Graduation Plan

Master of Science Architecture, Urbanism & Building Sciences

Graduation Plan: All tracks

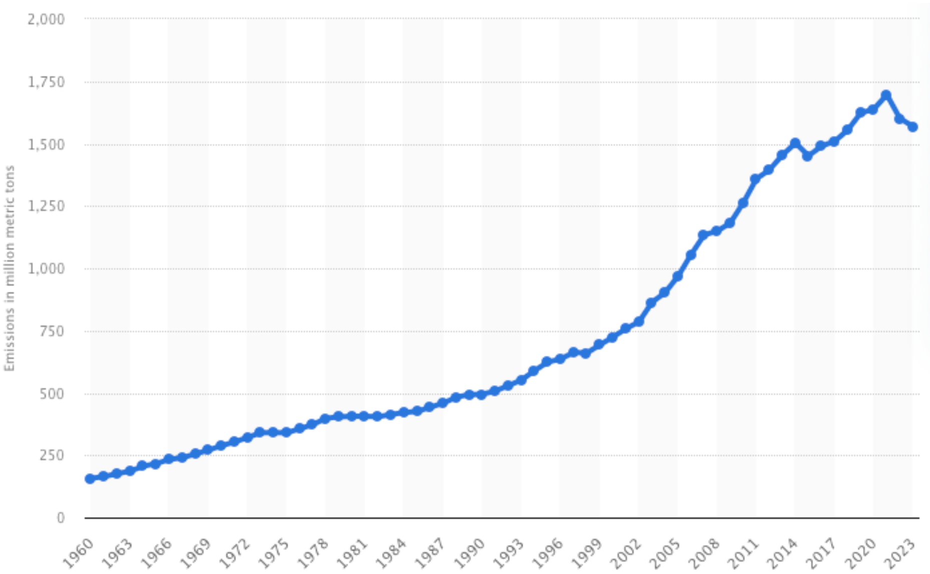
Submit your Graduation Plan to the Board of Examiners (Examencommissie-BK@tudelft.nl), Mentors and Delegate of the Board of Examiners one week before P2 at the latest.

The graduation plan consists of at least the following data/segments:

Personal information	
Name	Mauritz Frederik Volker Manfred von Kardorff
Student number	5145163

Studio		
Name / Theme	BT Graduation Studio	
Main mentor	Dr. Olga Ioannou	Facade & Product - Building Product Innovation
Second mentor	Dr. ir. Branko Šavija	Materials & Environment - Cements
Argumentation of choice of the studio	Even though concrete is the largest contributor to construction waste, its opportunities for reuse have not yet been exhausted. Its remaining structural performance shows a high potential for new ways of remanufacture. I chose this topic due to the potential scale concrete rubble reuse could be applied at. The demolition of concrete buildings is not confined to Central Europe and the treatment of this waste will become a major issue in the future. Furthermore, most low-carbon alternatives to concrete cannot compete in terms of heat storage capacity. Recent research has laid out the opportunities which lie within rubble. However, academic work on this topic is still scarce and the field still new. This framework fascinated me, so I would like to find out more about its potential through this thesis.	

Graduation project	
Title of the graduation project	Cyclopean Spolia - Integration of Concrete Rubble into Precast Load-Bearing Wall Elements
Goal	
Location:	The Netherlands
The posed problem,	As the backbone of the built environment, concrete is the key material which shapes our modern world. In the 20th century, it became the most popular structural material, but the unprecedent urbanisation of the past 30 years led to a boom of the material. Concrete is projected to outweigh all biomass on the planet in the 21st century. China, the world's largest consumer of cement (cemnet, 2024), poured more concrete between 2010

	and 2013 than the US did in the entire 20th century (Cement Statistics and Information | U.S. Geological Survey, n.d.). The reasons for this are the material's unique advantages like the adaptability to various shapes linked with a high compressive strength and low maintenance costs. Furthermore, it presents excellent thermal storage capacities and is flexible to build with. However, concrete production contributed to 5% of global C02 emissions in 2021 (Statista, 2024b, 2024a) and sand, one of its main resources, starts to become scarce (UNEA, 2022). - Between 2010 and 2013, China alone poured more concrete than the US did in the entire 20th century - Furthermore, concrete presents us with another challenge. Its waste accounts for about 30% of the total mass of waste in Europe (Böhmer et al., 2008). Current demolition methods turn the material into irregular sized rubble, which either get used as infill material for road fills, as aggregates for new concrete, or like 80% of construction waste (Uotila et al., 2024), the concrete gets landfilled.  Figure 1 Carbon dioxide emissions from the manufacture of cement worldwide from 1960 to 2023 (Statista, 2024) However, many concrete buildings are demolished due to functional obsolescence, not because the material has reached the end of its structural life. This presents an opportunity to reuse the components in new structural applications. Today, this is a rarely practiced method. Industrial processes for the reuse of building products do not exist yet, which leads to increased manual labour during construction and an increased complexity for planning the building. Entire concrete elements are also difficult to extract without breaking them, their weight leads to high transport costs and the non-standard elements have to be

	integrated into the design of the new building (Küpfer & Fivet, 2023). There are clear opportunities to overcome these challenges however. Firstly, there an increased incentive, because the concrete industry is forced to search for new alternatives. The scarcity of sand for fine concrete aggregates (UNEA, 2022) will hinder the continuation of the growth of concrete and leads to a current search for alternative materials. The reduction of cement in the built environment is also a major goal of political policies and government funding (European Commission, 2020), whose aim is to reduce carbon emissions during construction processes. Furthermore, academics develop frameworks for circular concepts for concrete and technological advances offer computational tools, which enable precise and efficient planning with non-standardized elements. The simultaneous digitization of prefabrication processes for the construction industry facilitates mass customization of building products. All of these developments lead to new opportunities for reuse.
research questions and	Main Research Question *How can we engineer load bearing prefabricated concrete elements while integrating parallel sided concrete demolition waste with regards to structural performance and aesthetics?* Subquestions *What is the current state of Concrete Rubble Reuse?* *What is the research needed to realize the scalability of Cyclopean Spolia walls?* *How would a future workflow for prefabricated concrete rubble elements look like?* *How freely can concrete rubble be arranged within Cyclopean Spolia walls to offer a design variety while maintaining structural integrity?* *Which materials are suitable as a matrix binder for Cyclopean Spolia Walls?* *How can concrete rubble elements be arranged in a formwork to ensure the matrix binder works to its full potential?* *How could Cyclopean Spolia Walls be used for low-rise residential buildings in the Netherlands?*

design assignment in which these result.	The research designs a process for the prefabrication of structural concrete walls with embedded parallel sided large concrete construction waste elements. With the use of physical experiments, it aims to develop a workflow for the optimal arrangement of rubble within the new wall, regarding structural performance and design freedom. As a computational tool, nesting and stacking algorithms are compared. Furthermore, structural tests are conducted to compare multiple arrangements of rubble within concrete. Finally, a 1:10 demonstrator is designed and built, which showcases the workflow, the resulting wall panels and the surfaces created.

Process

Method description

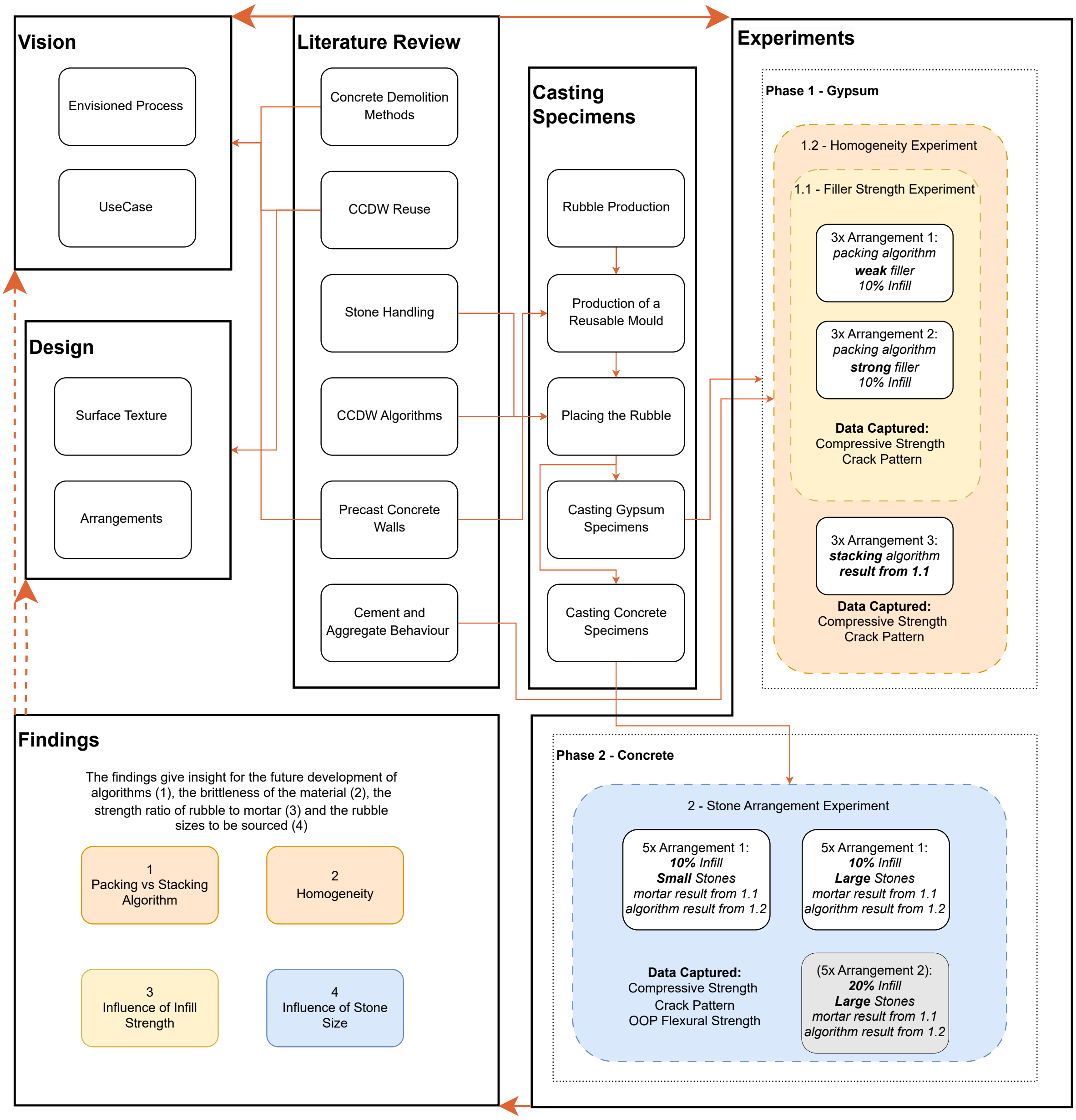


Figure 2- Research Diagram

The methodology for this research combines a literature review on topics which influence the performance of precast rubble walls with two experiment phases and the design of a demonstrator. The structural tests are done in a first experimental phase with gypsum and a later phase with concrete to gather the data needed to assess multiple rubble arrangements.

Stage 1 - Literature Review

The literature review is structured in the six chapters mentioned below. The first gives an overview of existing processes and maps the opportunities and challenges which were identified. The following five sections evolve around the keys areas which influence the process for structural reuse of concrete rubble.

Examples - existing CCDW Reuse
Supply - Concrete Demolition Methods
Handling - Lifting / Scanning
Computation - CCDW Algorithms
Construction - Precast Concrete Walls
Filler Material - Cement and Aggregate Behaviour

The process starts with the identification of the concrete rubble supply coming from demolition projects. Therefore, current demolition methods are outlined. These inform the shapes which are adopted for the project. As the handling of the heavy rubble is key to feasibility on the 1:1 production scale and important for an accurate representation in the 1:10 scale used for this project, lifting and scanning techniques are discussed in section 3. The influence which the arrangement of the rubble has on the structural performance is a key part of the experimental phase of this project. Therefore, packing and stacking algorithms are compared in a section dedicated to computation. To ensure a scalability of the process, the construction section focuses on rules for precast concrete walls. Finally, the properties of concrete and aggregates are discussed, to inform the choice of the filler materials used during the experiments and reveal potential challenges and opportunities of large scale aggregates in concrete.

The academic research papers for this literature review were found through two online portals (Scopus and Google Scholar) and through references from papers read throughout the process. Additionally, the TU Delft library was accessed to find general information about concrete and precast methods. To include non-academic CCDW reuse methods and reference projects, sources like blogs, magazines, architecture websites and online video platforms were consulted.

Stage 2 - Experimental Gypsum Tests

One of the aims of this research is to find out whether nesting algorithms can be used for horizontally prefabricated CS walls. Therefore, a first round of experimental test seeks to investigate the behaviour of stones arranged with nesting and stacking algorithms. For comparability, both specimens use a filler of similar strength to the rubble for. In case of a comparable performance of the nesting algorithm, a second setup is prepared to investigate filler, which has a lower strength than the rubble.

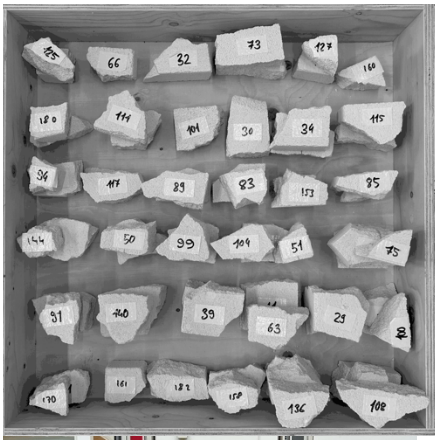


Figure 3 Rubble Scanned and Digitalised During the Mosaic Walls Project

Due to concrete's long curing period of 28 days (Eurocode, 2004), an alternative had to be found for these preliminary tests. Therefore, existing AAC elements from the Mosaic Walls project (Hany et al., 2024) are used as rubble in connection with concrete and gypsum as fillers. The stones outlines were already captured with OpenCV based on 2D photos. OpenNest (*OpenNest - Parametric House*, 2020) is used as a nesting algorithm, due to the low computational power required. For the stacking specimens, the algorithm by Wang et al. (2024) is chosen, to enable a comparison of the results to the 'Structural Concrete Rubble Arrangements' project from EPFL (Grangeot et al., 2024). The experiment setup compares the crack behaviour under compression of precast elements of 300mm x 250mm x 50mm with a Digital Image Capturing (DIC) method. The specimens are painted in white and a black spray can is used to create a speckle pattern on the surface. The tests are filmed and analysed with μDIC (Olufsen et al., 2020). For the compressive load, a universal testing machine by Zwick (Z100) with a maximum load of 100kN is used. This test setup is therefore able to measure a strength up to 6.7MPa for a specimen surface of 15'000mm2.

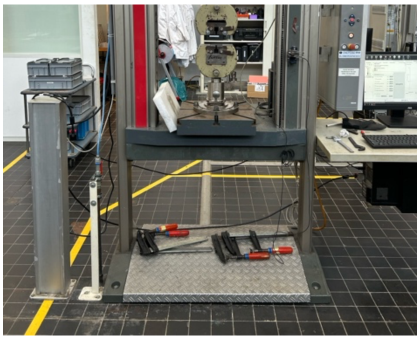


Figure 4 Universal Testing Machine Zwick Z100 with a maximum load of 100kN

Stage 3 - Data Collection Concrete Tests

With the knowledge from the first round of tests, a suitable algorithm and filler / rubble strength ratio (f_s/r_s) is found. With this data, a second round if prepared with the aim of finding optimal rubble sizes and arrangements for horizontal prefabrication of CS walls. The setup is the same than the first round, but both the rubble and the filler material is made from concrete. The findings show a comparison between different filler / rubble volume ratios (f_v/r_v) and an option of adding smaller rubble stones as infill.

Four different scenarios are compared:

I. Large Stones + f/r = 0.3
II. Large Stones + f/r = 0.5
III. Small Stones + f/r = 0.3
IV. Large Stones + f/r = 0.5 + Small Stones as Infill

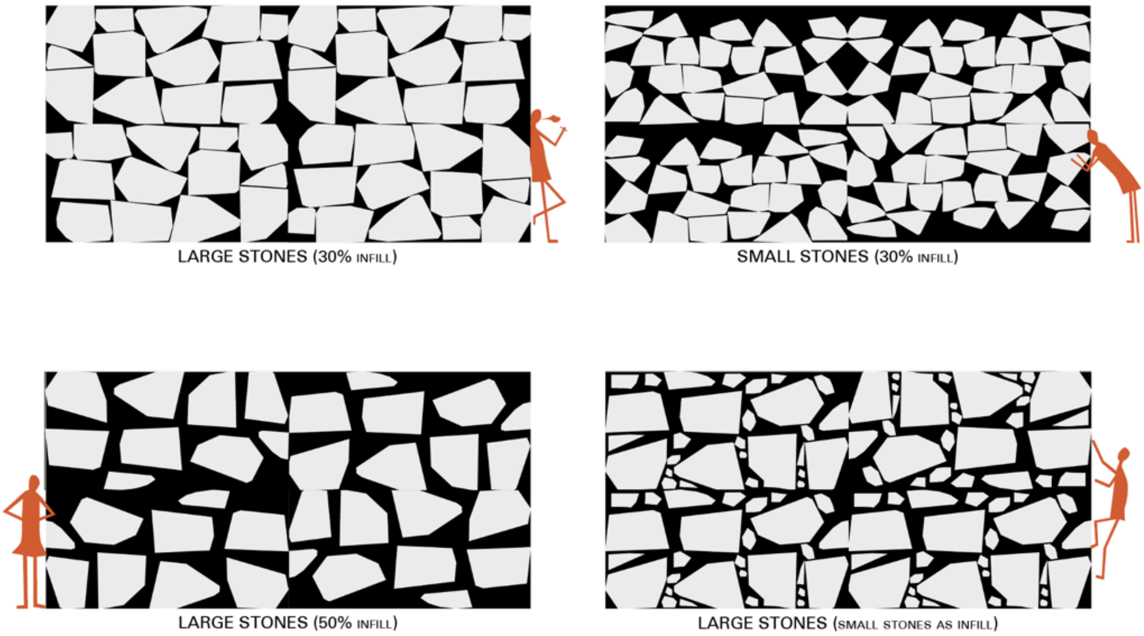


Figure 5 Rubble Configurations

Rubble sourced from a waste centre typically comes from various construction sites and the background and strength of the individual elements is unclear. Furthermore, the 1:5 scale of the tests requires rubble with a thickness of 50mm, which is difficult to find in waste centres. To ensure a comparability between the specimens and the rubble elements, the concrete is therefore produced by the author and broken by hand. For reproducibility, all rubble elements have the same thickness.

Design

The final part of the report is centred around the design of a demonstrator for Cyclopean Spolia walls. It focuses on the concrete surface, with regards to rubble thickness, rubble size and the forms included into the wall. Additionally, it takes the lessons learned from the experimental tests into account and uses the algorithm which performed best during the tests. To demonstrate possible arrangements and connections between the walls, a small prefabricated pavilion is developed and realized in a 1:5 model.

Literature and general practical references

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Reflection

1. What is the relation between your graduation (project) topic, the studio topic (if applicable), your master track (A,U,BT,LA,MBE), and your master programme (MSc AUBS)?

The graduation topic combines the topics of circularity, structural mechanics, fabrication and product design in the search for alternative building materials with a lower carbon footprint. It is therefore deeply rooted in knowledge taught within the Building Technology Master's. Courses like Eco-Friendly Material Choices, SAMS and Climate Design were a main inspiration for the thesis. Furthermore, the topic is tightly connected to the CORE studio, due to its roots within this courses group work. MSc AUBS is committed to innovation in the construction industry and the topic aligns with its aim for a more environmentally friendly architecture.

2. What is the relevance of your graduation work in the larger social, professional and scientific framework.

While the construction industry searches for alternatives for concrete due to its high carbon footprint, its demolition waste is currently downcycled or landfilled. Even though we have the digital tools for the planning and fabrication with irregular elements, building with large concrete rubble is still an underdeveloped topic. Recent research has however demonstrated the potential of this material. This thesis contributes to the ongoing search for feasible and scalable solutions to concrete rubble reuse, with a specific focus on the arrangement of rubble within precast load-bearing walls. The outcomes will inform researchers and the construction industry on the structural impact of rubble arrangements and can serve as a base for large scale tests with real concrete rubble.

The remanufacture of CCDW offers an alternative to carbon intensive concrete walls, while using a waste material. It provides the benefits of heat storage within the structure, which is often difficult to achieve with low-carbon materials.

Furthermore, the concrete boom of this century will lead to an enormous amount of concrete waste in the future. This research contributes to the creation of a new method for the treatment of this waste.