improve the tolerances of the segment interface connections. Further research or experiments into milling strategies to improve this process's speed would benefit.

Code Generation

The design tool can generate fabrication code in two languages: G-code for gantry systems and Rapid Code for ABB robots. Incorporating other robotic fabrication methods, such as the application of sensors or reinforcement, could be included to bring extra value. Fabrication tests should also occur with these systems to ensure the workflow functions.

Recommendation for Additional Capabilities

The design tool focuses on the generation of bridge beams. Additional capabilities of benefit include the generation of bridge supports, further investigations into deck designs and beam-to-deck connection strategies. Also, surrounding activities such as site preparation, abutments and foundations could be explored and integrated into the tool.

Structural health monitoring and the embedding of sensors during the digital fabrication process could be included. Monitoring would aid with maintenance and challenges associated with labour shortages. Initial investigations into monitoring took place with strain gauges being manually applied to printed beams.

Whilst making design decisions, life cycle analysis (LCA) feedback could give increased information about the impact of the structure. Related to this could be the inclusion of circularity indicators [30]. A combined ´dashboard´ including structural performance, cost, time, LCA and circularity indicators could be created to be used during the design process.

As this tool grows and complexity increases, the process could be automated. Starting with the initial boundary conditions and then outputting several potential options. The user could remain in control to tweak and adapt the options but could aid as a starting point, embedding the structural and manufacturing constraints right at the beginning of the process.

Public Dissemination

To meet the ambition of disseminating knowledge and the project results, participation in three international events occurred: the Built Environment Additive Manufacturing Exhibition in Frankfurt (BE-AM), the Digital Concrete Conference in Loughborough and the Dutch Design Week in Eindhoven. The Dutch Design Week is currently in preparation and will open to audiences shortly after the publication of this report. Interactions with industry, academic, and general public audiences occur during these events, shaping the design tool´s development. These conversations also helped raise awareness of integrated design and manufacturing, which can have ramifications beyond this project.

Outlook

The tool offers a step toward the vast sustainability challenges we face. It presents a realistic integrated design and fabrication method that can be used today. It addresses materials available on the market, existing printing systems, and is based in a software environment known to designers operating in the built environment. These ingredients were chosen to maximise the usability of the tool. Each step of the tool was tested through fabrication and manufacturability tests to ensure a direct link between design and manufacture.

To address the challenges of the bridge repair and replacement project undertaken by Rijkswaterstaat, the tool can be used to design and fabricate bridges which can be used and if necessary, disassembled, moved, and reused.

The sustainability and productivity challenges discussed throughout this project are not confined to bridge applications. The broader construction industry and built environment also require integrating digital design and manufacturing processes along with circularity principles. While specific features of the tool may not be applicable, the workflow developed here can provoke thought into how design processes can be re-evaluated.

87. Opposite, printed test segments.

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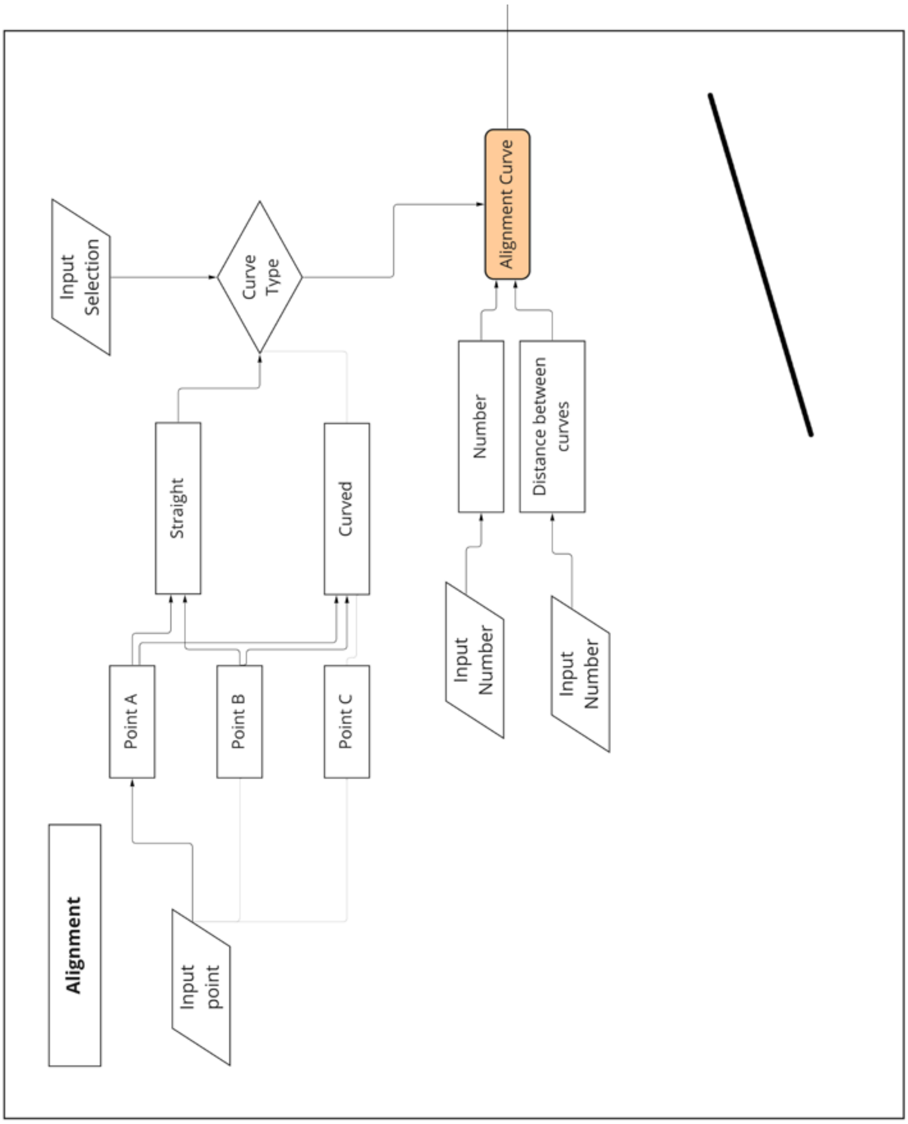
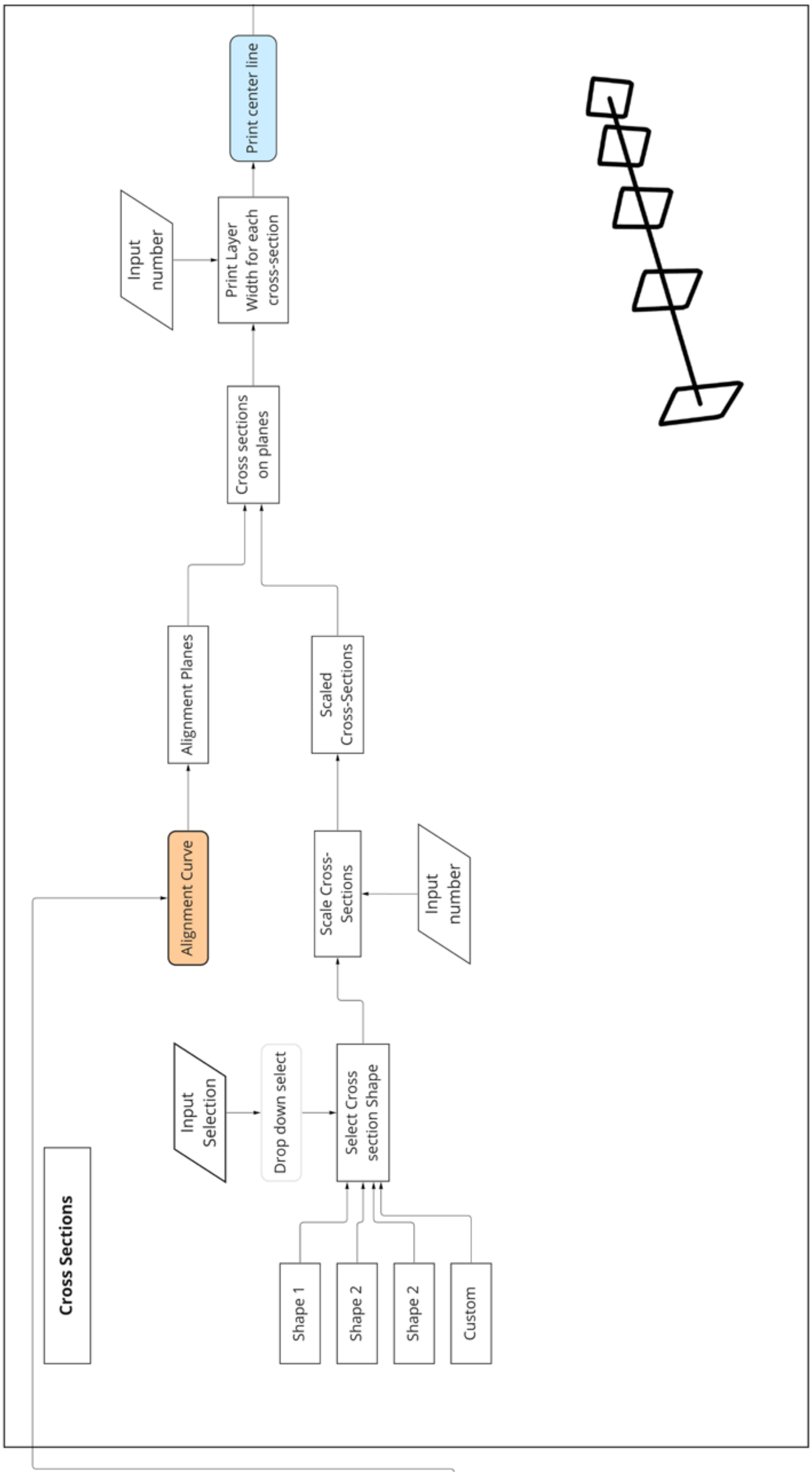
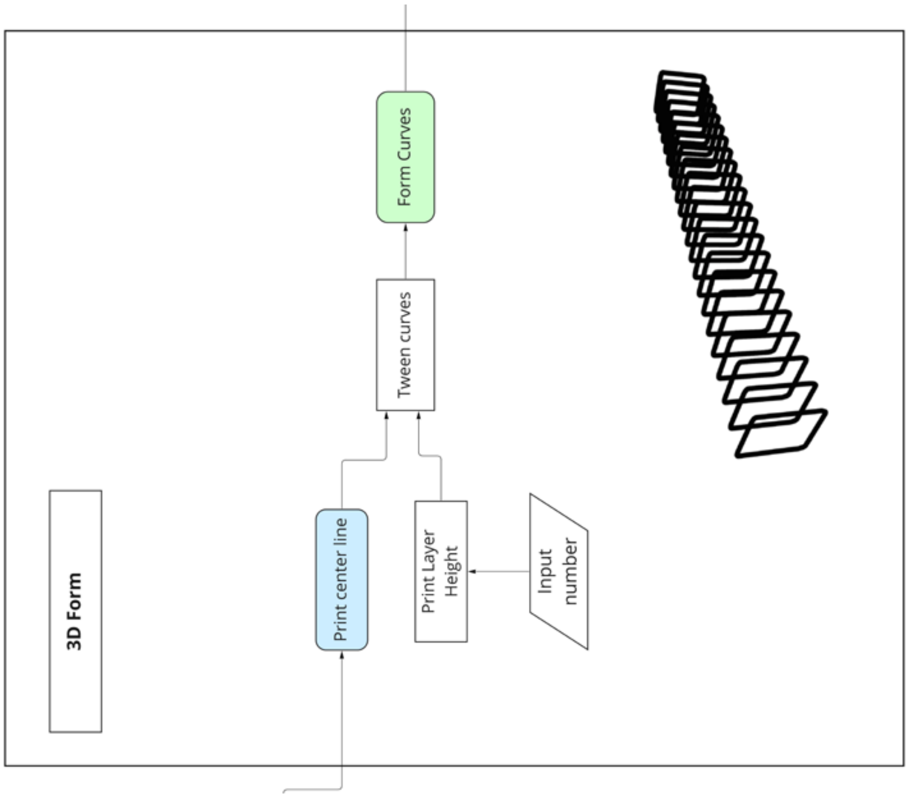
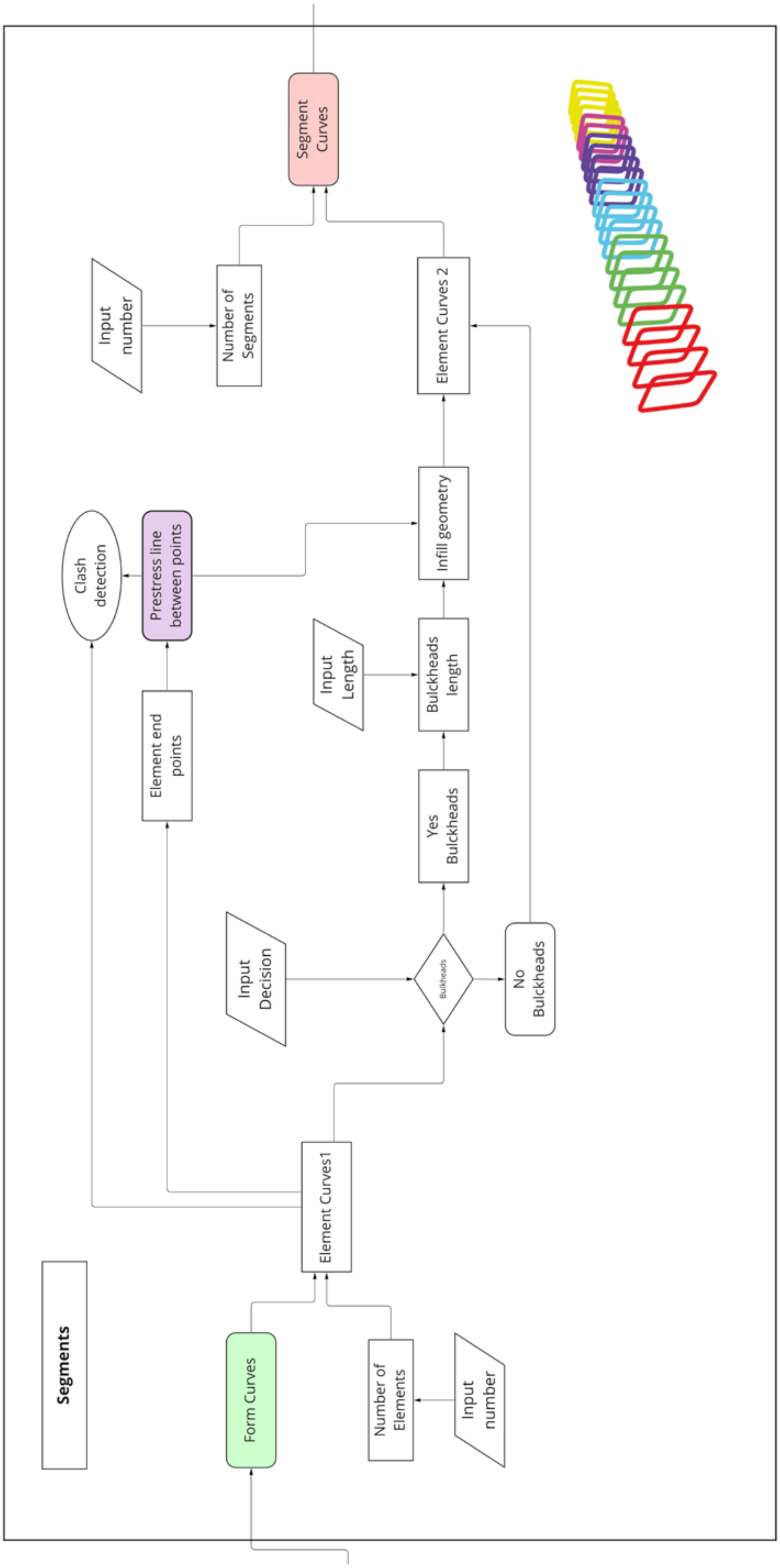
8. Appendix

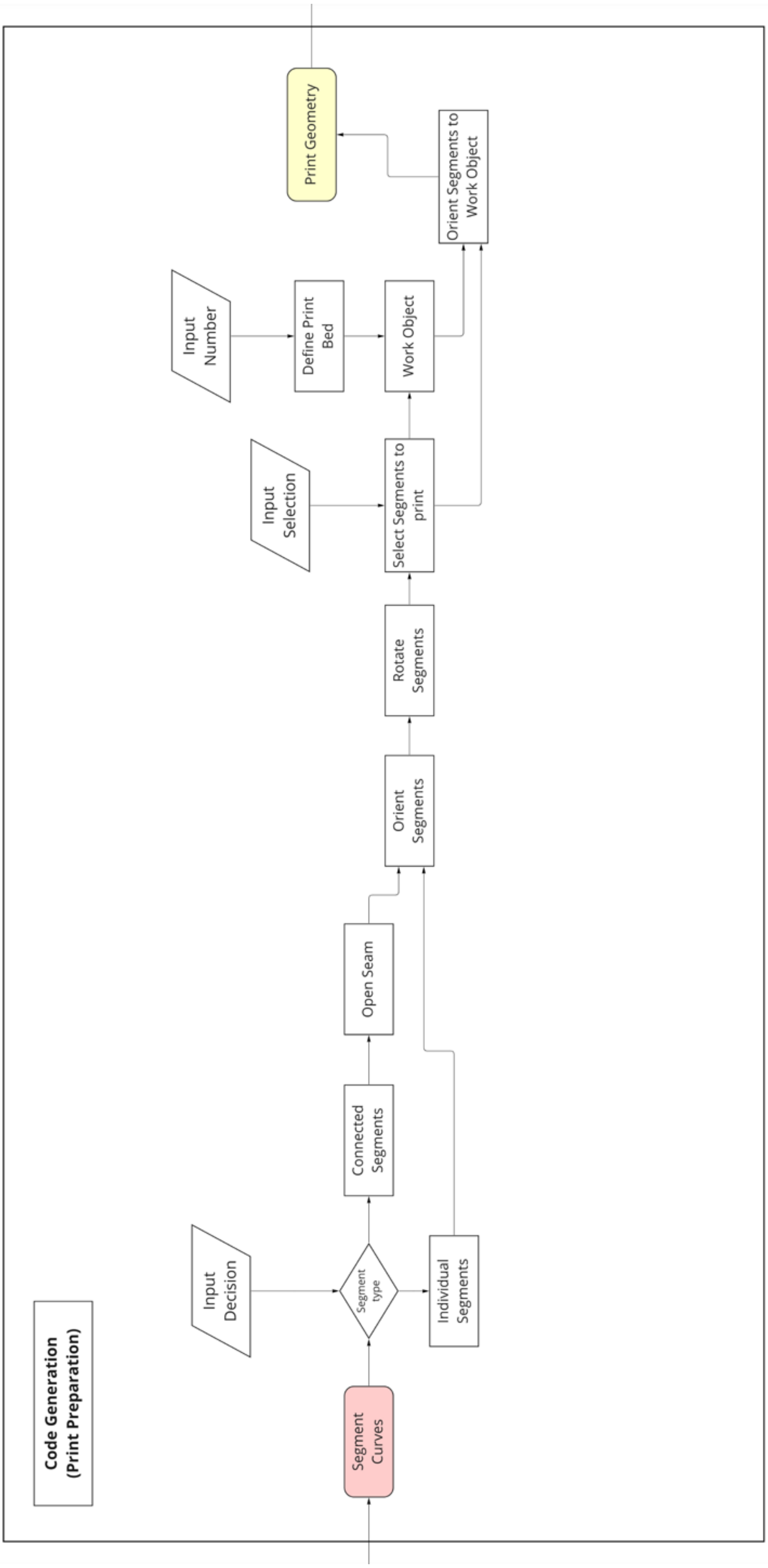


Simplified diagram of the design tool.
Inputs, options and outputs.


Cross Sections
Shape 1
Shape 2
Shape 2
Custom
Input Selection
Drop down select
Select Cross section Shape
Scale Cross-Sections
Input number
Alignment Curve
Alignment Planes
Scaled Cross-Sections
Cross sections on planes
Input number
Print Layer Width for each cross-section
Print center line


3D Form
Print center line
Print Layer Height
Input number
Tween curves
Form Curves


Segments
Form Curves
Number of Elements
Input number
Element Curves1
Element end points
Clash detection
Prestress line between points
Input Decision
Bulkheads
Yes Bulckheads
No Bulckheads
Input Length
Bulckheads length
Infill geometry
Element Curves 2
Input number
Number of Segments
Segment Curves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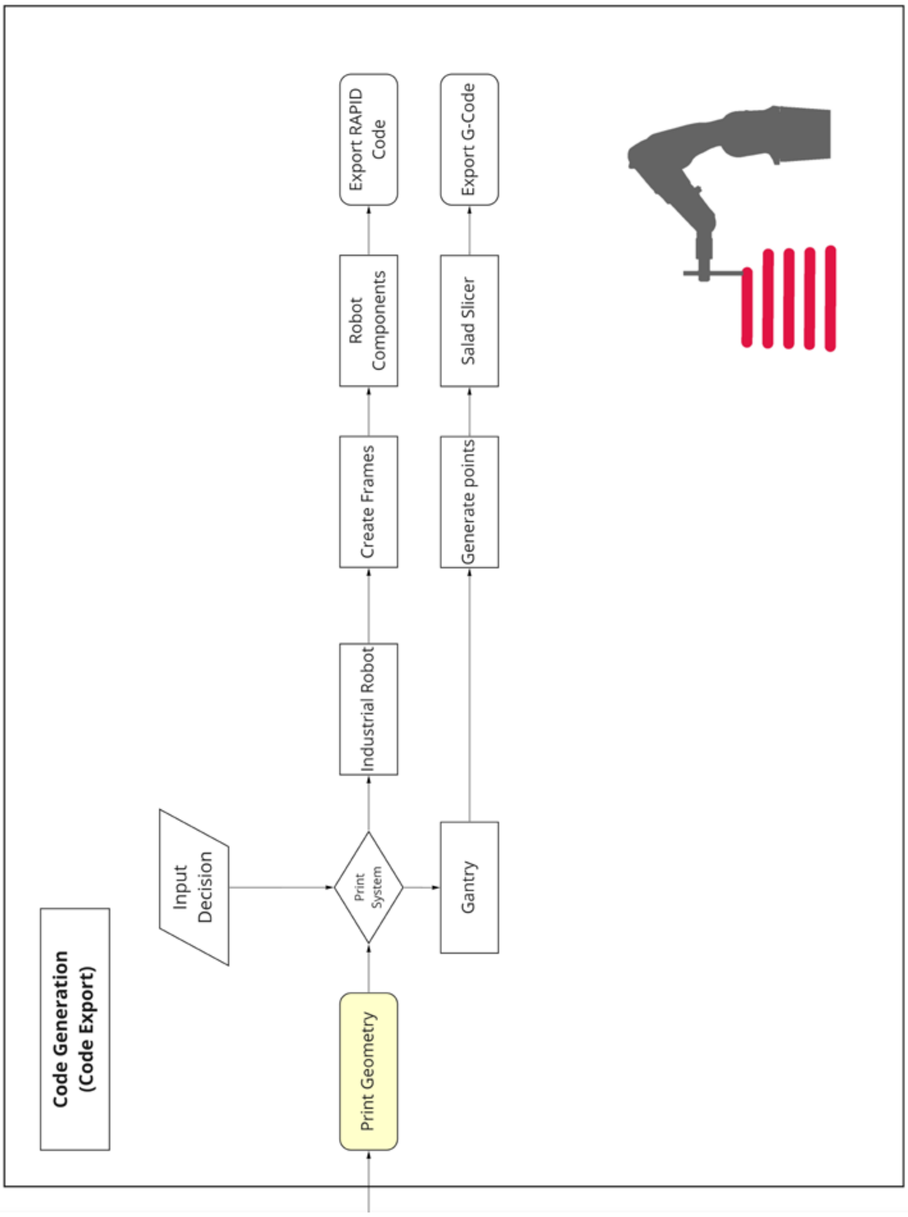
(Print Preparation)
Segment Curves
Input Decision
Segment type
Individual Segments
Connected Segments
Open Seam
Orient Segments
Rotate Segments
Input Selection
Select Segments to print
Input Number
Define Print Bed
Work Object
Orient Segments to Work Object
Print Geometry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(Code Export)
Input
Decision
Print Geometry
Print
System
Industrial Robot
Gantry
Create Frames
Robot
Components
Export RAPID
Code
Generate points
Salad Slicer
Export G-Code


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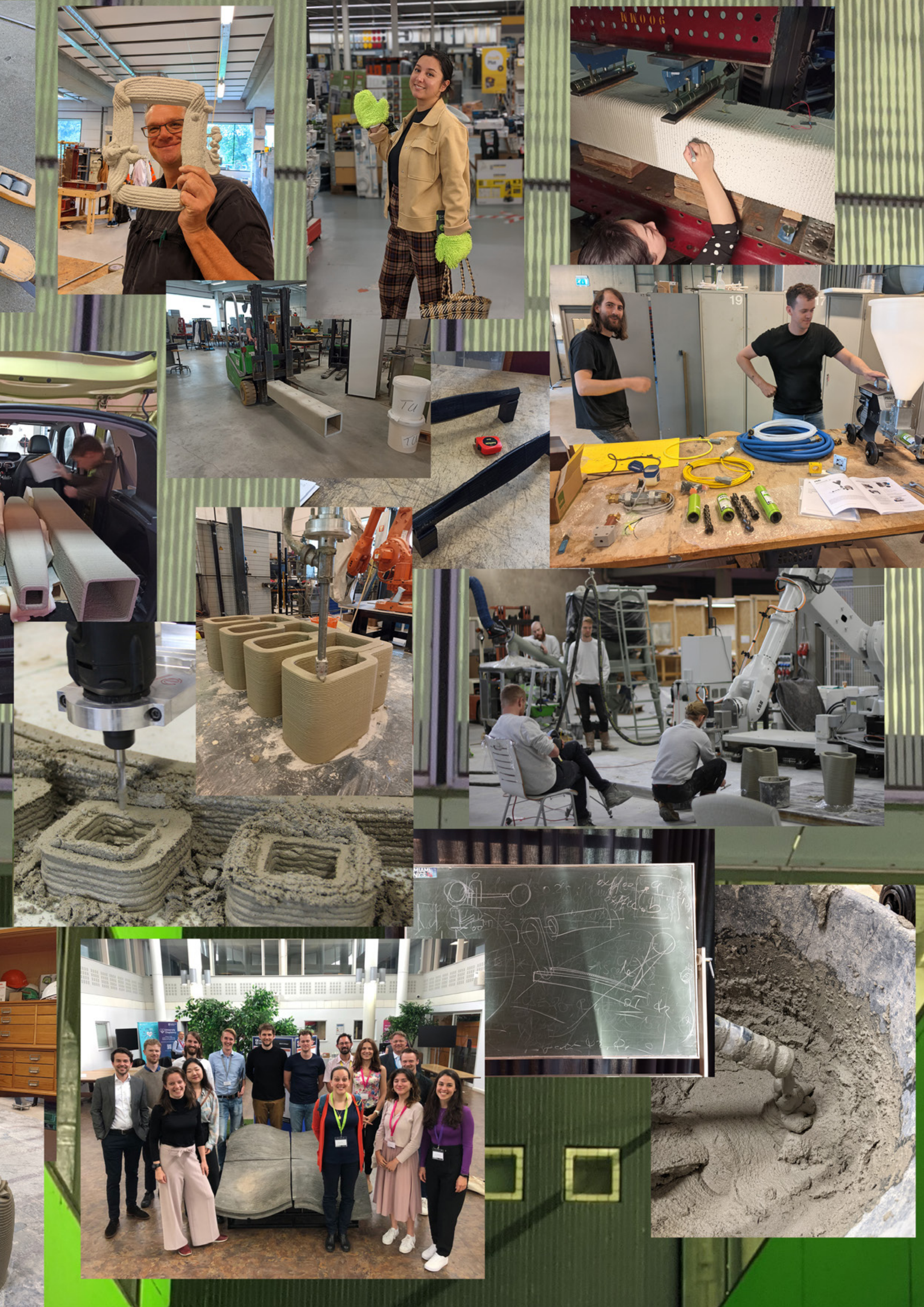
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