DEVELOPING A DESIGN FRAMEWORK FOR THE 3D PRINTING PRODUCTION OF CONCRETE BUILDING COMPONENTS

A case study on column optimisation for efficient housing solutions in Saudi Arabia

MOHAMMAD ALABBASI, HAN-MEI CHEN, ASTERIOS AGKATHIDIS
University of Liverpool

EMAIL ADDRESS: M.ALABBASI@LIVERPOOL.AC.UK
HANMEI.CHEN / ASTERIOS.AGKATHIDIS @LIVERPOOL.AC.UK

Abstract. This paper is examining the development of a design and fabrication framework aiming to increase the efficiency of the construction of concrete building components by introducing 3D concrete printing in the context of Saudi Arabia. In particular, we will present an algorithmic process focusing on the design and fabrication of a typical, mass customised, single-family house, which incorporates parametric modelling, topology optimisation, finite element (FE) analysis and robotic 3D printing techniques. We will test and verify our framework by designing and fabricating a loadbearing concrete column with structural and material properties defined by the Saudi Building Code of Construction. Our findings are highlighting the advantages and challenges of the proposed file-to-factory framework in comparison to the conventional construction methods currently applied in Saudi Arabia, or other similar sociopolitical contexts. By comparing the material usage in both conventional and optimised columns, the results have shown that material consumption has been reduced by 25%, the required labour in the construction site has been mitigated by 28 and the duration time has been reduced by 80% without the need for formwork.

Keywords: *Building Technologies; Additive Manufacturing of Concrete; Housing Construction; 3D Printing; Topology Optimisation; Parametric Design.*

ملخص. تبحث هذه الورقة في تطوير منهجية لأتمتة عملية التصميم والتصنيع بهدف زيادة كفاءة البناء الخرساني باستخدام الطباعة الخرسانية ثلاثية الأبعاد في سياق منظومة صناعة البناء في المملكة العربية السعودية، قمنا بتطوير خوارزمية تركز على تصميم وتصنيع فيلا سكنية، يمكن للمستفيد من تخصيصها وتصميمها حسب احتياجه بناء على عدد أفراد أسرته من خلال عرضها بشكل ثلاثي الأبعاد ، تعتمد هذه الخوارزمية على نظام النمذجة البارامترية، وتحسين الهيكل الانشائي، مما يتيح تهيئة العنصر المحسن لعملية طباعة

الخرسانة باستخدام الروبوت. سنقوم باختبار إطار العمل الخاص بنا والتحقق منه من خلال تصميم وتصنيع عمود خرساني مسلح بما يتوافق مع كود الانشاء للمباني السكنية بالمملكة. تسلط النتائج التي توصلنا إليها الضوء على مزايا وتحديات منهجية الدراسة المقترحة -أتمتة التصميم والتصنيع- و مقارنتها بأساليب البناء التقليدية المطبقة حاليًا في سوق البناء السعودي ، من خلال مقارنة كمية استخدام المواد للأعمدة في عملية البناء المسلح والمنهجية المتبعة في هذه الدراسة عن طريق تحسين الطبوغرافية بما يتلاءم مع الطباعة الثلاثية الأبعاد، حيث أظهرت النتائج أنه تم تقليل استهلاك المواد بنسبة 25% ، وتم تخفيف العمالة المطلوبة في موقع البناء بمقدار 28% وتم تقليل المدة الزمنية بنسبة 80% مع الأخذ في الاعتبار عدم الحاجة إلى استخدام قوالب خشبية لصب الخرسانة.

الكلمات المفتاحية: *تقنيات البناء- المباني المطبوعة- أتمتة التصميم- الإسكان- أتمتة البناء.*

1. Introduction

The typical construction method used for housing construction in Saudi Arabia in current days is the in-situ fabrication of reinforced concrete. This method has shown many inefficiencies for such as high labour force demand, lack of construction quality and high time demand (Theodore Karasik, 2017). Moreover, prefabrication in the housing construction industry is uncommon due to the high cost and lack of customisation. The average Saudi homeowners prefer to live in a house designed for their particular needs, rather than to live in a standardised house (Alqahtany and Mohanna 2019; and Alhubashi 2018).

In 2016, the ministry of housing had announced a new delivery plan, which targets building half a million residential units to increase housing ownership (Saudi Ministry of Housing, 2016). As the main factors behind housing shortage are construction delays and lack of labour force (Alhajri and Alshibani, 2018), the Ministry of Housing in Saudi Arabia has sought to establish an initiative to support novel construction technologies and made contracts, as part of its contribution to the National Transformation Plan 2030. The targets of these contracts are to raise the ownership rate from 24% to 52% (Government of Saudi Arabia, 2016).

Having identified the main challenges and reviewed the requirements of the Saudi Concrete Building Structures (SBC 304), the proposed design-to-fabrication framework will adopt its requirements and specifications for the production of 3D printed reinforced concrete components. Accordingly, we will develop a parametric reinforced-concrete frame structure of a typical Saudi Villa. One of the columns will be optimised and analysed under an axial load of 31kN/m^2. As mentioned in SBC 304, the concrete's compressive strength should not be less than 20 MPa (SBC Committee 304, 2007). Therefore, we chose to use C40 concrete in the optimisation process.

This research examines how robotic technologies and additive manufacturing techniques can be implemented in the current construction setting of Saudi Arabia in order to optimise the production of housing construction components. Our research aims to improve construction cost-efficiency by decreasing material consumption and cost of labour as well as increasing the productivity and construction quality. Our research objectives include eliminating the waste of formwork materials, reducing labour intensity, and reducing the construction time by using robotic technology. In particular, we will investigate the application of robotics in construction in order to increase construction efficiency and reduce construction time, thus reduce construction cost. Consequently, our research questions are as follows:

- How can we develop a design and fabrication framework for a typical single-family house in Saudi Arabia?
- How can the use of robotic technologies increase construction efficiency in Saudi Arabia?
- How can the reinforced-concrete frame structure of such a house be optimised and prepared for 3D printing?

The above questions will be answered in three phases: a) developing a design to fabrication framework for a typical single-family house; b) using this framework to design, optimise and analyse of 3D printed load-bearing concrete column; c) verifying its efficiency, by simulating the fabrication process of the column and compare it with a conventional fabrication process.

2. Background and Literature Review

2.1. ADDITIVE MANUFACTURING IN CONSTRUCTION

Additive manufacturing (AM) of concrete technologies, well known as cement-based 3D printing, have been developing rapidly in the past decade and are continuously proving their potential to rationalise the construction industry. AM of concrete can produce high accuracy building components in cost and high time-efficiency (Mechtcherine et al., 2019). The amount of required labour can be reduced accordingly. Most of the AM applications in the construction industry implement an extrusion-based material technique to create concrete layers, based on sliced CAD geometry (Buswell et al., 2018). This approach enables more flexibility to construct complex geometries without requiring a mould to cast concrete (Comminal et al., 2020).

The application for AM of concrete can be performed either in-situ or as a prefabricated component. A common technique of in-situ 3D printing concrete in-situ focuses on the fabrication of building walls as performed in the BOD building by COBOD in Denmark; Studio 2030 by CyBe in Saudi Arabia; and Dubai municipality building by ApisCore in UAE. These precedents are just indicators of the existing possibilities. However, there is a clear gap between buildings regulations and AM technologies, which required an approach to link these two sides.

The applications of AM in construction demonstrated advantages over conventional construction method. One such advantage is the reduction of construction time and cost. Other significant advantages are the increase in the health and safety standards of the construction workers as well as the formal freedom made available to architects enabling the implement complex design (Hager et al., 2016). However, one of the limitations of AM in construction is the lack of a comprehensive design to fabrication framework enabling the direct link between design product and its fabrication process (Kontovourkis and Konatzii, 2018). Buswell et al. 2018 observed another key challenge, which is the geometry compliance with material proprieties.

2.2. TOPOLOGY OPTIMISATION FOR ADDITIVE MANUFACTURING

Topology optimisation (TO) is a mathematical method of geometrical connectivity to optimise the performance of the structural system based on a given load and boundary (Leary, 2020). The implementation of TO in construction is not new. TO has been used to increase the cost-efficiency by maximising the stiffness and minimising material use in structure (Kontovourkis et al., 2020).

One of the first examples of TO in architecture is “Illa de Blanes”, a multi-space project in Spain. A digital evolutionary structural optimisation technique (ESO) was implemented in the project. Another example of a project utilising TO application is the Akutagawa office building in Takatsuki in Japan by f-tai architects, with the collaboration of structural engineer Hiroshi Ohmori in 2005. The building consists of four storeys. In this project, the extended evolutionary structural optimisation (ESO) method, was implemented as the primary optimisation process. The implementation of the ESO technique defined the shape of the walls in the building. Its architectural and structural design succeed to work in unison with the building’s facade. Other structural factors such as live, dead and earthquake loads were taken into consideration as part of the optimisation process. The final result of the TO was verified in an elastoplastic numerical model, based on structural deflections and cracking patterns (Januszkiewicz and Banachowicz, 2017). Its structural frame was made out of reinforced concrete. It required the use of a complex formwork, which is one of the limitations for implementing TO in architecture using the conventional construction method (Donofrio, 2016).

Furthermore, the Qatar National Convention Centre (QNCC) in Doha is another realised project utilising a TO technique by Ohmori and Saski in 2011 (Januszkiewicz and Banachowicz, 2017). The project developed the extend ESO method (XESO which was applied to the buildings large roof (36m wide x 150m long). Buro Happold consultancy, the project’s engineers integrated parameters such as constructability and rationality of the geometry are within the design process. Thus, the optimised geometry was simplified, and the steel frame structure was proposed to speed up the construction process and reduce construction cost (Donofrio, 2016).

A voxel-based 3D model is often used in topology optimisation to create an efficient lattice structure. The word voxel stands for the representation of a pixel in 3D. The voxel 3D model is a representation of volume, not a series of boundaries. Thus, material distribution can be more efficient. In a weak area, the density will be increased and in a robust area, the density will be reduced (Bacciaglia et al., 2019; and Aremu et al., 2017).

Consequently, to the precedence presented here, we have decided to use the TO method known as ‘material distribution and boundary variation method’. It allows optimal material distribution in the optimised structure. This approach consists of the homogenisation method, Solid Isotropic Material with Penalisation method (SIMP) and ESO (Abdi, 2015). It will also be combined with voxels-based modelling, to predict the optimum material distribution/robustness based on the given variables. In broad terms, the material distribution approach is an element-based method which uses optimisation algorithms with the finite element method in order to provide a solution for a structural element, with design parameters acting as the components, or properties of the components (Bacciaglia et al., 2019). This approach is shown to be useful in topology optimisation applications when it comes to ascertaining optimal structure. Moreover, additive manufacturing technology will be used as a fabrication tool in our case study. Our aim is that by combining AM of concrete and TO we will reduce inefficient use of materials, increase safety, quality, and productivity in a construction site.

3. Research Methodology

The work presented in this paper consists of three main phases (Figure 1). Firstly, developing a design to fabrication framework for a typical single-family house using Grasshopper, Karamba plug-in, to create a parametric finite element model (FEM) for reinforced frame structure. This phase includes defining the boundary of the column, for topology optimisation, using the same dimensions used in the simulated parametric house. Secondly, testing the framework by optimising a load-bearing column, using the topology optimisation tool Millipede. Finally, 3D printing preparation of the result, using a robotic simulation tool, RoboDK, to generate robotic instructions through G-code.

We will verify this process by testing one column and compare its efficiency (material waste, labour demand, and construction duration) with a column which has been designed and fabricated conventionally. We will only focus on the load-bearing system. Walls and finishes are not part of this research.

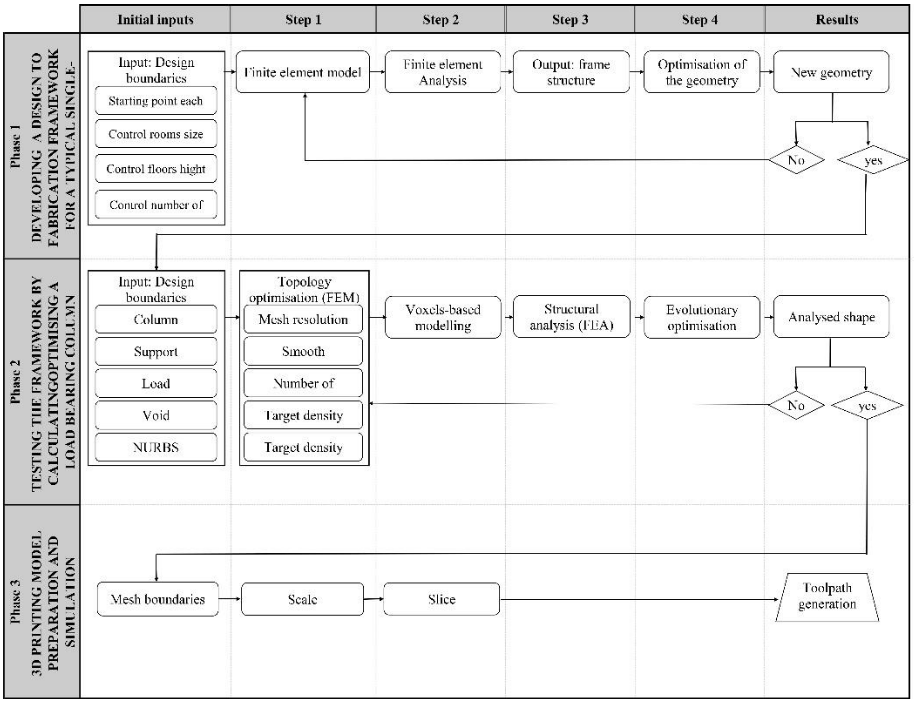

Figure 1. The workflow of the proposed design-to-fabrication framework

3.1. PHASE ONE: DEVELOPING A DESIGN TO FABRICATION FRAMEWORK FOR A TYPICAL SINGLE-FAMILY HOUSE

As a starting point, we have used the floor plans of a typical, Villa, single-family house, obtained from ‘Khatib and Alami’, an engineering consultant company working with the Saudi Ministry of Housing. We have then parametrised the house, using Grasshopper and its structural simulation tool Karamba (Figure 2). Thus, the plans can be adapted to different building sites and user needs, by adjusting parameters such as room size, floor height and number of stories (Figure 3). The algorithm produces a finite element model (FEM), which represents the framed structure of the house. The FEM is calculated according to properties set by the Saudi Building Code, such as material selection and structural performance. In addition, the house can be subdivided to individual structural rooms and their building components, such as columns, beams and slabs. In the next phase, the individual structural components are being topologically optimised and structurally verified.

Finally, the components are being contoured, and the 3D printing process is being simulated.

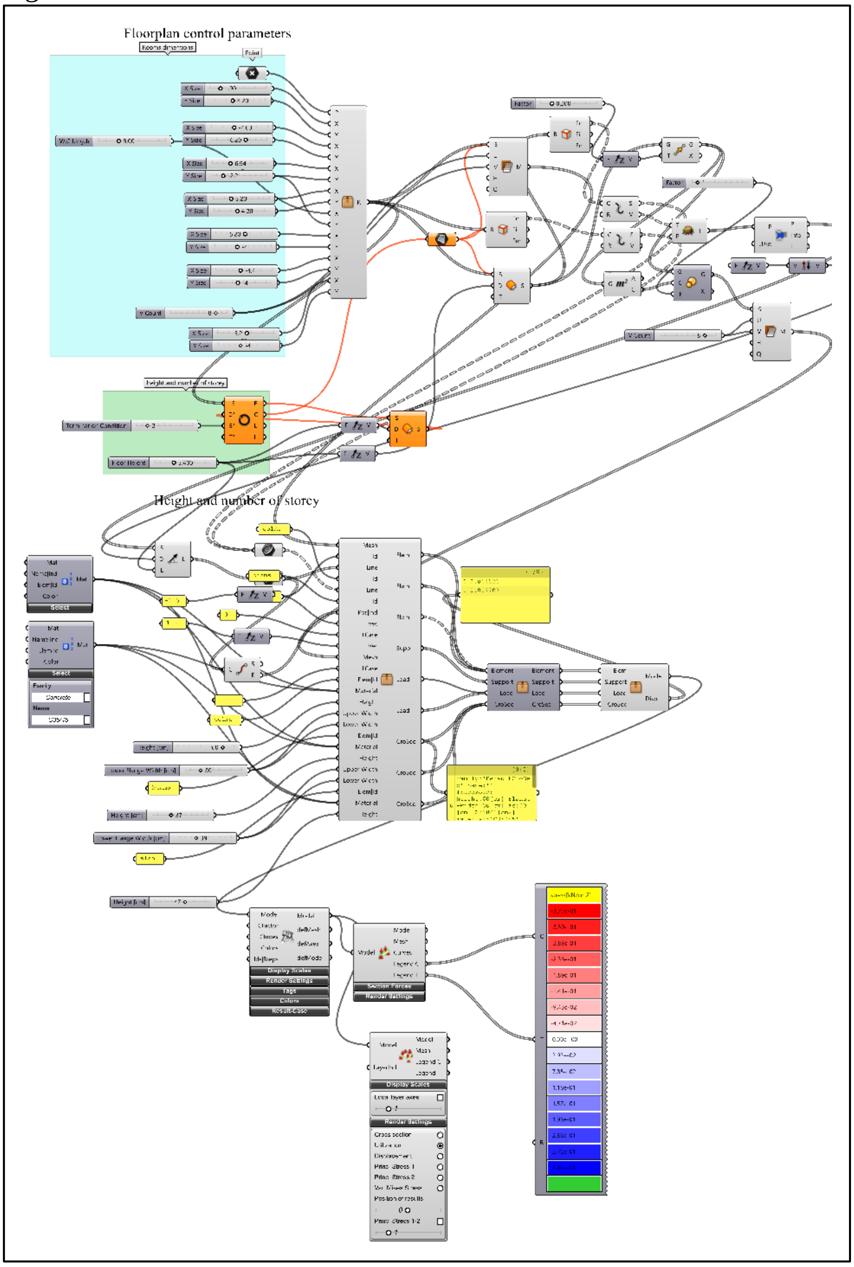

Figure 2. Grasshopper algorithm including floorplan control parameters

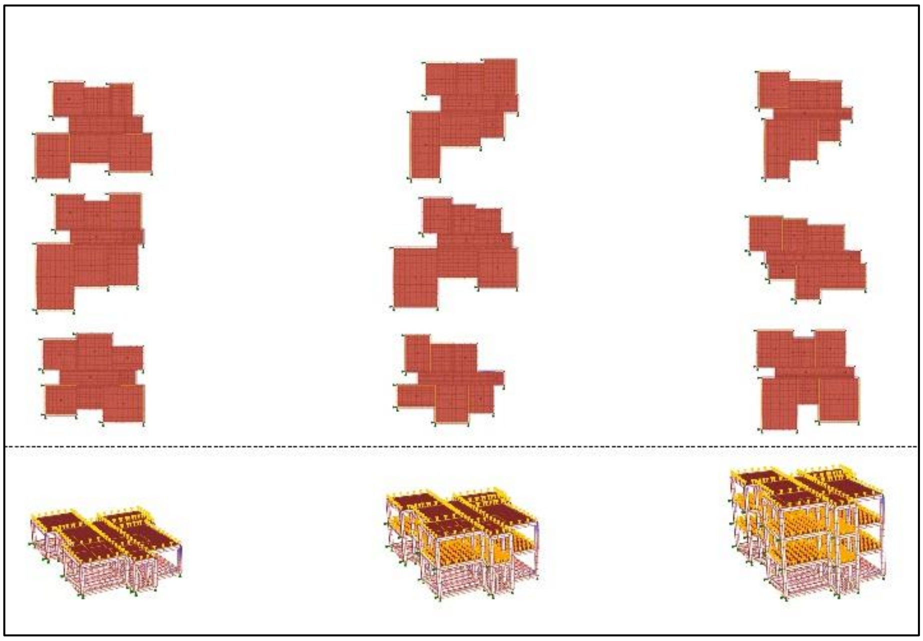

Figure 3. Different iterations showing the parametrisation of floor plans and the number of stories

3.2. PHASE TWO: TESTING THE FRAMEWORK BY OPTIMISING A LOAD BEARING COLUMN

The topology optimisation and verification of the column have been conducted through three steps sequentially including 1) defining the column boundaries; 2) topology optimisation; 3) structural verification. The column boundaries were defined as a surface box with diminution of 0.3 m × 0.6 m × 3.4 m (width × length × height). A C# script has been developed to outline the direction value (u, v) of the shape. The surface of the column was transformed into NURBS to define the frequency and amplitude and use these values as part of the optimisation process (Figure 4).

The model is then fed to the topology optimisation processor (Millipede plug-in). The applied load on the column was calculated as part of the FEM for the house that has been described in Section [3.1]. Thus, due to the fact that Karamba's units are different from the units of the inputs in Millipede, the calculated load is multiplied by 1000 to convert from kN to N.

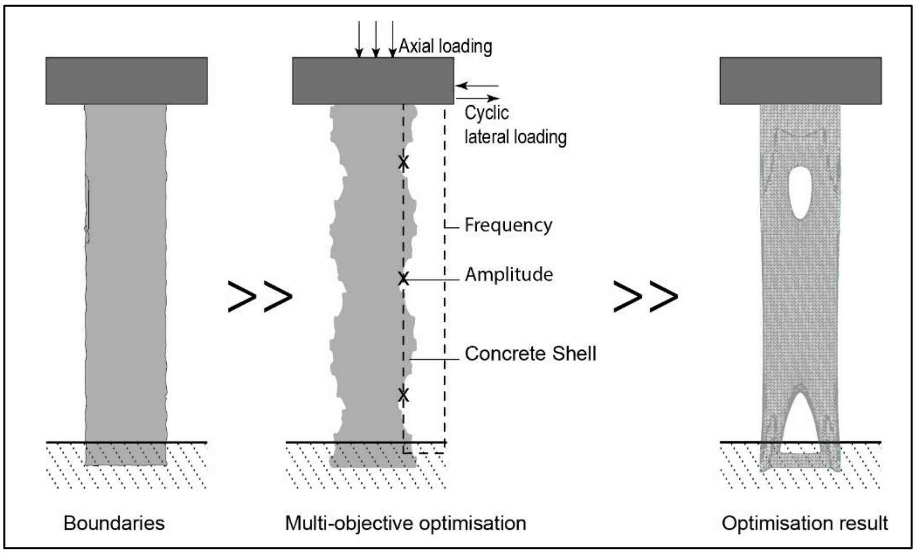

Figure 4. Defining the NURB boundaries of the column, then identifying loads and optimisation objectives

Moreover, the optimisation process works for distributing materials with minimum stress to subtract material accurately. The voxelisation based method was used, taking the advantages of the Monolith plug-in in Grasshopper. In the final step, the optimisation parameters were inputted into the evolutionary solver Galapagos, which is a heuristic solver that compare approximate solutions because the exact solution cannot be detected (Tedeschi, 2014), using genetic-algorithms in our case study. The inputs variables in Galapagos include the amplitude, frequencies, number of optimisation iterations, target density, and material density. The Galapagos solver compares different results based on the inputs variables, aiming to maximise structural stiffness and minimise structural deflection as well as coming up with optimum solutions.

In order to ensure that the Millipede plug-in can operate efficiently, the x-axis mesh resolution along had to be 12, which voxelised the main boundaries and created the primary FEM. The recommended value based on the software guidance should be between 12-40 because this number can drastically affect the time and memory consumed during the optimisation process.

After running Galapagos to compare iterations and coming up with an optimum solution based on minimum structural deflection, Karamba plug-in in Grasshopper has been used to verify the optimised structures. The structural performance performed using FE simulation based on the Saudi building code (SBC Committee 304, 2007). The column was tested using C40 concrete with a vertical load of 31.2 kN/m^2, and set fixed support for the base. Karamba simulation engine allows the visualisation of stress on structural elements. The minimum stress for the resulted structure is 2.00e-02 kN/cm^2, and the maximum stress is 5.00e-01 kN/cm^2.

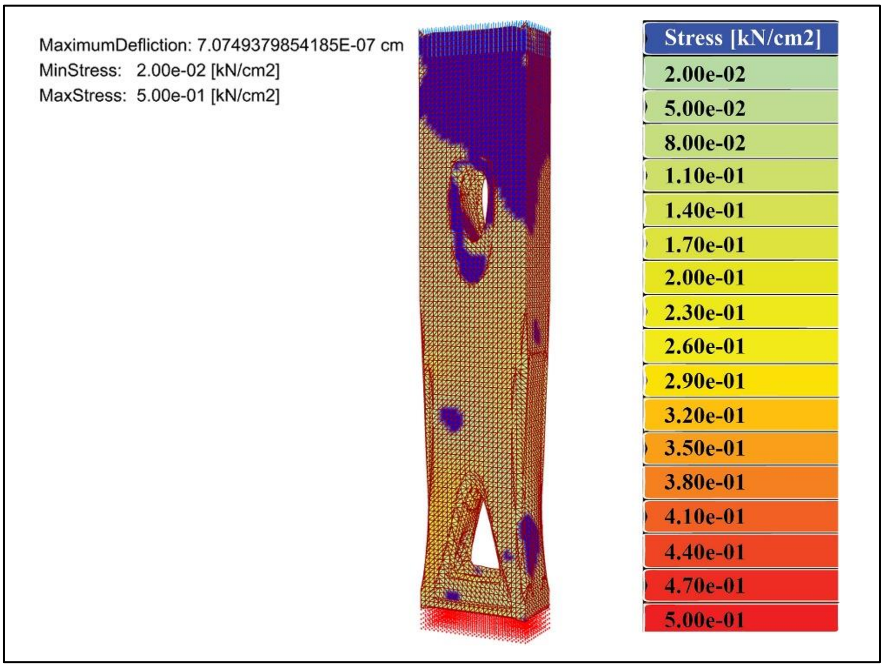

Figure 5. Simulation result of the optimised column showing maximum and minimum stress

3.3. PHASE THREE: 3D PRINTING PREPARATION AND SIMULATION

The model was contoured and scaled using the Grasshopper plug-in RoboDK, an off-line programming firmware suite used for robotic fabrication applications (Figure 6). Its integration with Grasshopper is essential for the toolpath generation. The slicing algorithm can adjust the printing layers' height and printing speed according to the material proprieties. Eventually, the 3D printing process was simulated again by using RoboDK. The layer height is 5cm, with a printing speed of 50 mm/second. However, these variables are parameters and can be modified based on material proprieties.

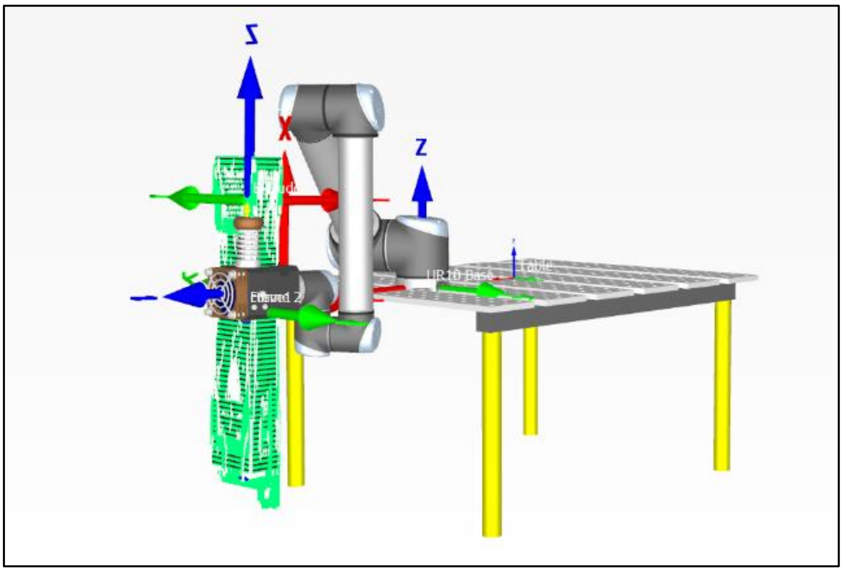

Figure 6. 3D printing simulation

4. Findings and Conclusion

The optimisation and 3D printing simulation of a typical column have demonstrated the efficiency of implementing our framework in real-world scenarios in Saudi Arabia, to improve issues related to labour shortage, construction duration, and cost. By comparing the material usage in both conventional and optimised columns, we found out that material consumption has been reduced by 25%. The use of robotic technologies alongside additive manufacturing can mitigate the required labour in construction site by 28%. Besides, the duration time will be reduced by 80% as the column will be printed in one go, without the need for formwork. According to our calculations, it will improve the overall cost-efficiency compared to the conventional construction method as shown in *Figure 7*.

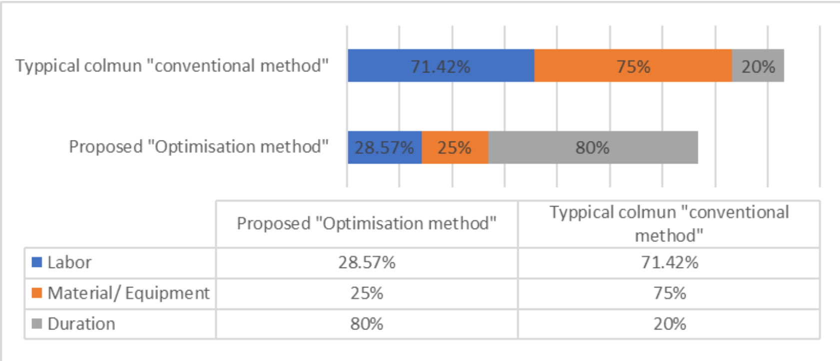

Figure 7. Comparison between conventional construction of a column with the digitalised method

Besides, the key features of our proposed approach are the fulfilment of user needs by enabling future clients to customise the design for their houses. Conventionally, the design process starts with an architect and an engineer, followed by client's approval. If a client was not satisfied, the whole process must start again. In our approach, the clients can adjust the design parameters based on their individual needs. It is considered to be more time-efficient compared with current conventional construction in the country (Figure 8).

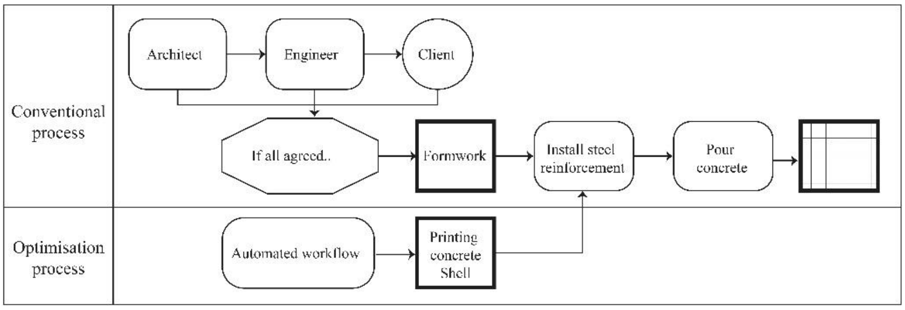

Figure 8. Comparison between procedures between conventional and proposed construction method

Furthermore, the reinforced-concrete frame structure of a typical house can be optimised and prepared for 3D printing by abstracting the building to its essential structural components (columns, beams, and slabs). The topology optimisation, performing on the column, shows that the specific implemented method is able to adapt the applied loads. It takes into consideration the limitations of the chosen materials. This method works to maximise structure stiffness and minimise material consumption. For structural verification, we have used FE analysis to assure structural stability. However, to adapt the proposed method with the current Saudi Code, we propose using steel bars to infill the inner patterns with proper reinforcement. This can be done through a second round using FE analysis with authentic materials proprieties that will be used in the fabrication process. The optimisation presents its potential to be introduced for robot toolpath through slicing algorithms, which will be connected to RoboDK to generate G-code.

Finally, due to the nature of this project, our next steps will include the fabrication of a full-scale physical model in order to compare the physical process with the one simulated and presented here.

References

Abdi, M., 2015. Evolutionary topology optimization of continuum structures using X-FEM and isovalues of structural performance. Univ. Nottingham PhD thesis.

Alhajri, A.R., Alshibani, A., 2018. Critical factors behind construction delay in petrochemical projects in Saudi Arabia. Energies 11, 1–18. https://doi.org/10.3390/en11071652

Alhubashi, H., 2018. HOUSING SECTOR IN SAUDI ARABIA: PREFERENCES AND ASPIRATIONS OF SAUDI CITIZENS IN THE MAIN REGIONS. Universidad Politécnica de Cataluña.

Alqahtany, A., Mohanna, A. Bin, 2019. Housing challenges in Saudi Arabia : the shortage of suitable housing units for various socioeconomic segments of Saudi society 22, 162–178. https://doi.org/10.1108/HCS-01-2019-0002

Aremu, A.O., Brennan-Craddock, J.P.J., Panesar, A., Ashcroft, I.A., Hague, R.J.M., Wildman, R.D., Tuck, C., 2017. A voxel-based method of constructing and skinning conformal and functionally graded lattice structures suitable for additive manufacturing. Addit. Manuf. 13, 1–13. https://doi.org/10.1016/j.addma.2016.10.006

Bacciaglia, A., Ceruti, A., Liverani, A., 2019. A systematic review of voxelization method in additive manufacturing. Mech. Ind. 20, 630. https://doi.org/10.1051/meca/2019058

Buswell, R.A., Leal de Silva, W.R., Jones, S.Z., Dirrenberger, J., 2018. 3D printing using concrete extrusion: A roadmap for research. Cem. Concr. Res. 112, 37–49. https://doi.org/10.1016/j.cemconres.2018.05.006

Comminal, R., Leal da Silva, W.R., Andersen, T.J., Stang, H., Spangenberg, J., 2020. Modelling of 3D concrete printing based on computational fluid dynamics. Cem. Concr. Res. 138, 106256. https://doi.org/10.1016/j.cemconres.2020.106256

Donofrio, M., 2016. Topology Optimization and Advanced Manufacturing as a Means for the Design of Sustainable Building Components. Procedia Eng. 145, 638–645. https://doi.org/10.1016/j.proeng.2016.04.054

Government of Saudi Arabia, 2016. Vison 2030 Kingdom of Saudi Arabia, Report. Government of Saudi Arabia.

Hager, I., Golonka, A., Putanowicz, R., 2016. 3D Printing of Buildings and Building Components as the Future of Sustainable Construction? Procedia Eng. 151, 292–299. https://doi.org/10.1016/j.proeng.2016.07.357

Januszkiewicz, K., Banachowicz, M., 2017. Nonlinear Shaping Architecture Designed with Using Evolutionary Structural Optimization Tools. IOP Conf. Ser. Mater. Sci. Eng.

245. https://doi.org/10.1088/1757-899X/245/8/082042

Kontovourkis, O., Konatzii, P., 2018. Design-static analysis and environmental assessment investigation based on a kinetic formwork-driven by digital fabrication principles. Odysseas Kontovourkis (ed.), Sustain. Comput. Work. [6th eCAADe Reg. Int. Work. Proceedings], Dep. Archit. Univ. Cyprus 131–140.

Kontovourkis, O., Tryfonos, G., Georgiou, C., 2020. Robotic additive manufacturing (RAM) with clay using topology optimization principles for toolpath planning: the example of a building element. Archit. Sci. Rev. 63, 105–118. https://doi.org/10.1080/00038628.2019.1620170

Leary, M., 2020. Design for additive manufacturing.

Mechtcherine, V., Nerella, V.N., Will, F., Näther, M., Otto, J., Krause, M., 2019. Large-scale digital concrete construction – CONPrint3D concept for on-site, monolithic 3D-printing. Autom. Constr. 107, 102933. https://doi.org/10.1016/j.autcon.2019.102933

Saudi Ministry of Housing, 2016. The Housing Program Delivery Plan. Government of Saudi Arabia.

SBC Committee 304, 2007. Structural - Concrete structures 274.

Tedeschi, A., 2014. Algorithims Aided Design. Le Penseur.

Theodore Karasik, 2017. Saudi Housing Requirements for a Strong and Secure Future [WWW Document]. Int. Policy Dig. URL https://intpolicydigest.org/2017/06/09/saudi-housing-requirements-strong-secure-future/