LESS THE BETTER: OPTIMISING ADDITIVE MANUFACTURE WORKFLOWS FOR CONCRETE WALL CONSTRUCTION

Sustainable Manufacturing

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Abstract. Despite the technological improvement in construction industry, waste from the construction and demolition industry remains responsible for one third of all waste going to landfill (Construction Waste). Yet, additive manufacturing technology (3D printing) offers alternate and potentially more efficient ways to reduce material quantity in wall construction in the housing sector, which accordingly, can have significant impacts on the natural environment by reducing material usage and production. Concrete 3D printing is based on extruding a cement-based concrete against a trowel that allows a smooth surface finish created through the build-up of subsequent layers (Sanjayan, Nazari & Nematollahi 2019 p. 4). This research looks to redesign housing walls by optimising material which then will require different 3D printing application. To achieve this, Rhino and Grasshopper are used to build and analyse a wall structure, using Karamba3D for topology optimisation. From here a 3D printer path of the wall is generated in a G-code script that can understand when to change the nozzle size. The final stage involves connecting the optimised wall model with the G-code script by instruct the movement of the aperture nozzle as the exact same diameter size of the printing path. This paper's focus on exploring how modified 3D printing practices can address time, cost and material wastage issues contributes to the pressing imperative to investigate more sustainable design and construction practices.

Keywords. Three-dimensional printing, concrete, digital fabrication, sustainable construction, material optimization

1. Introduction: (Research context and motivations)

The research main objective is to help with opening wider thoughts about increasing the benefits of digital fabrication methods for the natural environment and social communities. Nowadays, many environmental issues are being investigated and mainly human-made activities that has a significant impact on the planet and natural habitats. Building our civilization is growing very fast, and one of the major elements of human civilization is construction. Furthermore, construction industry is a significant sector within human activities, from building small houses, to high skyscrapers. Unfortunately, Statistics show that "building construction activities have generated the largest volume of waste across the globe" (Akinade, Oyedele, Ajayi, Bilal, Alaka, Owolabi & Arawomo 2018, p. 375). For example, "China's annual output of construction waste has reached 600 million tones, accounting for 30–40% of the total amount of urban garbage" (Liu1, Gong1, Wang, Lai1 & Zhu1 2018). Not only this, some of the production progresses of these materials adversely affects the natural environment. For example, concrete production is the source of about 8% of the world's carbon dioxide (CO_2) emissions (Rodgers, 2018).

This research exploring how can we reduce the downsides of construction industry by using additive manufacturing as a main production method that allows for use of the exact required martial. 3D printing is a great tool to build unique forms, faster and cheaper, and concrete is a naturally sustainable building material which can be recycled. However, this technology is still new to the construction industry and needs more experimenting and researches to be improved and gain the most of it. The current applications of 3D printed construction are too big and heavy for such a one- or two-story house, or even an office building.

Computational manufacturing is a powerful technology than can be improved significantly by guiding it toward human needs and solving environmental issues. This can be done by exploring how to reduce a wall structure material by computational analysis tools, such as finite element analysis 'FEA'. In addition, adding an extra tool to the printer nozzle that can control the diameter size of the printing process, according to redefined G-code script that the printer can understand.

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2. Research Aims

The main objective of this research is developing a computational workflow in more than one aspects. First, guiding the engineering technologies towards architectural elements, in this case, a wall structure analyzed and optimized using FEA methods for the purpose of reducing material use within construction (Figure 1).

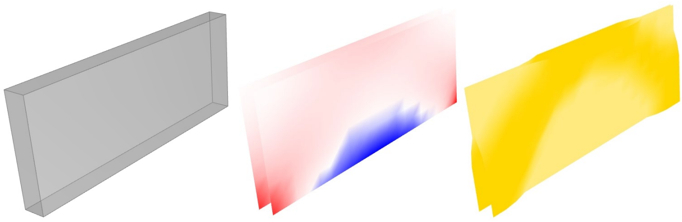

Figure 1. work process of a wall structure to reduce material use

The following aim is to improve 3D printing process by adding an extra aperture tool to the printing nozzle, that can change the nozzle's diameter within the printing process, wherever needed (Figure 2).

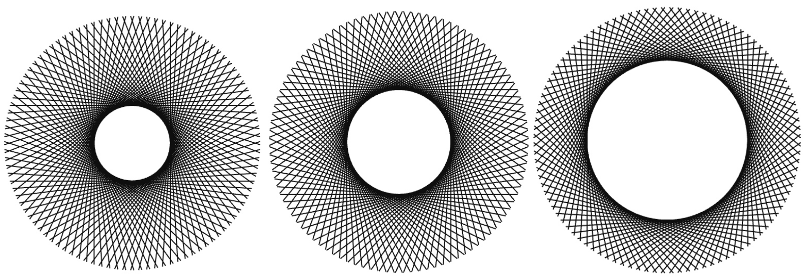

Figure 2. A digital simulation for the changeable size nozzle. Lift:3mm, 4mm, 6mm

The last goal is to join the optimised wall model and the new printing method using a modified G-code script that applies different extrusion data for different model parts depending on the extrusion diameter and the model dimensions.

3. Research Question(s)

Based on the issues outlined in the introduction and the derived aims, the question the research this project investigates is:

How can 3D printing operations be improved to achieve faster printing for an optimized wall structure?

4. Methodology

Action research (AR) is a term produced by Kurt Lewin, he explained the method as "a way of generating knowledge about a social system while, at the same time, attempting to change it" (Azhar, Ahmad & Sein 2009). To understand the meaning of AR, 'research' most be defined first. Research is defined as the creation of new knowledge and/or the use of existing knowledge in a new and creative way so as to generate new concepts, methodologies and understandings (O'DONNELL, 2012). As the global changes in cultures and emerging of new theories after World War II, new social researches were needed, especially in applied studies to fill the gap between theoretical concepts and practical problems (Azhar, Ahmad & Sein 2009)

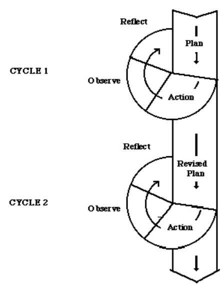

Figure 3. Action Research Protocol after Kemmis (cited in Gabel, 1995)

The characteristic cycle of AR is explained by Elliott (cited in Gabel, 1995) as:

- The Reconnaissance & General: beginning with an adopted preparatory position, where a perception of an issue is progressing, and plans are produced for "interventionary strategy"
- The Action in Action Research: the interventionary strategy is accomplished.
- Monitoring the implementation by Observation: notes and related observations in different are being collected through and around the time of the intervention.

• Reflection and Revision: “The new interventional strategies are carried out, and the cyclic process repeats” until the reach the completed understanding of the process.

This research carrying out the AR methodology by the following processes. Optimizing a wall component with analytic softwares and evaluate each result, then select the most suitable model for 3D printing process.

Understand, evaluate and test clay 3D printing to apply new improvements to the printing process. After that, designing new changeable diameter printing nozzle is needed. Then, testing different aperture mechanisms which are suitable for small size objects. After different experiments and 3D printed modules, few different deign possibilities were found for a novel 3D printing process.

The last step is to modify a G-code script for the new wall design, that can command the printer to change the nozzle size during a printing process. G-code scripts were created, evaluated and redefined to achieve a different nozzle size G-code script.

Action research is used in practical status, rather than in “contrived, experimental studies, since its primary focus is on solving real problems” (O'Brien, 1998). Therefore, this research cannot take place without a practical test to see the findings, to connect it with theoretical concept of the research such as sustainable design by reducing material use and studying new technologies abilities in construction industry.

5. Background Research/Literature review

Additive manufacturing (AM) consists several emerging technological procedures that use computer-aided designs (digital data) to concoct objects through the additive layering of material (Stein 2017)

3D printing and CNC (computer numerical control) technologies are not new in the manufacturing scale, as computers has been used in the industry since 1960’s. According to Ratto (2012), industrial rapid prototyping processes can be known as either ‘additive’ (building up material to make an object) or ‘subtractive’ (removing or cutting away material to make an object). The main concept of almost all additive techniques, such as 3D printing, is including layerization, which is ‘slicing digital models into horizontal layers and building the object up one layer at a time’ (Ratto & Ree 2012).

Ratto and Ree (2012) discussed in their article, materialization information: 3d printing and social change, how 3D printing changing the manufacturing field by open the ‘making’ principle to a wider boundary of consumers. The effects of this technology on the industry and economy are significant while a new fabrication space is now available for everyone.

Furthermore, they experimented the user's attitude with design and making for rapid prototyping.

Moreover, Ratto and Ree (2012) explained well the background of 3D printing in small prototyping scale, as they call it 'rapid', and how open sources make 3D printing reachable for everyone. However, they didn't discuss the possibilities of whether the technology can be used in the industry for large scale models rather than rapid prototyping method.

Construction automation school has been propagated through researchers and industries during the last decade, such as collaborative robotics. There are several construction processes can be associated with construction automation to build components such as walls and facades, for example, bricklaying, sprayed concrete, precast techniques and robotic milling. Furthermore, attention moves towards these novel technologies for different benefits, such as reduction in labor, construction time, production cost and also opens wider design ideas such as contemporary forms (Lim, Buswell, Le, Austin, Gibb & Thrope 2012).

Lim, Buswell, Le, Austin, Gibb and Thrope discussed the capabilities of AM (additive manufacturing) processes to produce large components, especially for construction. They compared between these techniques and how important they are to be developed for specific applications. Then they focus on the 3D printed concrete and issues behind using it in construction applications.

Although this journal wrote 7 years ago, some issues discussed of AM are still under research even when there have been important improvements in many scales such as accuracy and efficiency. For example, the difference between CAD model and reality depends on the model form and material drying time, also the nuzzle traveling path through printing which needs optimization before the process to save time. Printing complex forms still a challenge for 3D printing and can be associated with external involvement rather than being independent.

Looking at current successful cases of 3D printed constructions, Netherlands began last year to print first houses to be used commercially for habitation last year (ABC News 2018). The developers of the project claim that customization is easier and lower-priced with 3D-printed houses, as their main aim is to build 'environmentally friendly' architecture by avoiding use of natural gas connections. Moreover, this technology allows to reduce material quantify which 'reduces the CO2 emissions originating from cement production' for more sustainable environment (ABC News 2018). The article introduces the developers of the Netherlands project and promises an optimistic future of 3D printed housing system. Apparently, these houses expected to be dwelled this year, so it is still early to compare these houses with ordinary ones in real experiences.

3D printed concrete is one of the manufacturing methods which has been introduced with robots such as CNC and using various materials. Additive manufacturing of concrete is being explored and experimented by many private companies and academic schools around the world. The benefits of using 3D concrete printing are varying, such as opens design freedom, mass customization and reduction of CO2 footprint, physical labor and material use (AHMED, FREEK, WOLFS & SALET 2016).

Although 3D printing manufacturing has numerous benefits, there are several adjustments can be applied to improve the printing behaviors. There are many research projects that exploring remodifying G-code for different purposes, such as creating new 3D printed forms or improve the process by using non-planer printing. For example, Emerging Objects has explored how to write G-code, to create printing outside the actual boundary, which provides interesting forms that different from the digital model (2016).

In the case of concrete 3D printing, there are several occurring problems that many research organizations globally working with developing this process in a large scale. Buswella, Leal de Silvab, Jonesc and Dirrenberger discuss in their article 3D printing using concrete extrusion: A roadmap for research, current examples of 3D printed concrete and issues appear with this process (2018). For example, the different results from using different nozzles form and the extrusion speed that effect the result significantly. They didn’t explain issues with amount of material used, such as how different printing methods can affect the amount by ether reduction or addition.

6. Case Study

The case study explores the current applications of concrete 3D printing in the architecture industry and examine the abilities of computational methods to improve construction practices by using additive manufacturing. Analysis softwares were used for the purpose of minimizing material quantity in a wall structure. For the improvement of 3D printing process, a clay 3D printer was tested to understand the printing process, therefor, to design a different printing method that can benefit the printing process. Given this, a new 3D printer tool was designed to achieve a novel understanding of 3D printed construction. Finally, this research explored G-code for 3D printing and how to modify G-code for novel printing way.

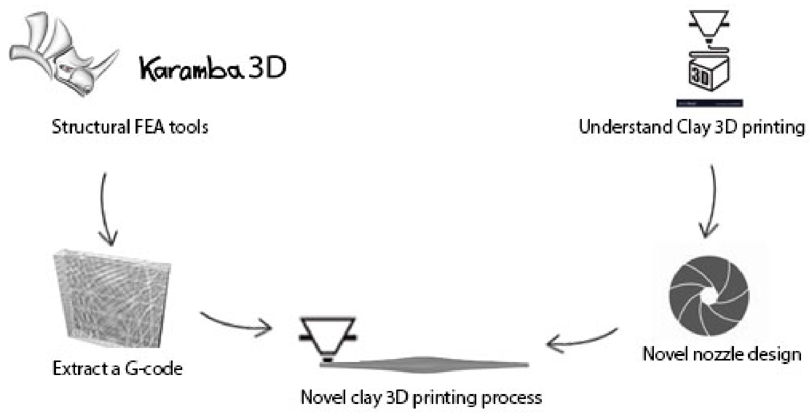

Figure 4. Research steps are mainly two parts: digital structural analysis and physical improvement for 3D printer nozzle

The wall structure was analyzed by finite element analysis method, using computational techniques. The results were more complex forms than a normal wall form, which make 3D printing as a preferred construction technique. To gain the most benefits from 3D printing, for more efficient process, a new additional printer tool was introduced. The tool is added to the printer nozzle, which is an aperture-like mechanism that allows the nozzle to change its diameter within a printing process.

6.1 FIRST ITERATION

The first iteration includes investigations within the first two main objectives, wall material optimization and novel nozzle design, and an introduction to G-code.

6.1.1 Wall Optimization

The first stage of this research is to modify a wall form for the purpose of reducing material quantity. To do so, an analytic software needed to be used to analyse the structure and reducing material quantity according to material type, wall dimensions and modified load.

First program used was Karamba3D which is a plugin in Grasshopper Rhinoceros 3D. a simple wall design were used to test the abilities of this software and how it does change the form. The first result didn't work in Karamba as the surface used were in different thicknesses and the components allowed choosing only one thickness.

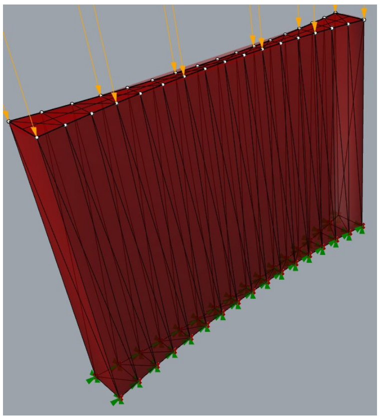

Figure 5. First wall structural analysis in Karamba using shell components, showing no results

Another software used was Autodesk Inventor 2020, it is a software used mostly for engineering rather than architecture. The inputs were load applied quantity and direction, strict regions (not to be changed in form), supports, and reduction percentage (how much material to remove). There was a resulted wall that has less weight with holes, as Inventor does hard-kill, which means it removes material from certain spots instead of reduce thickness. (figures show different steps).

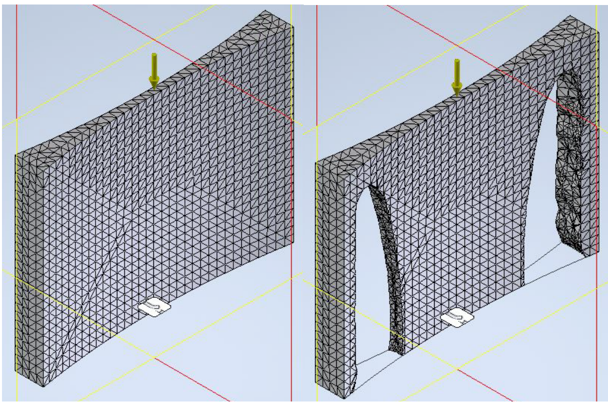

Figure 6. Autodesk Inventor 2020 result from the structural analysis

6.1.2 G-CODE DEVELOPMENT

After modifying the wall form, a G-code script needed for the 3D printer. The purpose of modifying G-code is to apply different thicknesses along the wall form, for the 3D printer to change the nozzle diameter according to the printing path.

To achieve this, Rhinoceros and Grasshopper 3D were used, in addition to Xylunis plugin. The inputs used are the printer specifications such as extrusion width, layer height, temperature, and extrusion speed. At this stage, this script is for one nozzle diameter.

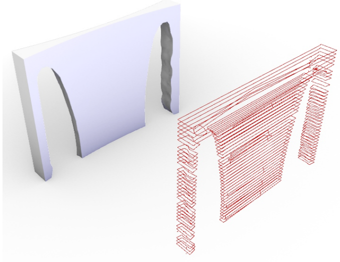

Figure 7. A G-code script from the resulted model from Inventor

6.1.3 Aperture design

To understand the process and evaluations of 3D printed concrete, a clay 3D printer was tested to see how it can be improved and propose solutions for future directions. The printer was Potterbot XLS-2, a large-scale clay 3D printing arm with different size print nozzles, ranged from 4-8mm.

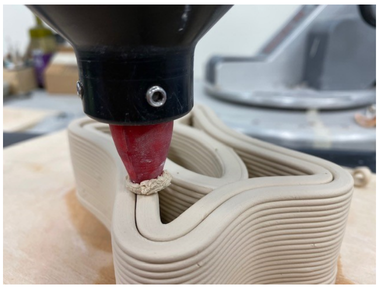

Figure 8. testing the clay printing process to understand how it can be improved

In order to achieve different diameter printing process, the printer nozzle was redesigned. To start with the new design, an aperture mechanism was chosen to be added to the 3D printer nozzle. After understanding the mechanism, there were different types and 3d model designs of apertures that available online, ether buying one or 3D print it. Different 3D printed models were tested to see what design works, after trying several options, many didn't work for ether a wrong size or complexity which leaded to failure of movement or work.

Figure 9. Different printed modules to test the several possibilities to improve the printing nozzle

A new design was made with corporation of Grasshopper3D and Solidworks, as Solidworks is a perfect software for industrial design, that allows some features such as Thread Cut and lofting for small objects.

Figure 10. The first 3D printed aperture to test the movement

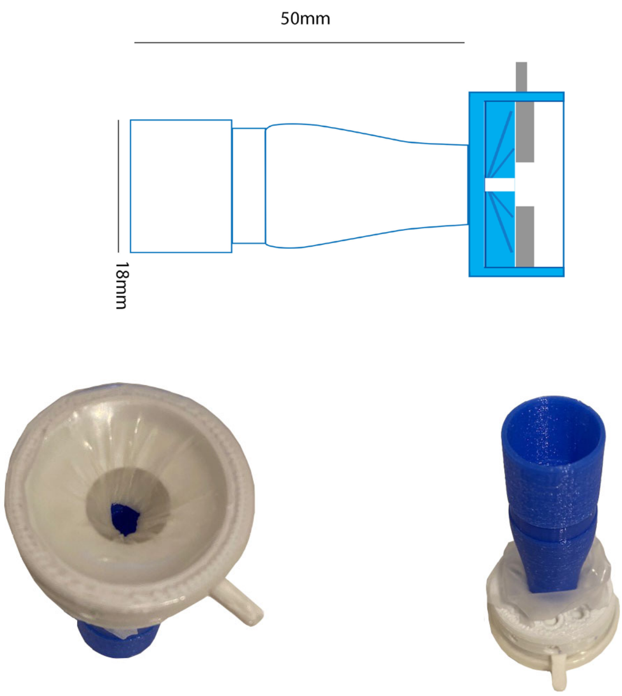

Figure 11. First nozzle design with elastic layer to prevent clay leak into the small parts

The first iteration worked and moved but was hard and slow moving. The inner aperture arms were a little too thick and large for the size of the holder (Figure 10). This design creates more distance between the extrusion hole and the printing surface which can affect the texture and form of the printed object. In addition, the ring that moves the aperture arms makes the movement limited because of its form.

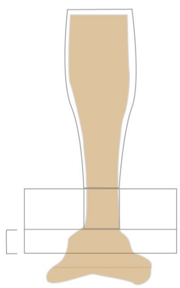

Figure 12. Showing the distance between the extrusion hole and the printing surface

The second iteration of the nozzle design was made by fixing the aperture arms size, reduce their thickness to 0.5mm. The moving ring was modified to a sharper angle design (Figure 11). After modifying the aperture nozzle design, the movement was more smooth and the size of the extrusion hole can be reduced to minimum and increased to maximum.

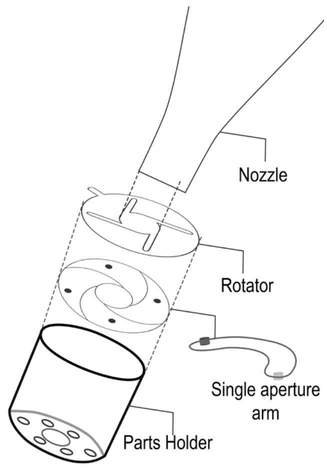

Figure 13. Exploded view for the novel nozzle design

After exploring the first design, more few other designs where explored, for the purpose of future work and what are other possibilities to redesign a 3D printer nozzle. These designs don't use aperture mechanism, but can produce a similar result. The nozzle extrusion hole has been cut in the middle (Figure 14) and bolts and nuts were added in both sides which can control the extrusion width by twisting the bolts in or out (Figure 14).

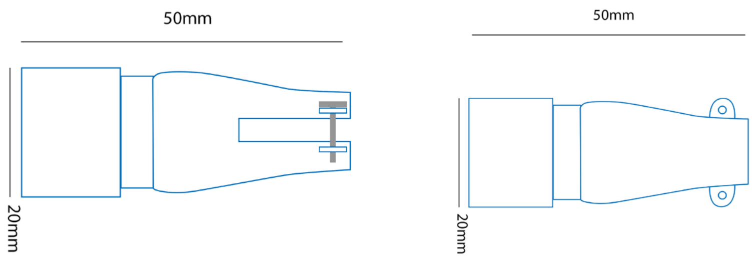

Figure 14. Different side views for the second nozzle design

The third design has a similar idea to the previous model, but instead of bolts, using extra piece was added to control the hole size by twisting this piece inward to reduce the hole size, or outward to increase it (Figure 15).

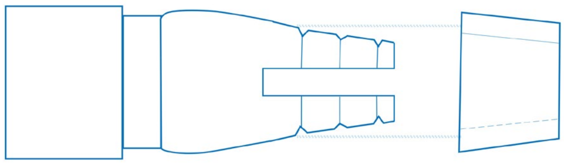

Figure 15. Side view of another possible design idea

There is a high possibility that these three designs can work with 3D printers, when using more efficient materials and improved design. The aperture design has more assembly pieces, but gives more accurate results when changing the size is faster. The other non-aperture designs have a similar idea, both are less complex and need only a twist to change the size of the extrusion hole. Furthermore, the distance between the extrusion hole and printing surface is similar to the current clay 3D printer nozzles, which will avoid changing texture and form while printing.

6.2 Second iteration

The second iteration includes more accurate results and investigation within the wall structural optimization and the G-code modifying.

6.2.1 Wall Optimization

In the second iteration of the wall analysis section, Grasshopper was used with different Karamba and Ameba components. Karamba and Ameba are both additional plugins for Grasshopper, and they usually used for structural analysis. Karamba analyses architectural structures by using inputs such as material, cross sections, load, supports type and joints. It does understand lines only, from a geometry, or single surfaces, thus it was hard at the beginning to analyse a different thicknesses structure.

However, there is a different way to achieve reducing material quantity using Karamba. It requires starting with a simple rectangular wall form, then after analysing it, it can be reformed by using BESOShell components to modify form using inputs such as reduction percentage and minimum thickness. The modified form results with only 2 main thicknesses. The result is two mesh surfaces on each wall side, instead of solid geometry (Figure 16).

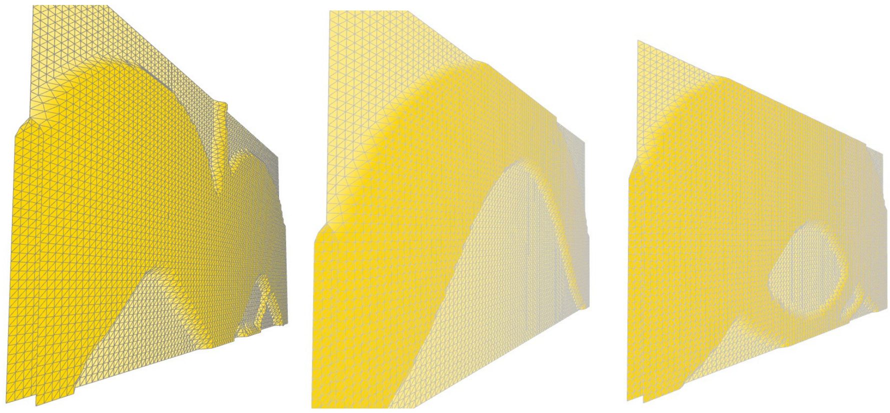

Figure 16. Different types of Karamba results from several percentage reduction values, from left 50%, 30% and 20%

Another method used with Grasshopper was Ameba components. Ameba reduce material by using hard-kill, which means removing material instead of reduce thickness. Ameba's results were more complex forms than Karamba, and produces solid meshes when using 3D components. Ameba didn't work softly as the Grasshopper script crashes every time when opening it, thus couldn't document the results.

6.2.2 G-code Modification

After finding the suitable wall form, a script in Grasshopper were used to extract and modify a G-code printing pathway for clay 3D printer. The important inputs in this script are the printing speed for the extrusion and movement, extrusion width, layer height, and infill ratio. The resulted mesh from Karamba has been converted to a “closed breb” which means it is a closed solid form instead of two mesh surfaces.

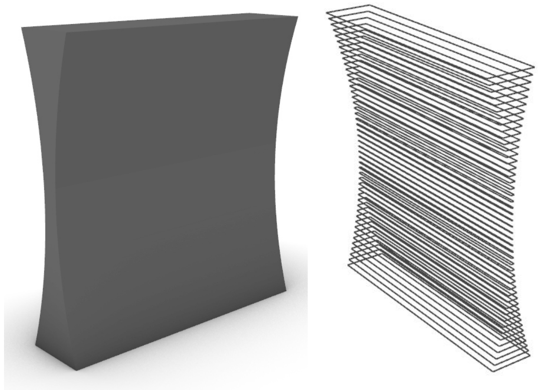

Figure 17. A simple wall design with different thicknesses and a G-code script from it

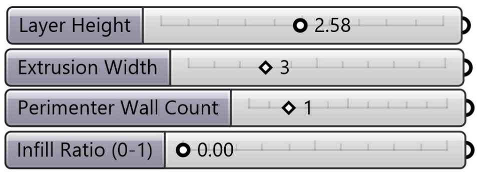

Figure 18. The main variables used to adjust the printing pathway were four main sliders in Grasshopper

The main issue at this stage was producing a G-code script but with different extrusion information for different parts of the wall depending on the part thickness and form. Currently, there are not enough sources for defining several extrusion commands in one printing process in a G-code script. Therefore, ether to draw the printing path manually, or use more than one G-code scripts to determine different information for each part (Figure 18). To do so, a simple wall model was tested to understand how printing pathways can be defined with more than one extrusion commands (Figure 17).

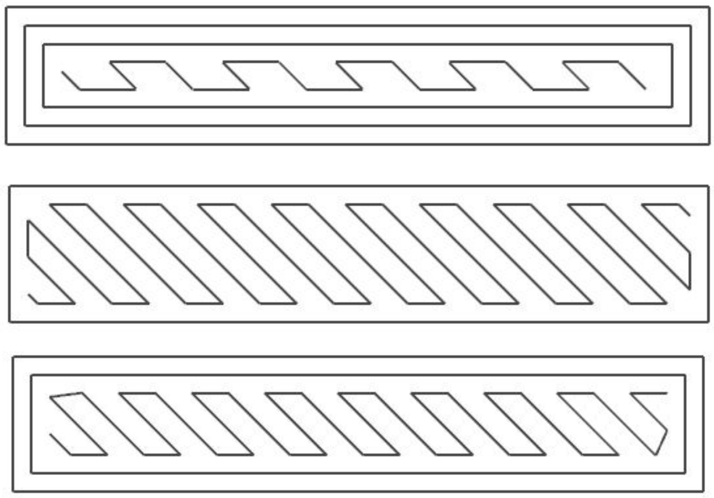

Figure 19. The g-code pathway layer for the base of the wall model, but with different inputs values, such as perimenter wall count and infill ratio

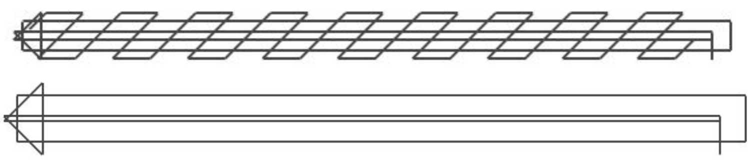

Figure 20. Problems found in the meddle part of the wall, as it is the narrowest, the printing paths are intersecting while ether increasing the wall count or the ration infill.

This wall model could be printed by using smallest possible nozzle size, but the printing process will be longer. Therefore, a modifying G-code script needed here to save printing time by using different printing information in each different part (Figure 10).

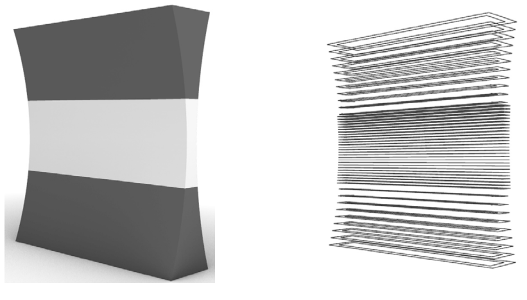

Figure 21. the wall model has been divided into 3 parts to produce 3 different G-code scripts. Left: divided wall model. Right: 3 G-code scripts

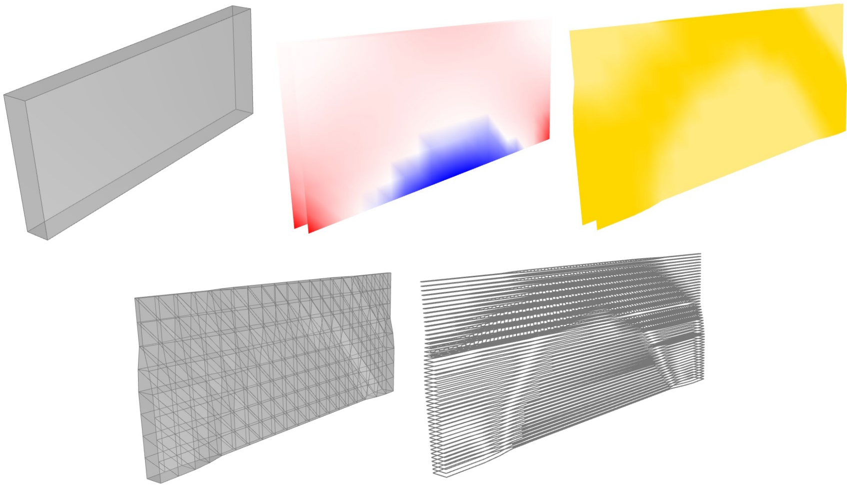

Figure 22. The process of developing a wall structure from karamba to produce G-code scrip

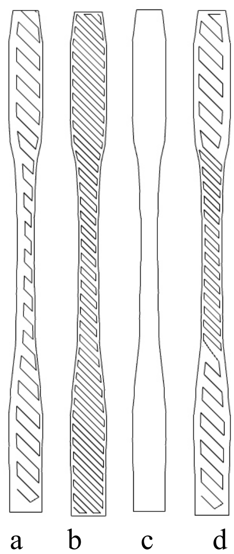

Figure 23. This graph shows how effective to modify G-code before printing with different options

The importance of modifying G-code is to reduce printing time. From Fig9, the shape ‘b’ is the result of smallest printing nozzle size (1mm) and the length is 2008.8mm. While the modified printing path, shape ‘d’, is about

15046mm with 2 different sizes, 1mm and 3mm. The saved printing time is nearly 25%.

6.2.3 APERTURE SIMULATION

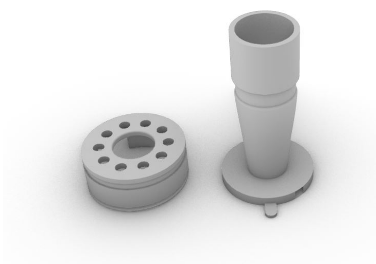

Figure 24. 3D model of the aperture nozzle design

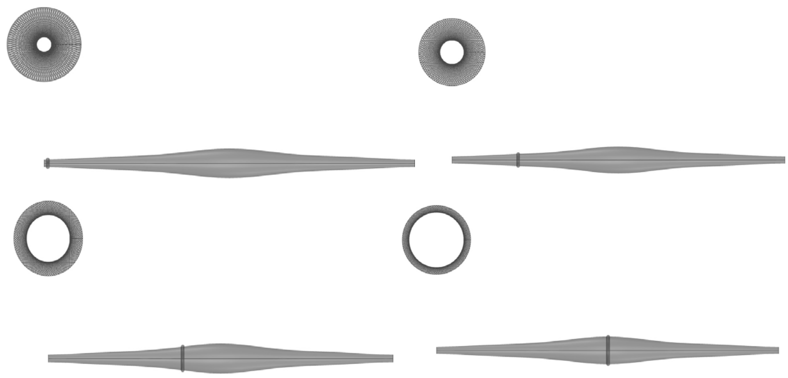

Figure 25. Simulation of aperture nozzle when printing different thicknesses line

Figure 25 shows how the aperture nozzle can change its diameter according to a single line different thicknesses.

7. Discussion (evaluation and significance)

This research has explored the benefits of using 3D printing in the construction industry. The has explained possible methods of using this technology by material optimisation of a wall structure, and reducing material use during printing process.

The outcomes of this research are first, a wall structure that has been analysed and material optimised and suitable for concrete 3D printing.in addition, design a concrete 3D printing adaptive nozzle that can change size according to the model layer thickness and height. Finally, a digital method of turning geometries forms into g-code script and then into a command script of the nozzle diameter to change printing process according to the geometry. The concept of digital wall material optimisation and concrete 3D printing adaptive nozzle is possible.

The limitations are first, time was a challenge for further experimenting and comparison within other fabrication tools such as robotic arms or CNC, also testing 3D printing with different nozzle design. Furthermore, the finite element analysis tools for architecture are is not enough qualified for suitable material optimisation, they are rather great for engineering more than architecture. In addition, clay 3D printer that used has some limitation in term of mechanical aspect, such as printing within continues line and respond to commands.

There are different research directions can be taken from this project. The main concept is how to use digital fabrication tools in order to reduce material quantity in construction industry, not only considered as rapid and cheap methods. For a concrete 3D printer, it does need to be redesigned mechanically, and define a G-coding system suitable for adaptive nozzles machine.

8. Conclusion

Material optimization for a simple rectangular wall component can significantly reduce construction waste practices and material quantities. This can be done by using analytic software to analyze a wall model using applied load, material cross section, material type in general. The resulted wall models were more complicated forms rather than a simple geometry. Given this, additive manufacturing is necessary as it prints complicated forms more accurate and faster than traditional construction methods.

Additive manufacturing within the construction industry needs improvements for more sustainable process. In this case, using changeable size printing nozzle were necessary to achieve time saving printing for complex forms. After several tests for 3D printed nozzle modules, few different designs were proposed for further experimenting.

After finding the required optimized wall design, a G-code script used to convert the geometry to printing pathway for 3D printing. This script needed adjustments and remodifying to achieve the adaptive printing process. There is no current solution for extracting a single G-code script for different diameter size nozzle, which can take a further research for future experiments. However, more than one G-code scripts were made to understand the different method for converting a model with different layer heights and extrusion widths.

The main research aspects were reducing material use with computational analytic tools, and applying digital fabrication methods to achieve resulted form. One of the key finding is remodifying form of a building component is very effective, in term of saving material quantity. In addition, the resulted complex forms can be built more efficiently with additive manufacturing machines as they are curved and complex. Saving printing time is another important finding, using different thickness printing nozzle can effectively reduce printing time.

Future work is to improve G-coding to understand changing nozzle size within single printing job. In addition, improve 3D printer's nozzles to print finer forms with different nozzle size. This research helps with opening wider thoughts for applying novel fabrication methods, to achieve sustainable environments and social communities.

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