Optimierung der biomimetischen Topologie und Roboterherstellung von 3D-gedruckten Hochleistungskonstruktionssystemen
Biomimetic Topology Optimization and Robotic Fabrication of 3-D Printed High-Performance Construction Systems

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Kurzfassung

Gegenwärtige konventionelle Bauweisen tragen zu einer erheblichen Menge an Gesamtabfall bei, was erhebliche negative finanzielle und ökologische Auswirkungen hat. Die additive Fertigung (AM) bietet schnellere, sicherere, kostengünstigere und umweltverträglichere Konstruktionssysteme als zukünftige Alternative zu den derzeit üblichen Methoden. Darüber hinaus hat die potenzielle Anwendung von AM im Bauwesen in den letzten Jahren erheblich zugenommen, war jedoch auf kleine Prototypen beschränkt. Die jüngste Entwicklung von Berechnungsformfindung und AM hat die Möglichkeiten für umfassende Untersuchungen zum Entwurf hocheffizienter Struktursysteme erweitert. Die vorgestellte Forschung untersucht das Potenzial, mit dem Topologieoptimierung und AM verwendet werden können, um die Grenzen des Entwurfs von Hochleistungsbausystemen zu erweitern. Dieser Prozess baut Material nur in Bereichen mit hoher Beanspruchung auf, basierend auf in der Natur vorkommenden biomimetischen Prinzipien, wodurch die strukturelle Leistung maximiert und das Gewicht minimiert wird. Die vorgeschlagene robotergesteuerte Plattform für additive Fertigung und rechnergestütztes Design wird die Bauindustrie revolutionieren, indem neue Verfahren entwickelt werden, um hochleistungsfähige 3D-gedruckte Bauteile in Originalgröße zu entwerfen und herzustellen. Die Ergebnisse der neuen vorgeschlagenen Technologie werden der erste Schritt in Richtung eines neuartigen, vollständig integrierten Ansatzes zur Herstellung von Robotern für Konstruktionen sein, der von der Materialwirtschaftlichkeit intelligenter Netto-Null-Kohlenstoff-Bauteile angetrieben wird.

Short Abstract

Current conventional construction methods contribute to a significant amount of waste, which has major negative financial and environmental impacts. Additive manufacturing (AM) offers faster, safer, cost-effective, and environmentally sustainable construction systems as a future alternative to the current conventional methods. Furthermore, the potential application of AM in

construction has expanded significantly in recent years but has been limited to small scale prototypes. The recent development of computational form-finding and AM has broadened the opportunity for extensive exploration into the design of highly-efficient structural systems. The research presented in this paper investigates the potential to which topology optimization and AM can be used to extend the boundaries of the design of high-performance construction systems. This process builds up material only in areas of high stress based on biomimetic principles found in nature, maximizing structural performance while minimizing weight. The proposed robotically controlled additive manufacturing and computational design platform will revolutionize the construction industry by developing new processes to design and fabricate full-scale high-performance 3D - printed building components. The results of the new proposed technology will be the first step toward a novel, fully integrated robotic fabrication approach to construction driven by the material economy of net-zero carbon smart building components.

Figure 1: 3d-printed model of topologically optimized U-House prototype.

1 Introduction

Topology optimization is a computational form-finding method of determining the best possible forms based on optimal material distribution within a discretized design space with a specific set of boundary conditions, including loads, supports, and other design constraints. Through an iterative process, the algorithm refines material distribution within the model volume boundary to meet a specific set of performance goals to maximize the performance of the structural system by increasing stiffness while reducing the weight by reserving material only in areas of high stress. These goals follow similar biomimetic principles found in nature for animals, birds, and plants where optimal strength-to-weight ratios are significant to ensure the efficient use of limited material resources [1] (Fig.1, 2). There are various topology optimization algorithms include Evolutionary Structural Optimization (ESO), Bi-directional Evolutionary Structural Optimization (BESO), and Solid Isotropic Microstructure with Penalization (SIMP). The work presented in this paper focuses on BESO and generative design methods [2,3].

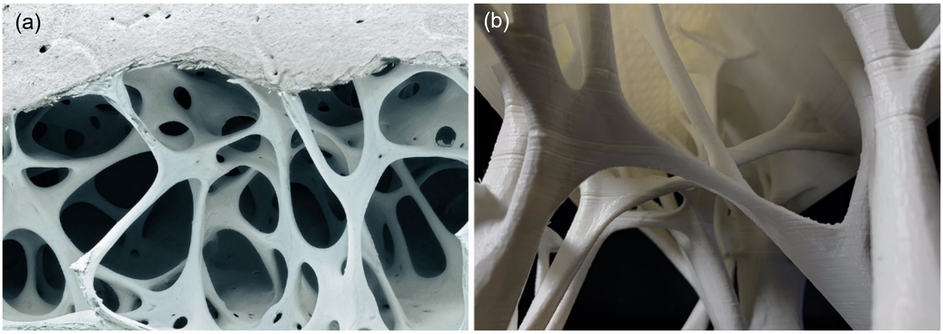

Figure 2: Biomimetic principles of topology optimization: (a) Bird bone tissue. Coloured scanning electron micrograph (SEM) of a starling's skull. The internal bone structure is optimized to provides support and strength while maintaining minimal weight. [Photo credit: Steve Gschmeissner / Science Photo Library], (b) detail of the topologically optimized U-House 3d-printed model.

Topology optimization has transformed major mechanical engineering industries, including automotive and aerospace, which typically can achieving 20-40% weight savings [4,5]. On the other hand, traditional construction practices have seen little of the technological revolution that has transformed these fields and still lacks substantive change to the construction framing of houses in decades. Despite the efforts to implement topology optimization in large scale construction applications, full scale built examples are rare. This partially due to a) the lack of a workflow to prepare complex topologically optimized 3d models for fabrication, b) the limitation of the current large scale AM methods c) the limitation of novel materials such as biodegradable reinforced polymers that are sustainable and more suitable for AM methods.

Current construction relies on subtractive methods that produce significant material waste, which, in turn, has a significant impact on the environment. Additive manufacturing (AM), also known as 3d-printing, offers innovative, safer, cost-effective, and environmentally sustainable alternatives to conventional construction. AM has the potential to eliminate construction waste, and when paired with the biomimetic design principle such as topology optimization, AM can be easily adapted to create the complex geometric forms required for higher structural efficiency. Furthermore, Biodegradable and recycled composite material can be utilized in 3d-printing for sustainable building material alternatives to wood, masonry, concrete, and steel. However, AM and topology optimization of components have been limited to small-scale applications and has not been fully implemented in the construction industry. Addressing these possibilities, this paper presents an overview of novel design to fabrication process of topologically optimized framing structure composed entirely of biodegradable composites to serve as a future alternative to the current conventional wood structural framing used in building construction.

2 Background

Our published research and preliminary data indicates that polymer-based AM applications in large-scale building construction is possible and can offer innovative alternatives to conventional construction techniques. AM could provide quicker, safer, and more sustainable options. The Additive Manufacturing Integrated Energy (AMIE 1.0) Research project is a 3d-printed full-scale high-performance building enclosure prototype. The structure was printed using the Big Area Additive Manufacturing (BAAM) technology and incorporates next-generation modified atmosphere insulation panels (MAI) The research utilizes advanced computational tools for design optimization, integrated project delivery, rapid prototyping and fabrication of building elements using additive manufacturing. Funded by the Department of Energy (DOE), AMIE was a multidisciplinary research project in collaboration with the UT Governor's Chair, ORNL, Clayton Homes, and Skidmore, Owings & Merrill (SOM) (Fig.3) [6, 7, 8]. The research presented in this paper continues to contribute to these efforts by developing a novel workflow for robotically controlled additive-manufacturing processes using a Kuka robotic arm with polymer-based pellet feed Fused Deposition Modeling (FDM) end effector extruder.

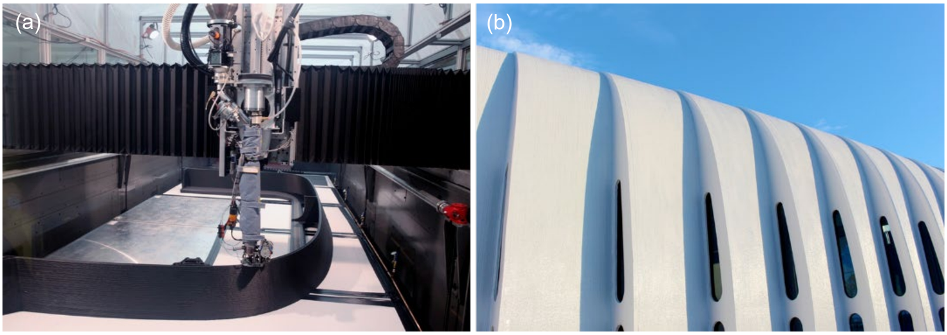

Figure 3: Polymer-based additive manufacturing for Large-scale construction application: (a) printing of ABS layers of the wall panel on the BAAM system (b) assembled panels with integrated window (Guerguis et al., 2016).

3 Computational design and form finding

The computational design and form finding workflow for this research was developed with the objective of designing a load-bearing structural framing for a house prototype, the U-House. The U-House is 120 square meter model with a standard gabled roof consists of two roof sections sloping in opposite directions where the horizontal highest edges meet forming the roof ridge (Fig. 1). The computational design procedure is broken down into four steps which are described in detail in following sections: 1) planar topology optimization using stiffness-based Bi-directional Evolutionary Structural Optimization (BESO); 2) 3d topology optimization using generative design; 3) finite element analysis (FEM) to evaluate the design performance of generative design iterations; 4) post-processing of mesh model and G-Code generation for robotic 3d-printing (Fig. 3). The preliminary workflows described above were an essential step in the design process. The formal design guidelines derived from interpretations of the topology optimization form-finding process and finite element analysis of the generative design outcome. Different mesh post-processing approaches were tested to prepare the model for robotically controlled 3d-printing.

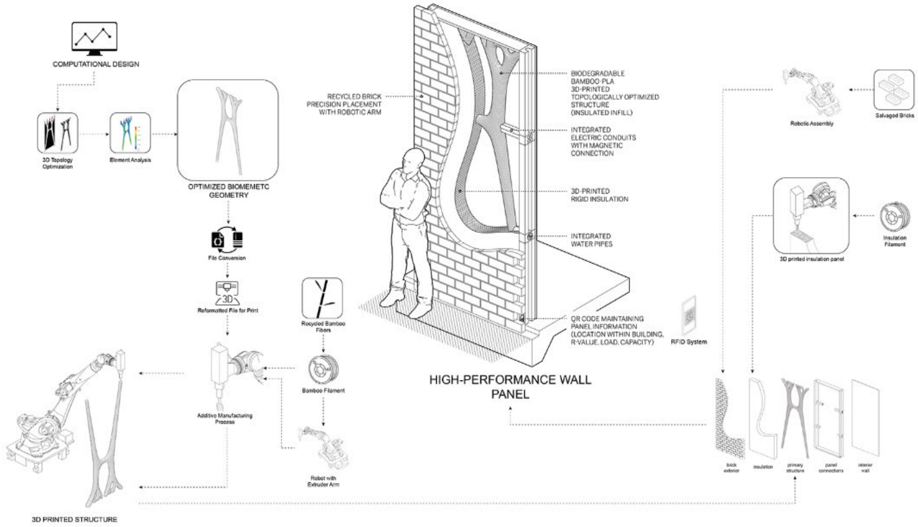

Figure 3: Workflow diagram of computational form finding, topology optimization and 3d printing.

4 Planar topology optimization

The planar topology optimization process provides an efficient method for understanding the possibilities of topology optimization outcome of a given discretized volume in relation to specifically defined force load and support combinations. The two dimensional topology optimization algorithm was generated using Millipede plugin for McNeel Rhinoceros ® and Grasshopper ® [9]. Since these 2d studies can be generated quickly and with relatively low computing power, compared to 3d optimization, they allow for a high degree of iteration in the design process. The outcome of the optimization process depends strongly on the choice of loading cases and support locations. The speed of iteration of this step helped the research team to rapidly make changes to the design space for various loads, boundary conditions, and constraints. To illustrate

this aspect, we investigated the influence of varying load scenarios on each surface of the U-House model with the goal of maximizing stiffness while reducing weight through optimal material distribution.
At first, a basic volume of the structure was created, then it was broken into individual surfaces. Façades and roof sections were defined as discretized boundaries for optimization. Specific load cases were defined based on each surface location within the structure. The topology optimization iterative steps could be repeated to refine the outcome until all the design criteria have been satisfied (Fig. 4)

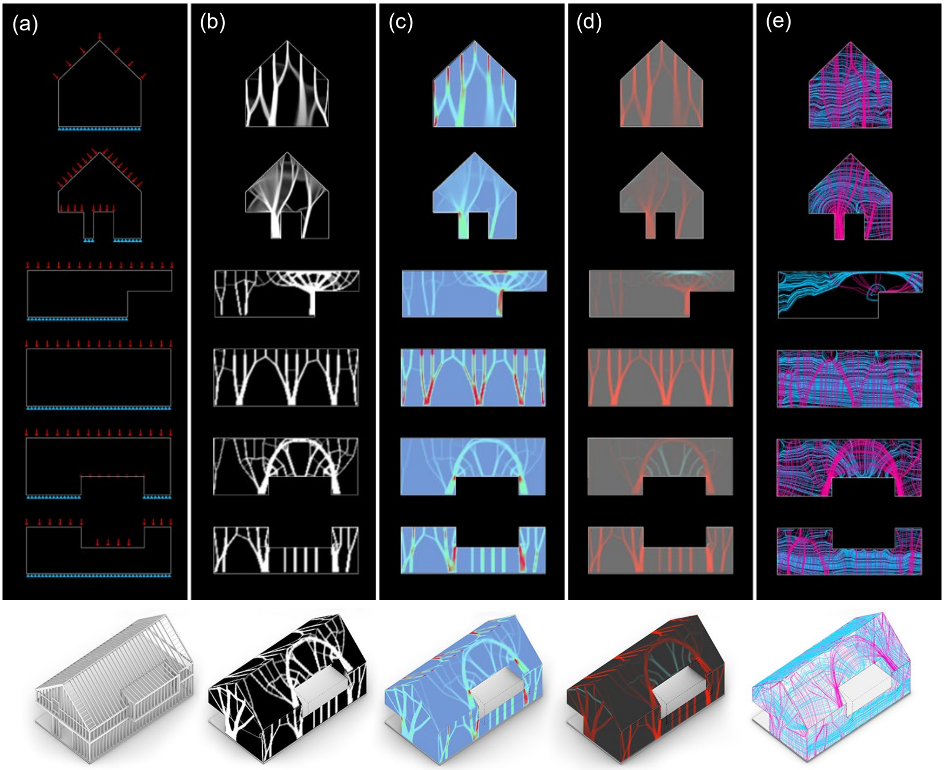

Figure 4: Traditional wood framing in comparison to the topologically optimized model: (a) standard wood framing of the U-House 400 mm on center (b) assembled topologically optimized planar surfaces of the U-House model stiffness factor, (c) Von Mises stress, (d) principal Stress, (e) principal stress lines.

5 Topology optimization Interpretation

Several workflows were investigated to interpret the 2d topology optimization results to a 3d model while maintaining the initial design goals and the performance criteria. Initially, the team developed a hybrid process based on the results from the 2d topology optimization as reference for the reconstruction of a 3 x 1.25 meters wall panel. The process starts by creating a low polygon mesh for a free form surface using T-spline ,a Non-Uniform B-Spline (NURBS) surfaces modeling plugin for McNeel Rhinoceros ®, with control grids permit T-junctions [10]. This workflow allows for geometrically continuous construction of (NURBS) surfaces of any complex topology. This method is suitable for initial testing of topology optimization results, requires no post-editing and produces a mesh of sufficient fidelity for direct 3d-printing. However, this method requires additional manual modeling, which could present a challenge for larger and more complex models (Fig. 5).

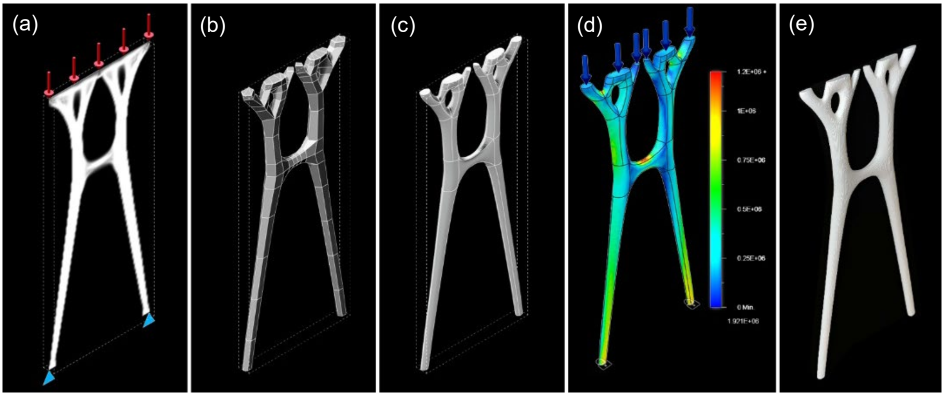

Figure 5: Reconstruction of the 2d topology optimization: (a) initial stiffness mesh representing material distribution of the topologically optimized panel, (b) T-spline low-polygon mesh, (c) smooth NURBS surface, (d) finite element stress analysis (e) 3d-printed model.

Additional finite element stress analysis of the topologically optimized models was performed to validate the performance of the 3d model and to evaluate initial design criteria. The result was 33% material reduction with higher stiffness compared to the standard wood framing wall panel of the same size.

6 Three dimensional topology optimization and generative design

Three dimensional topology optimization or shape optimization is generated based on paths between fixed constraint and the applied load on the volume boundary, including preserved regions, voids, and obstacle geometry in 3d space. The process of topology optimization minimizes the compliance of the elastic structure subject to constraints on the available material while maximizing stiffness. The iterative algorithm uses a numerical method for determining optimal material distribution. In this implementation, the elasticity equations are solved using finite element, and sparse direct solver. A multi-resolution finite element mesh volume represents the design field and the design update is performed using gradient-based criteria. The output mesh of shape optimization often requires model reconstruction, post mesh editing and smoothing algorithm for the generation of parts that are ready for 3d-printing.

Similarly, generative design process starts with defining boundary volume, load cases definition, and constraints including initial, preserved and obstacle geometries in Fusion 360 which is a cloud based modeling and computational simulation software developed by Autodesk ®. Generative design takes into consideration stress distribution through an iterative process. Each iteration evaluates areas of high and low stress within the defined volume boundary. In low-stress areas, the algorithm gradually removes material and correspondingly in high-stress areas preserves material while avoiding obstacle parts. The process goes through different iterations until all the design criteria with a specified targeted factor of safety have been fulfilled (Fig. 6).

Generative design iterative processes of 3d topology optimization generate editable T-spline geometry and take into consideration constraints influenced by manufacturing methods such as 3-axis milling or additive manufacturing. It can solve complex design problems such as consolidating parts, minimizing mass while maximizing stiffness compared to all solid part of similar design. Next, each iteration was compared and evaluated to meet the design objectives of the result of the finite element topologically optimized mesh was converged and converted into a smooth T-spline surface, which either can be saved as Stereolithography (STL) file and printed directly or can be exported as T-Spline surface for further editing. One of the significant advantages of the generative design workflow is that the final model requires virtually no post-processing and ready for slicing and g-code generation for 3d printing. The algorithm generated 45 iterations reducing the overall volume of the topologically optimized model to 4.98 cubic meters compared to 8.73 Cubic meters of standard wood framing, achieving a total of approximately 43% material reduction.

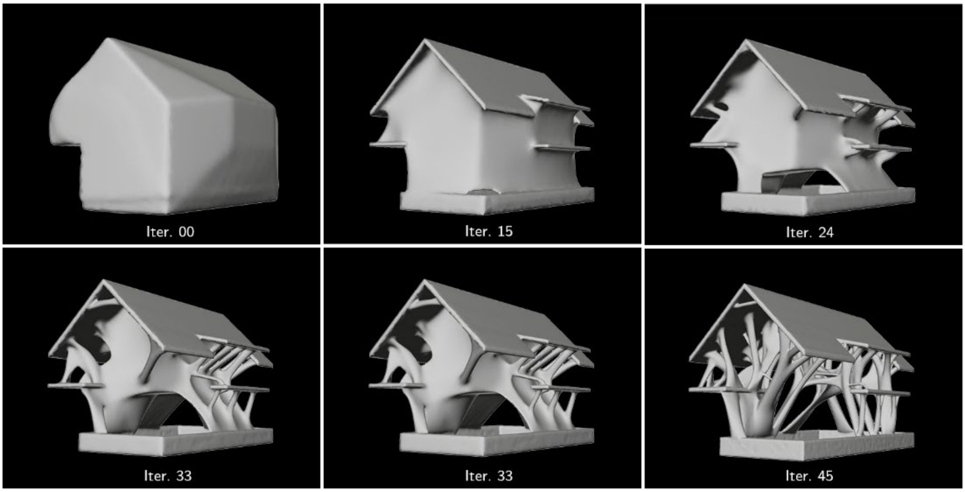

Figure 6: 3d topology optimization: permutations of the U-House generative design for additive manufacturing fabrication method constraints.

It is remarkable to see how the optimized geometries (Fig. 7) resemble the organic forms of the natural bone structure of the starling's skull shown in (Fig. 2a). This is not a coincidence. As Wolff's law states that animal bone varies in densities based loads applied on it [11], computational form-finding morphologies of topology optimization follow the same principles that drives the weight reduction of the bird skeletal structure. Both structures need to be stiff towards applied surface pressure to resist longitudinal bending, therefore resulting in a similar distribution of the internal structural elements.

7 3d-printing of scale model prototype

Scale models were used to investigate the 3d-printing direction and the orientation of the models on the build plate with minimal or no support material. Preliminary 3d-printed tests of the branching of the tubular forms of the 3d topologically optimized model resulted in a self-supported geometry that does not require additional support material and can be a method to test and simulate common large-scale 3d-printing issues, such as built plate adhesion, layers delamination and overhanging parts support (Fig. 7).

The use of large-scale 3d-printed structure to further the understanding of the capabilities and limitations of polymer-based 3d-printing in an architectural application. The research approaches in this paper have provided new insight into the efficiency of the topologically optimized 3d-printed building structure. The use of 3d-printing scale models allows for the fabrication of high-performance topologically optimized structures at a high level of detail, accuracy, and precision. Additionally, the potential application of biodegradable reinforced polymers can provide the structural strength necessary for large-scale applications.

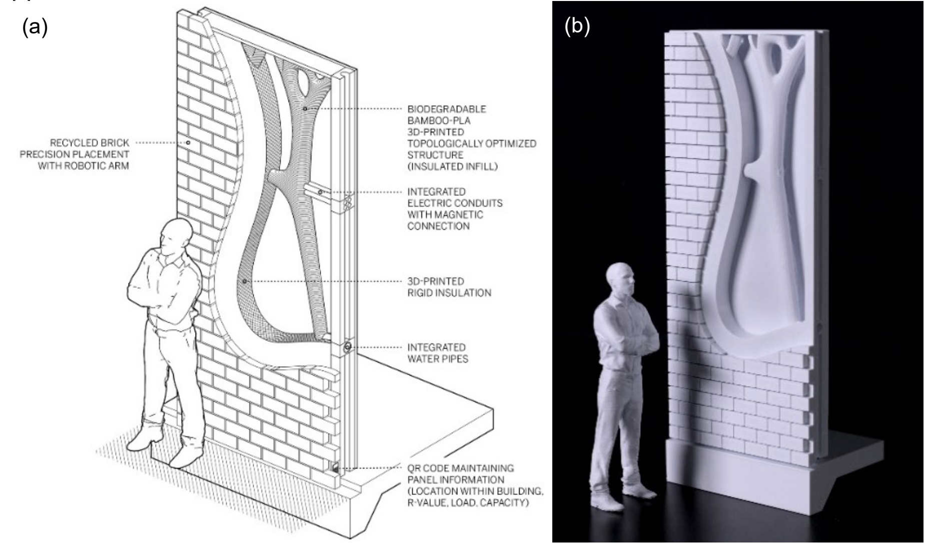

Figure 7: U-Panel: (a) Concept diagram of topologically optimized smart wall assembly with integrated building systems, (b) 3d printed scale model porotype.

8 Conclusion

With the two successful workflows described, this paper can conclude that 3d-printing can sufficiently produce high fidelity architectural components of geometric complexity directly through topology optimization. Additionally, this paper showed new directions for the use of topology optimization and generative design workflow, more accurate interpretations of the topology optimization results were achieved. 3d-printing technology, combined with a customized digital workflow for the design development and production, has been successfully used to efficiently build a topologically optimized scale model prototype with optimal structural performance.

The paper only showed the successful, first results of the developed workflow of the design of high-performance topologically optimized structural farming with novel forms. This can be considered as a first validation of the approach. More significantly, as the finite element analysis of the model (Fig. 5d) showed a higher performance of topology optimization results compared standard wood framing models. In applications of robotically controlled additive manufacturing for full-scale building components for an entire house, further research must address the following challenges:

Component-based design: The framing structure would need to be divided and assembled from multiple prefabricated panels taking into consideration the location of each panel when defining boundary conditions and different load cases. Additionally, connection design between each panel will also play a significant role in ensuring the integrity of the overall structure.

Integrative systems: This paper highlights the significant potential of using 3d-printing to fabricate large-scale parts with an optimal structural performance for specific material reduction targets. Nonetheless, to harness the full potential of AM, other integrative design approaches should be considered to incorporate other systems mechanical electrical and plumbing within the printed parts.

Alternative construction material: the structural optimization form-finding is one key aspect of the research. However, further exploration of novel materials is required for higher performance and lightweight, sustainable building material alternatives. The ‘materials by design’ approach and utilization of the material across length scale Nano-to-macro enable highly complex designs with optimal structural strength/stiffness and manufacturability in complex forms. The author consider this research as the first step toward a novel, fully integrated approach to construction driven by the material economy and have the potential to transform the current construction practices.

Acknowledgments

The author would like to thank Autodesk for providing access to Fusion 360 and cloud computing services for the 3d topology optimization and generative design calculations.

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