From the ground up:

Robotic Additive Manufacturing (RAM) of a structurally optimized earthen shell through computational design

Final Reflection

In partial fulfillment of the requirements for the degree of

Master of Science

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Studio

Name: Sustainable Design Graduation Studio

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Themes:

Robotic Additive Manufacturing (RAM)

Structural Design optimization

Sustainable materials innovation

Reflection

In this chapter, a final reflection is composed on the graduation process and topic.

Graduation Process

Relationship between graduation topic & studio theme/method

The thesis assignment is carried out within the Sustainable Graduation Studio. The graduation topic introduces a computationally-driven workflow for a structurally optimized building element, with a focus on shell geometries using earth as a construction material. It combines parametric design and robotic additive manufacturing in order to minimize the impact of the construction industry in the environment. It achieves this through efficient use of energy and resources using a recyclable and environmentally friendly material.

The topic is related to ongoing TU Delft research regarding 3D printing with clay as a construction material. It serves as a follow-up of Ammar Ibrahim's thesis on 3D printed clay facades that integrate ventilation systems and Tommaso Venturini' s research on earth extrusion. The main focus in this case is on Design Informatics and Structural Design, two fundamental directions of the Building Technology and Sustainable Graduation studio. Structural design and optimization processes have been limited by rationalization processes of typical construction methods, namely the cost of formwork. With the assistance of computational tools and digital fabrication methods, structural design can be freed from these constraints, resulting in a structurally optimal result. In this way, Design Informatics is very complimentary to Structural Design.

Relationship between research method & design

The main objective was to define an integrated pipeline for the successful design and fabrication using the methods mentioned above. The project follows the Design by Research & Research by Design approach. This was elaborated into four sub-objectives.

Firstly, critical examination was dealt on the state-of-the-art and best practices. This was important to define the design and performance criteria of the manufacturing process and the structure. The limited documentation and standards meant that the research was based on successful precedents and ongoing tests.

Secondly, a research by design process was carried out in the mixture exploration and extruder development. Literature on clay as a construction material provided a base for the material properties of earth. However, due to their alteration because of the manufacturing process, physical tests were deemed necessary as the basis of the design. Therefore, the project is dependent on the development of the extrusion system, especially the extruder. A non-linear process ensued where material requirements and extruder abilities were tested against each other. The completion of the extruder required a significant amount of time and alterations from the initial plan, as factors such as the availability of delivered parts, the insufficient motor strength and subsequent unsuccessful print tests inhibited the expected progress.

Nonetheless, successful and consistent extrusion is paramount for the realization of the project as the mechanical properties of additively manufactured earth are unknown. In the end, a working extruder was manufactured. However, due to the Covid-19 pandemic and closing of the University facilities, no samples were able to be printed and tested for strength. Assumptions for the material properties were made according to literature and ongoing research in agreement with the mentors. Though the decided values are reasonable, their accuracy can be contested due to the lack of physical tests.

Thirdly, a design by research exploration into the formal possibilities, informed by material and manufacturing process constraints ensued. On the definition and development of the necessary steps and tools, both physical and digital workflows were defined according to the available apparatus and the technical skills of the student. While this thesis developed an optimized shell, the use of grasshopper, which is a propagation-based system and its plug-ins, resulted in a linear process, which is not as effective as a fully parametric optimization model. Though the grasshopper and scripting skills of the author were sufficiently developed during the thesis process, in the end the computational skills to link grasshopper to the evaluation software, as well as advanced structural knowledge on non-linear FEA analysis, due to the lack of available material data were unfortunately beyond the current abilities of the author and the time scope of this thesis.

Finally, a prototyping process not only for the extruder, but also for the design task was intended. However, it was not possible to be performed due to the lack of access to a robotic arm or a clay extruder. Instead, scaled PLA samples were printed by a cartesian 3D printer to investigate infill overlapping and showcase the printing process. It is still the ambition of the author to find a way to manufacture a prototype section by clay until the final submission of the thesis.

A SWOT diagram analysis of the method is composed below. In general, the research approach led to a successful definition of a workflow that covers all the necessary steps from design to fabrication, which was the main aim of the research. Parts of this workflow that depended on external factors were not able to be realized. However, they constitute an essential part of decision making during the design, as an experimental & innovative way of construction.

	Helpful	Harmful
Internal origin	**Strengths** • Technical skills • Prototyping / Testing • Tool/workspace availability • Potential partnership	**Weaknesses** • Time/budgetary limitations • Insufficient literature • Broad nature of research • Limited scripting skills
External origin	**Opportunities** • Innovation contribution • Emerging topic • Database development • Evaluative method	**Threats** • External factor dependence • Sub-optimal design • Unreliable results

SWOT analysis of methodology

Societal impact

The thesis introduces an automated workflow for the practice of construction. It is currently limited by the adoption of robotic fabrication by construction companies and legal standards. However, more and more companies, especially the ones interested in prefabrication have integrated robotic arms in their processes, as well as a considerable number of startups develop robotically fabricated structures. In terms of standards development, universities and researchers already produce research aimed at providing standards for 3D printed materials, especially in the case of concrete. Therefore, the results of this thesis will be very useful and applicable in present and future practice.

The project is aligned to sustainable development goals. The presented method achieves a significant amount of material and cost reduction, as proven by the structural evaluations, while utilizing a globally available recyclable material. Moreover, this process of construction creates significantly less waste than typical construction where formwork as well as installation work, and end of life demolition cause an immense amount of waste. Therefore, the projected innovation is realized to the extent of delivering an efficient stable structure to provide shelter and safety conditions through a responsible consumption of resources. Additional performance criteria should be developed further to ensure acceptable comfort conditions and waterproofing methods in order to extend the construction's lifespan and improve the wellbeing of inhabitants. The adoption of the proposed technologies has the potential to create new jobs, while utilizing electric energy. The repeatability offered by the setup due to its adaptive and parametric capabilities contributes to the promotion and expansion of a sustainable built environment, that inhibits climate degradation. The multidisciplinary nature of the process enhances collaboration and partnerships between all related stakeholders, facilitating local economies due to the ubiquitousness of the main material.

Social impact is embedded to all the design decisions and ambitions, especially for areas where there is no lack of space. Currently, multistorey construction is inhibited by the low strength of the material. However, part of the workflow is applicable to 3D printing with stronger materials, such as concrete, where the benefit of material use reduction is even more impactful. Concrete replacement with earth, where it is applicable, will affect lifestyles, due to different construction properties (low insulation, odor, need for maintenance). However, by utilizing local on-site materials, the unsustainable network of material transportation is addressed, while the distinctive character of each location and culture is showcased.

The use of robots in the construction industry is expected to have a significant impact in reducing the need in human labor. Moreover, this process should be gradual enough that society adapts to these changes without major issues. As these digital tools become an integral part of design to construction workflows, the boundaries between disciplines are blurred and new transdisciplinary professions emerge. The basic goal of these tools is to construct a more sustainable, safe and comfortable environment. More and more engineers educate themselves in these tools and become interested in computational design, while having more expert knowledge in their respective fields than architects. This may eventually pose a risk to architecture. However, it can also be an opportunity. As this approach integrates design and performance, architects need to find a way to take agency and penetrate these new fields, by bringing their own expertise, sensibilities and way of thinking.