Designing for the Extreme: Computational Strategies for Adaptable and Sustainable Housing in Northern Canada's Permafrost Regions

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Abstract
This research paper explores the development of a Computational Design (CD) methodology for constructing adaptable homes in the permafrost landscapes of Northern Canada, particularly in regions like Nunavut. Leveraging the capabilities of Ameba and Karamba 3D, the study emphasizes optimizing structural configurations and material usage, integrating innovative approaches such as Cross-Laminated Timber (CLT) and in situ 3D printing. This strategy addresses the logistical and environmental challenges characteristic of off-site construction, where transportation costs are significant, and conditions are harsh. Additionally, the research underscores the necessity of incorporating Indigenous cultural considerations into the architectural design, ensuring that the final outcomes respect and align with local traditions and values. The paper showcases the transformative potential of CD in extreme and isolated environments. This proposal, while currently theoretical and intended for future research and potential real-world application, presents a significant step forward in environmentally and culturally sensitive architectural design.

Keywords: Computational Design (CD), Cross-Laminated Timber (CLT), 3D printing, Indigenous.

1 Introduction

The housing crisis faced in Nunavut and the wider Inuit Nunangat regions of Canada go beyond insufficient housing. These northern areas face overcrowding and deteriorating housing conditions reflecting rooted social and economic gaps, health concerns, and educational obstacles aggravated by harsh environmental factors and historical neglect. Some Inuit communities have overcrowding rates high as 72% leading to "hidden homelessness", where families move between the homes of friends and relatives due to limited housing options. (Sultan 2023)

Traditional building methods struggle in these climates causing buildings to deteriorate quickly and worsen the housing crisis. The poor living conditions have an impact on health and mental well-being with cramped and subpar homes supporting the spread of illnesses and affecting mental health. For children these conditions hinder success and future prospects.

This overview highlights the nature of the housing crisis paving the way for exploring new construction techniques like 3D printing and Cross Laminated Timber (CLT). By using design tools such, as Ameba and Karamba 3D we aim to bring efficiency, adaptability, and sustainability to construction practices.

These tools support simulations and structural enhancements that are crucial for creating housing solutions that not only work effectively but also align, with the cultural and environmental needs of Nunavut and Inuit Nunangat. When developing our designs we take inspiration from Inuit housing styles like the well-known Iqaluit house incorporating these cultural elements to ensure our solutions honor and represent the heritage and identity of Inuit communities. This paper summarizes existing research efforts. Aims to address gaps in delivering sustainable and culturally sensitive housing options in these isolated and demanding regions.

2 Background and Literature Review

2.1 Historical and current challenges

The housing crisis in Nunavut and Inuit Nunangat, deeply rooted in historical policies and cultural dislocations, has been exacerbated by federal housing strategies lacking Inuit perspectives. Policies, often crafted without genuine Inuit input as detailed by Sultan (2023) and the Canadian Human Rights Commission (2022), have resulted in homes that are both structurally unsuitable for the harsh Arctic conditions and culturally misaligned. This has led to severe overcrowding, rapid building deterioration, and significant socio-economic disparities, impacting health and educational outcomes within these communities.

Lillian & Patterson (2017) highlight that these inadequate policies have contributed to a widespread sense of dislocation among residents. The urgency for revised federal involvement and increased funding to Indigenous organizations is critical, aiming to develop housing that is both culturally and climatically appropriate. This approach seeks to rectify past oversights and improve living conditions.

In response to these longstanding issues, the "Nunavut 3000" strategic plan initiated by the Nunavut Housing Corporation proposes the construction of 3000 new housing units over the next decade. This ambitious plan is designed to bridge the historical gaps by offering a range from emergency shelters to homeownership opportunities and employing innovative construction methods, such as modular housing, to adapt to the unique challenges of the Arctic environment. However, the plan's success hinges on robust federal support, which remains inadequate. Emphasizing community involvement, the strategy ensures that the new developments are culturally resonant and address local needs, while also focusing on maintenance and energy efficiency improvements for existing structures.(igluliuqatigiingniq 2022)

2.2 Computational Design in Architecture

Computational Design (CD) software like Autodesk's Dynamo and Rhinoceros with Grasshopper are changing how architects approach environment such as the Arctic. Ameba, Karamba 3D, and Ladybug are tools that can be used with Grasshopper interface. Ameba assists in optimizing layouts and material choices based on environmental and structural requirements crucial for Arctic buildings to improve energy efficiency and withstand harsh weather conditions. Karamba 3D goes a step further by providing analysis within the Grasshopper 3D platform allowing simulations of stress and deformation. (Zhou 2020, Sadeghipour & Pak 2013)

This ensures that buildings not only have a suitable appearance but are also resilient enough to endure permafrost and heavy snowfall. Moreover, Ladybug offers, in depth energy analysis, an aspect of designing structures, it projects energy consumption and thermal performance helping in the creation of energy efficient and eco-friendly buildings. By leveraging these tools, architects can create structures that're not only environmentally sustainable and efficient but also better operational to tackle the unique challenges posed by extreme climates. This enhances resilience, functionality and minimizes waste.(Wu et al. 2022)

2.3 Innovative Materials and Techniques

2.3.1 3D Concrete Printing (3DCP)

3D printing technology is transforming the construction industry by allowing the creation of structures, from digital designs. This new method offers flexibility in architecture reduces waste and improves efficiency in building projects in remote places like the Arctic (De Schutter et al. 2018). The process starts with a Computer Aided Design (CAD) model from a software such as rhino with Grasshopper, that guides the printer to layer materials like concrete, geopolymer, and polymer-modified concrete according to specific instructions (Cao et al. 2022). Recent advancements, including the use of a cable driven parallel robot for printing enable larger and more complex constructions opening new design possibilities(Hahlbrock et al. 2022). Another innovative technique, Batiprint3DTM by Furet et al. (2019) involves a combination of polymer foam and concrete walls improving both insulation and strength. By combining CAD with manufacturing processes, these studies illustrate how 3D printing can adapt construction methods to environments and cultural requirements leading to reduced costs and environmental impacts. Further exploration by Li & Tsavdaridis (2023) presents an interlocking system, for Cross Laminated Timber optimized for 3D printing streamlining assembly processes and improving integrity. These studies suggest a move towards more effective construction methods with 3D printing to address the needs of complex building environment. These advancements play a role, in decreasing the impact of construction procedures while upholding top notch levels of strength and flexibility.

2.3.2 Cross-Laminated Timber (CLT)

Cross-Laminated Timber (CLT) is gaining recognition for its structural stability and efficiency, particularly beneficial in Arctic environments. CLT panels are made from crossed layers arranged with perpendicular softwoods. Glulam and CLT panels offer a high strength-to-weight ratio comparable to steel and concrete, making them suitable to resist some extreme environments(Bejtka 2011). Their excellent insulation properties, highlighted by Shan et al. (2023), help maintain indoor temperatures efficiently and reducing energy demands in cold climates. The prefabrication of CLT not only speeds up construction processes significantly cutting down labor and project timelines, but also proves crucial in remote areas where building periods are constrained by harsh weather. More improvements in CLT's design, such as Timber-Concrete Composite (TCC) floor systems studied by Shahnewaz et al. (2022), reveal an increase of 167% in shear capacity and better vibration control, optimizing it for taller structures and seismic activity. CLT's adoption promotes sustainable building by minimizing on-site waste and environmental impacts, aligning with modern architectural requirements for flexibility and eco-efficiency. With ongoing advancements in material science and building technology, CLT is poised to play an increasing role in future construction, particularly in challenging and sensitive environments like Northern Canada.

2.3.3 Cultural integration in modern architecture

The architectural practices of the Inuit are a testimony to their deep understanding of environmental adaptation and resource utilization, essential for survival in harsh climates. This figure highlights three distinctive structures: the Tupiq (figure 1a), a summer dwelling made from animal skins and supported by wood or whalebone, offering mobility for following migratory game paths; the Igloo (figure 1b), constructed from snow with superb insulating properties to maintain warmth during freezing temperatures; and the Thule Winter House (figure 1c), built partially underground using materials like stone and whalebones for enhanced warmth and stability in winter. Each structure not only underscores the Inuit's resourcefulness but also provides valuable insights into sustainable and adaptable architectural strategies relevant today.

Figure 1 Traditional Inuit Architectural Forms and Their Modern Relevance. (a), Tupic. (b), Igloo. (c), Thule winter house.(Historica Canada 2020)

3 Methodology

In this study, we focused on developing optimized architectural solutions for Arctic environments, using Grasshopper and its plugins Ameba, Karamba 3D, and Ladybug. Figure 2 displays a comprehensive workflow diagram that outlines the key stages of the project, from initial concept generation to optimization, and final design evaluation. This diagram acts as a visual guide to our systematic approach, illustrating how computational tools are effectively applied to overcome architectural challenges in extreme climates.

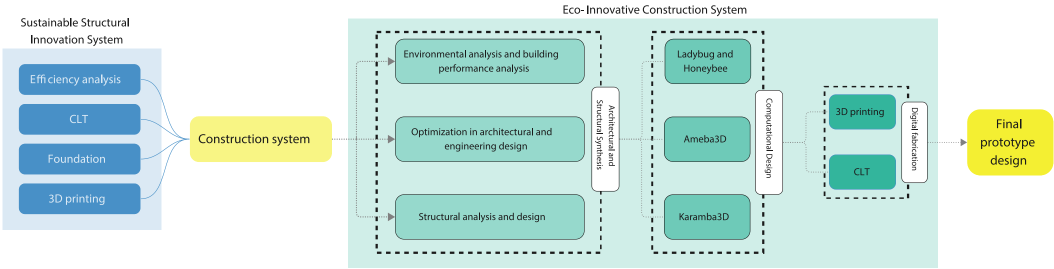

Figure 2. Schematic Overview of the Computational Design Workflow.

The workflow begins by defining a modifiable form, allowing for subsequent architectural modifications tailored to the unique challenges of the Arctic, as demonstrated in Figure 3, which showcases the Grasshopper script used in the design process.

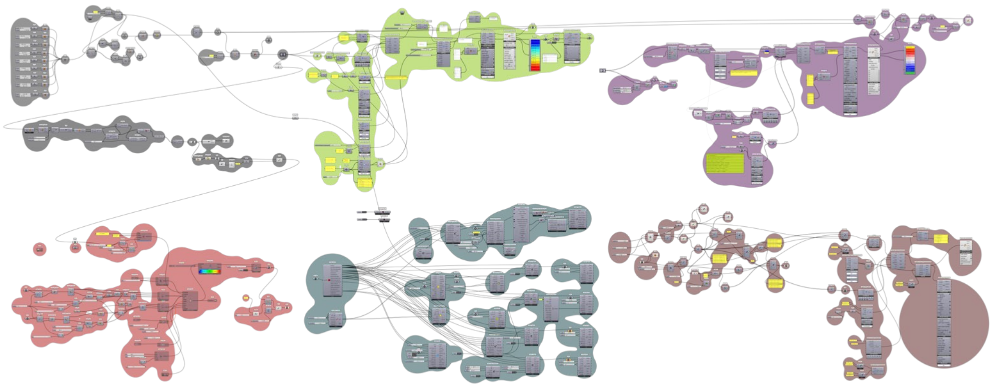

Figure 3. Parametric Design Workflow for Adaptable Housing in Arctic Environments.

The envelope's optimization process utilizes stress and displacement analyses to guide material selection, as shown in Figure 4a. This analysis informs the integration of 3D printed concrete and Cross-Laminated Timber (CLT) panels, chosen for their rapid fabrication capabilities and excellent thermal insulation properties, respectively. Additionally, the construction of a steel subframe provides a stable foundation for modular buildings on permafrost, depicted in Figure 4b. Following the subframe construction, the steel structure designed to support mass timber beams is optimized for strength and durability, detailed in Figure 4c.

Material optimization of the flooring through Ameba results in an organic form, enhancing both aesthetic and functional aspects of the building, as detailed in Figure 3d. Simultaneously, environmental optimization by Ladybug, shown in Figure 4e, assesses the climate impact and enhances solar efficiency, ensuring that the building's design is both energy-efficient and suitable for its environmental context.

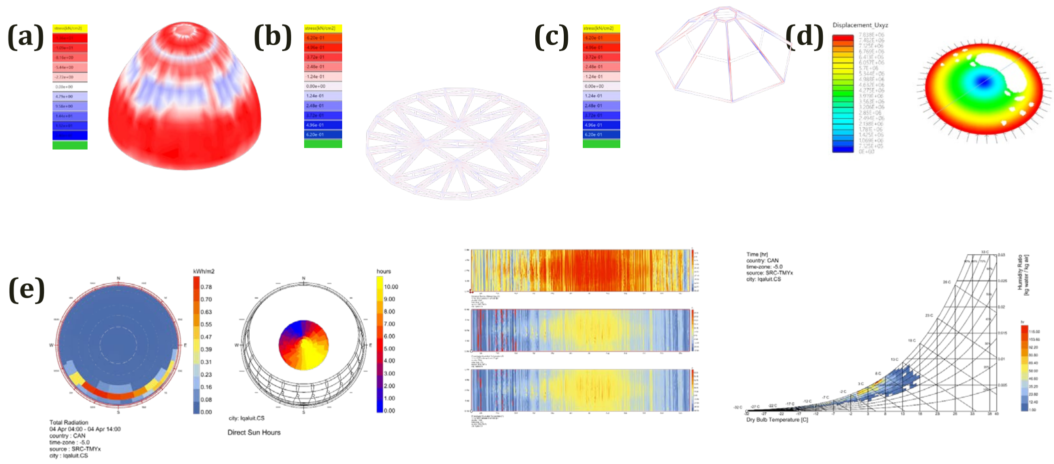

Figure4. Computational Analysis of Building Design for Arctic Environments. (a), envelope. (b), steel subframe. (c), structure. (d), material. (e), energy.

This integrated approach, combining advanced computational tools with practical design strategies, not only demonstrates the feasibility of architectural innovations in extreme environments but also enhances the sustainability, efficiency, and adaptability of construction practices. This methodology exemplifies how theoretical models transition into practical architectural solutions, thereby pushing the boundaries of architectural innovation.

This dynamic methodology, by allowing for the adjustment of input variables, offers a real-time visualization of how changes influence the design outcomes. Such adaptability enables the selection of the most effective design solutions, ensuring that each architectural concept is not only optimized for performance but also perfectly tailored to the unique demands of Arctic conditions.

4 Design Proposal

4.1 Transportation Logistics

To address the logistical challenges of constructing in remote Arctic regions, the depicted scenario integrates advanced onsite 3D printing with the efficiency of offsite prefabrication. This combination harnesses the precision of 3D-printed elements and the structural integrity of prefabricated Cross-Laminated Timber (CLT) walls, streamlining the entire building process from material transportation to final assembly.

The figure 5 illustrates a modern construction approach integrating onsite 3D printing with offsite prefabrication using Cross-Laminated Timber (CLT) for walls. Raw materials are brought to the site for use by the 3D printer, which crafts both structural elements and intricate internal features like kitchen units and bathrooms with high precision. Simultaneously, essential services such as plumbing and electrical systems are prefabricated to meet regulatory standards before their integration on site. The CLT walls, pre-assembled with necessary insulation and exteriors, are then transported and assembled at the site, merging with the pre-installed services to complete the building's envelope. This hybrid method efficiently combines the accuracy of 3D printing with the speed and quality control of prefabrication, streamlining the construction process while enhancing the building's structural integrity and environmental performance.

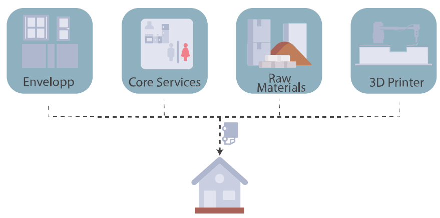

Figure 5 Integrated Construction Process Using Onsite 3D Printing and Offsite CLT Prefabrication.

4.2 Construction Process

In response to the harsh climatic challenges of Iqaluit, our design integrates advanced construction techniques suitable for extreme environments, as illustrated in Figure 6. The process begins with Foundation Preparation (a), followed by Frame Assembly (b) to establish the structural framework. 3D Printing the Structure (c) then adds the main building sections onsite, enhancing material precision and insulation. This is followed by Assembling the Prefabricated Components (d), where all structural elements are efficiently combined. The sections are then lifted into place using cranes during Installing the Assembled Structure (e), which minimizes labor exposure to severe cold and enhances safety. The construction sequence concludes with Final House Completion (f), ensuring all components are securely integrated and leveraging the thermal properties of CLT to optimize resource use. This sequence not only addresses the logistical challenges of Arctic construction but also promotes sustainability by reducing waste and improving construction speed.

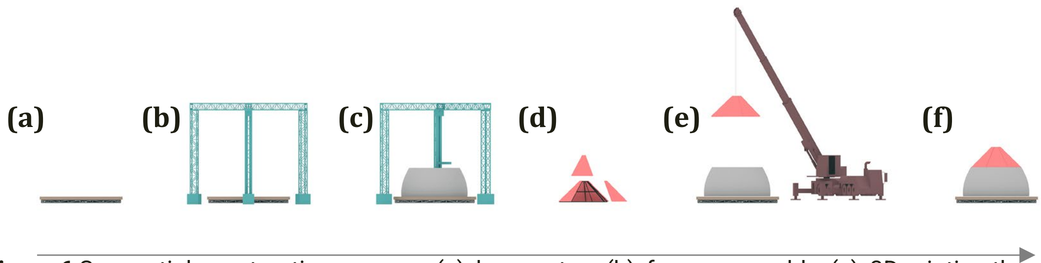

Figure 6 Sequential construction process. (a), base setup. (b), frame assembly. (c), 3D printing the structure. (d), assembling the prefabricated components. (e), installing the assembled structure. (f), final house

4.3 Program and Design

Figure 7 showcases the floor plan of a two-story unit created for the Arctic climate. The ground level presents an area with an open design for daily activities and family gatherings. It includes a sleek kitchen optimized for efficiency, a dedicated workspace for remote work or study, and storage to maximize available space. Additionally, there is a perimeter walkway that provides protection from weather conditions.

On the first level, there are two bedrooms designed for privacy and comfort, bathrooms for convenience and accessibility, and "open to below" spaces that enhance the feeling of openness and connectivity between the floors. The design emphasizes modularity and adaptability by incorporating construction methods such as 3D printing for components and prefabricated Cross-Laminated Timber (CLT) for walls. This combination ensures assembly, excellent thermal insulation, and the structural strength necessary for the Arctic climate.

One significant element of the house's design is the window positioned at the top. This window permits sunlight to reach the house, lessening the need for lighting and elevating the overall atmosphere. In regions like the Arctic, where daylight is limited in winter, this skylight serves as a natural light source, promoting the resident’s welfare and improving energy efficiency in their homes.

In principle, the proposed plan presents an approach to versatile housing by blending modern technology with traditional Inuit architectural principles to create a practical living space that respects cultural values.

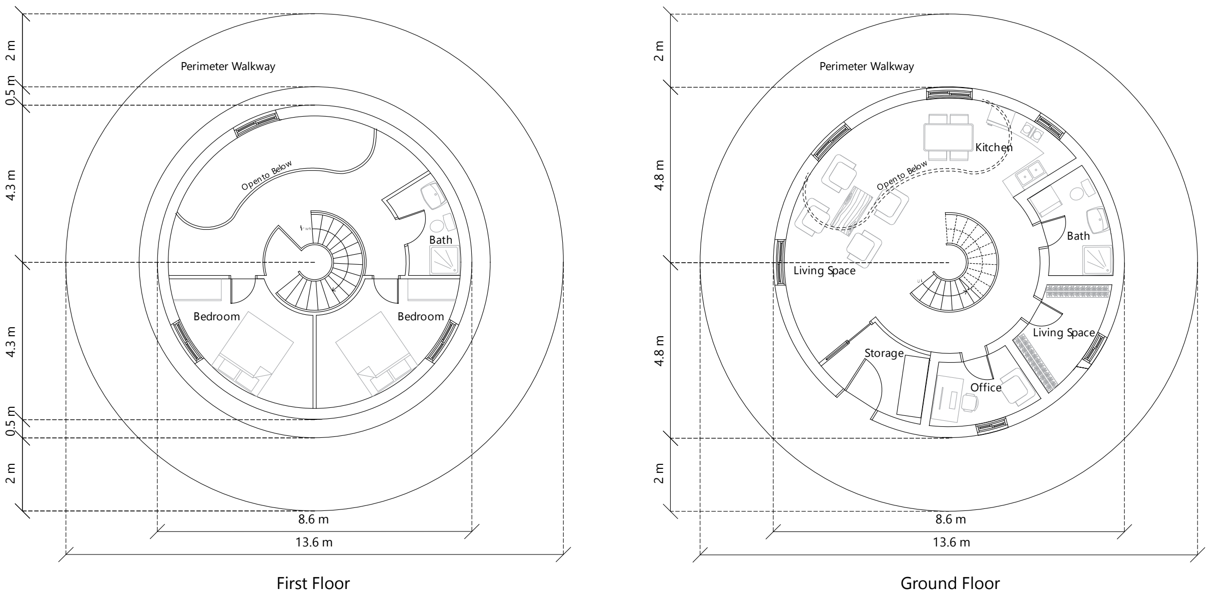

Figure 7 Plans of the proposed design

5 Discussion and Future Work

While this research primarily focuses on advancing the design and construction of structures using different techniques and both exploring new materials and improving existing ones, such as the concrete used for 3D printing. However, there is still much to explore when it comes to understanding wall structures and compositions. It is essential to understand the details of wall construction to increase efficiency, strength, and sustainability in Arctic regions. Future studies should investigate the materials and layering methods used in constructing walls for Arctic homes, including evaluating the effectiveness of insulation materials in extreme cold, testing various wall compositions for structural performance under heavy snow loads and permafrost conditions, and exploring eco-friendly materials to reduce environmental impact during construction.

To improve Inuit housing designs, future initiatives aim to merge traditional building practices with modern technology. This could involve collaborating with Inuit communities through workshops to gather perceptions on construction methods, and study existing structures for practical design understandings and performance evaluation. Additionally, employing tools to simulate different wall compositions under real Arctic conditions will be essential for future research works.

Developing compositions and integrating them into CD and sustainable construction methods is a significant advancement. Further research in this field will not only improve the strength of Arctic housing but also ensure that these solutions align with the cultural and environmental needs of the communities they serve. By continuously exploring and refining these elements, we can help create eco-friendly and culturally sensitive housing solutions for Northern Canada's conditions.

6 Conclusion

This paper explores the problem of the housing crisis in the Northern Canada regions, specifically focusing on Nunavut. By using Computational Design (CD) tools, along with building techniques such as Cross-Laminated Timber (CLT) and 3D printing, the study introduces a forward-looking strategy for developing adaptable, eco-friendly, and culturally innovative housing solutions where Indigenous people’s culture and tradition are rooted by the connection with their land.

The suggested design approach not only aim to improve efficiency and material application, but also highlights the significance of integrating Indigenous cultural elements into architectural processes. This methodology ensures that new housing solutions are not just technically sound but also align with the traditions and values of Inuit communities.

Prominent aspects of the proposed design include the incorporation of CLT structures for transport and the use of 3D-printed components to improve accuracy and minimize material waste. These tactics collectively face the environmental obstacles associated with building residences in harsh Arctic landscapes. While offering a framework and initial design ideas, the study underscores the necessity for further investigation, particularly in analyzing wall compositions, their detailed structural properties, and their thermal efficiency.

While this methodology is promising, this research is still primarily theoretical. Future research should focus on integration practical applications, even if partial, in order to validate the theoretical models. Through detailed studies on material characteristics, the ability to withstand extreme conditions, and real-world performance of suggested solutions are important. Furthermore, integration of advanced simulation tools would be beneficial for exploring new results and collaborative efforts with Indigenous communities may improve and suggest new design solutions.

In summary, this study focuses on how merging Computational Design (CD) with building methods can lead to eco-culturally sensitive housing options for harsh climates. By establishing a benchmark for forward-progressive architectural approaches, this investigation makes a meaningful impact on meeting the critical demand of housing in the permafrost areas of Northern Canada.

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