Computer Programming & Data Science
An Introduction with Python FS2025

“Optimising 3D-printed Concrete Structures for Carbon Capture”

Introduction

In recent years, the construction sector has experienced significant growth, leading to a corresponding increase in greenhouse gas emissions associated with the production and use of building materials, particularly concrete. To address this environmental challenge, a new construction method has emerged: 3D printing of concrete structures. This technique, based on additive construction technology, deposits layers of concrete without the use of formwork, enabling the creation of structures directly on site or in a controlled environment.

Within this context, the present research focuses on how to optimise 3D-printed concrete structures to reduce their overall carbon footprint, taking into account the role of carbonation—i.e., the material's ability to reabsorb CO_2 over time. The primary objective is to identify a geometric configuration that minimises CO_2 emissions while maximising absorption, all while maintaining adequate structural strength and printability.

Geometry is the first fundamental aspect to be addressed in an optimisation process. One of the key advantages of 3D printing is the ability to deposit material only where it is structurally necessary, thereby reducing the total volume of concrete used. However, this approach involves certain trade-offs: using less material requires higher strength, which often translates into a higher cement content—and consequently, higher emissions per cubic meter of concrete.

This technical report outlines the motivation and development of an interactive Python-based application for visualising printable 3D geometries. The aim is to support the optimisation of 3D-printed concrete structures for effective carbon capture. Understanding the influence of geometric variables, such as the thickness of the printed layers and the number of triangles defining the shape, is a crucial step in the search for a configuration that minimises environmental impact.

Functional Unit

The functional unit considered for the optimisation and analysis is **1 m^2 of 3D-printed concrete wall**. This unit serves as a standardised basis for comparing different geometric configurations and their performance in terms of carbon capture potential. By defining the functional unit as a fixed surface area, the study can consistently evaluate and optimise material usage, structural strength, and environmental impact across different design scenarios.

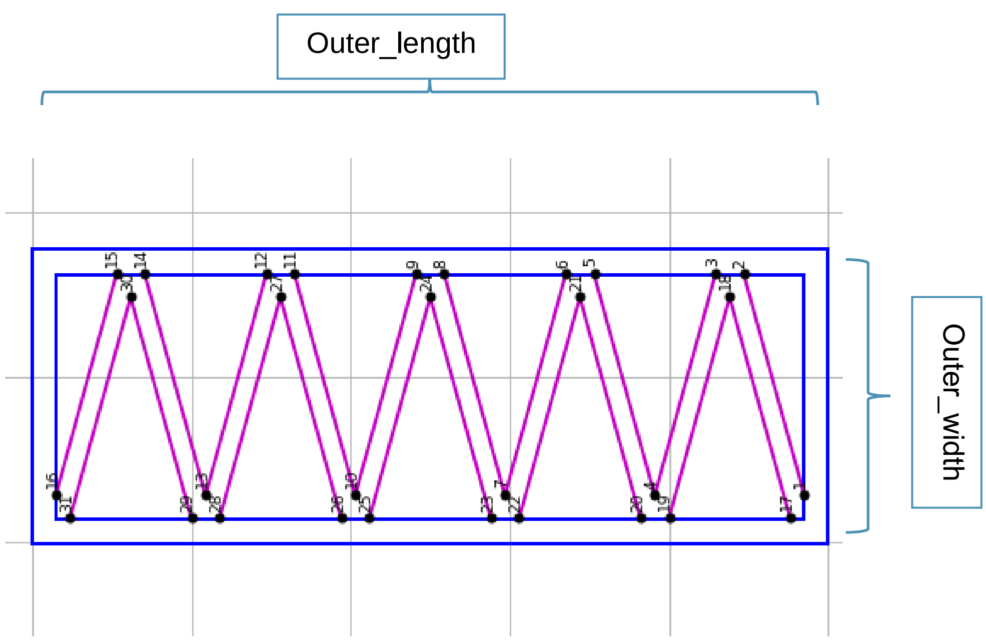
The goal is to develop a parametric model that generates the wall geometry based on two key design variables:

- The **number of isosceles triangles** printed within a fixed rectangular concrete frame.
- The **thickness** of the printed shape, which corresponds to the layer width defined by the extrusion nozzle of the 3D-printing arm.

The model dynamically generates a visual representation of the 3D-printed geometry and calculates the corresponding wall dimensions. While the **length** of the wall is fixed at **1 meter**, the **width** is computed iteratively based on structural and material constraints.

Specifically, the wall is designed to **withstand a compressive load of 5 MN/m**, with a **concrete compressive strength of 30 MPa**. Using these values, it is possible to calculate the required cross-sectional area, and consequently derive the width of the wall that satisfies both structural and printability requirements.

This geometric and structural framework provides the foundation for subsequent evaluations of carbon footprint and optimisation strategies, helping to identify designs that minimise emissions while preserving mechanical performance.



Application Purpose

The goal of the developed application is to provide a **visual and interactive platform** for exploring how geometric parameters affect the structure of 3D-printed concrete walls. This tool supports both research and communication by allowing users to **visually assess the effects of design choices** in real time.

Upon running the Python-based code, a **web interface automatically opens in the browser**, displaying a 3D visualization of the printed wall. Through this interface, users can **interactively adjust the number of isosceles triangles** within the wall structure and **modify the thickness** of the printed material, which corresponds to the extrusion width set by the 3D printer's mechanical arm.

This dynamic feedback enables designers, engineers, and researchers to:

- Understand the spatial impact of different geometric configurations.
- Estimate how changes in design influence material use and structural footprint.
- Communicate design concepts more clearly to stakeholders.

The application thus serves as a first step in the broader process of optimising 3D-printed structures for carbon capture, before moving on to more complex evaluations involving concrete mix design, carbonation potential, and life cycle emissions.

Code Instructions

This section provides a step-by-step explanation of how the developed Python code works, guiding the user through its logic, structure, and usage. The purpose of the code is to allow for real-time visualization of a 3D-printed concrete wall geometry based on customizable input parameters.

Step 1: Launching the Application

To start the application, it is necessary to run the Python script in the local environment. The script will automatically start a Dash web server, which will open a web page in the browser showing the interactive interface.

Step 2: Adjusting Input Parameters

Once the interface is open, you will see two sliders: the Number of triangles and the thickness.
The number of isosceles triangles used in the design model inside the 1-meter long wall can be controlled. Increasing this number increases the complexity of the internal geometry of the wall. Using the thickness slider, it is possible to define defines the extrusion thickness (in millimeters) of the concrete deposited by the 3D printer. This parameter represents the printing resolution and affects the overall width of the wall.

Step 3: Geometry Generation

The total length of the wall is fixed at 1 meter.
The geometry of the wall is defined based on user input; in fact, the width (depth) of the wall is not fixed, but is calculated to ensure that the wall can structurally resist a compressive load of 5 MN/m, assuming a concrete strength of 30 MPa. Based on the cross-sectional area obtained from the compressive load and concrete strength and the number of triangular voids created, the application iteratively calculates the width of the wall so that it satisfies the load-bearing requirement.

Step 4: Visualization

The code uses the **Plotly** library to render a 3D representation of the wall:

- A mesh of the wall is created using the `Mesh3d` function.
- Coordinates for the outer frame and inner triangular shapes are calculated dynamically with **NumPy**, depending on the selected number of triangles and thickness.
- A complete **3D model is displayed**, which updates in real time as the input sliders are moved.

Step 5: Application Purpose

The application is designed to:

- Help users **visualize the geometric structure** of the 3D-printed wall.
- Provide an intuitive understanding of how **design parameters affect the material usage**, wall volume, and load-bearing capacity.
- Serve as a **design tool** for early-stage geometry optimization before testing different concrete mixes for carbon capture potential.

Conclusion

This tool plays a pivotal role in bridging computational design and environmental performance analysis. By enabling real-time visualization and interaction with geometric parameters, it empowers designers and researchers to explore a wide range of configurations in a fast and intuitive manner. This immediate feedback is crucial for making informed decisions in the early design phase, particularly when aiming to reduce material usage while maintaining structural integrity and enhancing carbon capture potential.

The integration of visual computing and structural logic in this application serves as a foundation for more advanced optimization processes, including concrete mix design and carbon footprint assessment. Ultimately, this tool supports the development of more sustainable construction practices by combining geometric efficiency with environmental responsibility, paving the way toward more climate-conscious architectural and structural solutions.